SYMPOSIUM

PROCEEDINGS

9th - 10th August 2024

TAJ SAMUDRA HOTEL
COLOMBO

The 12th World Construction Symposium - 2024

Empowering Construction Industry: Towards Sustainable Development Goals

Organized by

CEYLON INSTITUTE OF BUILDERS (CIOB) SRI LANKA

DEPARTMENT OF BUILDING ECONOMICS
UNIVERSITY OF MORATUWA

Associate partners

WESTERN SYDNEY UNIVERSITY

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

DEAKIN UNIVERSITY

THE UNIVERSITY of ADELAIDE

MASSEY UNIVERSITY
UNIVERSITY OF NEW ZEALAND

SCHOOL OF BUILT ENVIRONMENT

PROCEEDINGS

of

THE 12TH WORLD CONSTRUCTION SYMPOSIUM 2024

ON

EMPOWERING CONSTRUCTION INDUSTRY: TOWARDS SUSTAINABLE DEVELOPMENT GOALS

09-10 August 2024

EDITORS

Prof. Y.G. Sandanayake
Prof. K.G.A.S. Waidyasekara
Dr. K.A.T.O. Ranadewa
Dr. H. Chandanie

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

Edited by Prof. Y. G. Sandanayake, Prof. K.G.A.S. Waidyasekara, Dr. K.A.T.O. Ranadewa and Dr. H. Chandanie

ISSN: 2362-0919

SYMPOSIUM ORGANISERS

The Ceylon Institute of Builders (CIOB), Sri Lanka

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

http://www.ciob.lk/

Department of Building Economics University of Moratuwa, Sri Lanka

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

https://uom.lk/becon

ASSOCIATE PARTNERS

Western Sydney University, Australia

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

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

The University of Newcastle, Australia

The University of Newcastle is a leader in university education, with a reputation for high quality teaching and learning and exciting, contemporary academic programs. It is a research-intensive university and a leading contributor to research in Australia and the world. The University of Newcastle is ranked in the top 10 Australian universities based on research excellence.

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

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. he 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/

Deakin University, Australia

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

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

ASSOCIATE PARTNERS

Massey University, New Zealand

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

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

Colombo School of Construction Technology (CSCT), Sri Lanka

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

https://csct.edu.lk/

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 recognised by CIB, and indexed by SCOPUS, EBSCO, INSPEC and the Emerging Sources Citation Index (ESCI) of Thomas Reuters.

www.emeraldinsight.com/bepam.htm

ACKNOWLEDGEMENT

We would like to express our sincere appreciation to the Ceylon Institute of Builders (CIOB) for inviting Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa to jointly organise this 12th World Construction Symposium (WCS) on the pertinent theme, “Empowering Construction Industry: Towards Sustainable Development Goals”. This year symposium marks the 12th milestone of the WCS series, which was initiated back in 2012 and was held with the contribution and support extended by many individuals and organisations. Thus, we want to extend our sincere gratitude to the numerous parties who contributed in various ways to make this event a success.

Firstly, we would like to thank our associate partners Western Sydney University, Australia; The University of Newcastle, Australia; Deakin University, Australia; Massey University, New Zealand; The University of Adelaide; Australia; Colombo School of Construction Technology (CSCT), Sri Lanka; and Built Environment Project and Asset Management (BEPAM): Journal, published by Emerald Group Publishing.

We particularly appreciate all the authors for selecting the 12th World Construction Symposium as a platform to disseminate their research work. Our special thanks also go to the eminent international and local scientific committee members for reviewing and offering constructive comments on the papers, which helped to ensure that the accepted papers for the symposium were of a high standard. We would like to extend our gratitude towards the chief guest, keynote speakers, panellists, session chairs, session coordinators, paper presenters and other invitees for their commitment and contributions towards the symposium. The support and enthusiasm of all these parties allowed us to still maintain the momentum of the annual WCS series even while using a digital platform.

Our special thanks also go to Editor-in-Chief of BEPAM Journal and the team at Emerald Group Publishing for their contributions to the symposium. A special thank you goes out to all the sponsors who have provided sponsorships to bring this year’s symposium to fruition. We are also thankful to all the government and other institutions and all our supporting partners who have supported the symposium in various ways.

The panel discussion on the theme "Optimising Use and Minimising Misuse of Public-Private Partnerships in Developing Countries" brought together expert panelists from Indonesia, China, Sri Lanka, and the UK. This insightful event was held in a hybrid mode, combining both online and physical participation, allowing a global exchange of ideas and experiences. The diverse panel highlighted the critical importance of tailoring Public-Private Partnerships (PPPs) to the unique needs and challenges of developing nations, emphasizing the need for careful planning, transparent governance, and effective collaboration between public and private sectors to ensure sustainable development and equitable growth.

Last but not least, a special thank you goes out to all our colleagues in the organising committee, symposium secretariat and the Department of Building Economics for devoting their time and efforts to make this 12th World Construction Symposium 2024 a success.

Editors

The 12th World Construction Symposium
Colombo, Sri Lanka
August 2024

PREFACE

The 12th World Construction Symposium (WCS 2024), jointly organised by the Ceylon Institute of Builders (CIOB) and Building Economics and Management Research Unit (BEMRU), Department of Building Economics, University of Moratuwa was held on hybrid mode from 09-10 August 2024. The symposium was held in partnership with Western Sydney University, Australia; The University of Newcastle, Australia; Deakin University, Australia; Massey University, New Zealand; The University of Adelaide; Australia; Colombo School of Construction Technology (CSCT), Sri Lanka; and Built Environment Project and Asset Management (BEPAM): Journal, published by Emerald Group Publishing. This year's symposium marks the 12th milestone of the WCS symposium series, which has been held annually since 2012. Throughout the past decade, we are happy to see WCS grow in success and gaining recognition from academics and industry participants from around the world, providing a multi-stakeholder platform for those involved in the built environment and construction industry related research and practice to come together to share their knowledge and experiences. While the Sri Lankan construction industry along with its economy is yet experiencing difficult times and struggling to recover, this year's symposium was organized around the theme "Empowering Construction Industry: Towards Sustainable Development Goals" on hybrid mode.

We received a large number of full papers for the symposium, all of which underwent a rigorous review process as detailed below:

- All submitted full papers were sent to at least two independent referees selected from the symposium scientific committee for double-blind peer review. Reviewers provided constructive comments with respect to the originality, significance, reliability, quality of presentation and relevance to the remit of the symposium of each paper. The Scientific Committee Co-chairs, who are the editors of the symposium proceedings, were responsible for final decisions on accepting or rejecting the papers based on these assessments.
- At least one of the authors of all the accepted papers were required to register and orally present the paper in the symposium.

Altogether, 87 papers were selected for publication following the review process. It is worthwhile to note that the authors of the selected papers are from a range of different countries including Australia, India, Indonesia, Sri Lanka, South Africa, Malaysia and United Kingdom. The papers covered a wide spectrum of areas under 19 sub-themes such as such as Cultural Implications of Built Environment Sustainability, Green Solutions for Construction, Sustainable and Resilient Built Facilities, Facilities Management Strategies for Enhancing Sustainability in the Built Environment, Innovative Approaches and Technologies for Improving Construction Project Performance, Sustainable Solutions for Construction, Modernising Construction Human Resource Management, Design for Human Wellbeing, Process Improvement Strategies for Construction Management, Human Contribution to Sustainable Construction, Circular Economy for Sustainable Construction, Optimizing Construction Efficiency Through Lean Methods and Strategic Procurement, Smart Digitalisation for Sustainable Construction, Strategies to Enhancing Process Management in Construction Organisations, Project Financing and Construction Cost Management, Smart Building Innovations towards Sustainability, Sustainable Construction Technologies, Smart Technologies for Resolving Construction Disputes, Sustainable Solutions for Residential Buildings.

We as the Scientific Committee Co-chairs are committed to ensuring ethics in publication and quality of articles. Hence, priority was given to the quality and standard of papers rather than the number of papers presented at the symposium. The proceedings emerging from this symposium represent the result of the tireless efforts of all authors and reviewers and has been supported by the support received from symposium organising committee members, associate partners and sponsors. We hope it would pave way for advancement of knowledge as we strive towards a smart, sustainable and resilient built environment.

ORGANISING COMMITTEE

Chairperson	Prof. Chitra Weddikkara
Co-Chairpersons	Eng. Sagara Gunawardena Mr. Kalana Alwis
Advisors	Dr. Rohan Karunaratne Eng. Saliya Kaluarachchi Prof. Yasangika Sandanayake
Organising Committee	Mr. Ruwan De Silva Mr. Jayakish Thudawe Eng. Ashoka Randeni Dr. Tissa Meepe Prof. H.L. Obeysekara
Scientific Committee Co-Chairpersons	Prof. Yasangika Sandanayake Prof. Anuradha Waidyasekara Dr. Tharusha Ranadewa Dr. Chandanie Hadiwattege
Symposium Secretariat	Mr. Isuru Eranga Ms. Niwanthika Kurukulasooriya Ms. Isuri Illeperuma Mr. Dulshan Costa Mr. Rohana Balasuriya Ms. Malathi Piyasena
Symposium Support Team	Mr. Sasanka Gallage Mr. Dilshan Akalanka Ms. Nishadi Nanayakkara Mr. Yasith Sandaruwan Mr. Dilan Weerasooriya Mr. Lakshitha Bandaranayake Ms. Dasuni Kodithuwakku Ms. Thilini Liyanawatta Ms. Vithusha Lingasabesan Mr. Hasith Chathuranga Ms. Ashinshana Ilangakoon Ms. Dewmini Wijerathna

Ms. Mathanky Sachinthanatham
Ms. Diyana Ranasinghe
Ms. Piyumi Tennakoon
Mr. Lakshitha Fernando
Mr. S.L.J.R. Perera

SCIENTIFIC COMMITTEE

Chairpersons

Prof. Yasangika Sandanayake	*University of Moratuwa, Sri Lanka*
Prof. Anuradha Waidyasekara	*University of Moratuwa, Sri Lanka*
Dr. Tharusha Ranadewa	*University of Moratuwa, Sri Lanka*
Dr. Chandanie Hadiwattege	*University of Moratuwa, Sri Lanka*

Members

Prof. Alfred Ngowi	*Central University of Technology, United States of America*
Dr. Amalka Nawarathne	*University of The West of England Bristol, United Kingdom*
Dr. Anupa Manewa	*Liverpool John Moores University, United Kingdom*
Dr. Aparna Samaraweera	*University of South Australia, Australia*
Dr. Argaw Gurmu	*Deakin University, Australia*
Dr. Anushika Chathurangi Ekanayake	*Birmingham City University, United Kingdom*
Prof. Arun Chandramohan	*National Institute of Construction Management and Research, India*
Dr. Ashan Asmone	*University of Cambridge, United Kingdom*
Prof. Ashwin Mahalingam	*Indian Institute of Technology, Madras, India*
Prof. Bingunath Ingirige	*University of Salford, United Kingdom*
Dr. Biyanka Ekanayake	*University of Technology Sydney, Australia*
Prof. Bon-Gang	*National University of Singapore, Singapore*
Dr. Buddhini Ginigaddara	*University of Newcastle, Australia*
Mr. Cameron Beard	*University of Newcastle, Australia*
Prof. Chaminda Pathirage	*University of Wolverhampton, United Kingdom*
Dr. Chamitha Wijewickrama	*University of Adelaide, Australia*
Dr. Chandanie Hadiwattage	*University of Moratuwa, Sri Lanka*
Dr. Chethana Illankoon	*University of New South Wales, Australia*
Mr. Chinthaka Atapattu	*Massey University, New Zealand*
Dr. Cong Yu	*University of Hong Kong, Hong Kong*
Dr. Devindi Geekiyanage	*University of Salford, United Kingdom*
Dr. Dilani Abeynayake	*University of Moratuwa, Sri Lanka*
Dr. Dumindu Soorige	*University of Moratuwa, Sri Lanka*
Dr. Gamini Weerasinghe	*University of Moratuwa, Sri Lanka*
Dr. Gayan Wedawatta	*University of Aston, United Kingdom*
Dr. Gayani Karunasena	*Deakin University, Australia*
Dr. Gihan Tennakoon	*University of South Australia, Australia*
Dr. Harshini Mallawarachchi	*University of Moratuwa, Sri Lanka*

SYMPOSIUM INFORMATION

IMPORTANT: To ensure the proper execution of WCS 2024 hybrid symposium, please pay special attention to the instructions below. If you have any questions or difficulties following the guidelines, please contact the WCS 2024 Secretariat (info@ciobwcs.com) who will be happy to help.

How will WCS 2024 hybrid symposium work?

The conference is delivered physically at Taj Samudra, 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 2024 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 is held in the WCS 2024 main meeting room.

As with in-person conferences, there is 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 05 August 2024 and the secretariat will manage the requests.

Preparing for your Virtual Session - Instructions for Virtual Presenters:

Use the instructions below when presenting your paper at WCS 2024 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 2024 Hybrid Symposium

To access the symposium virtually:

Join the 12th World Construction Symposium https://us06web.zoom.us/j/5808623059?pwd=AzkBwsYmOLoy9jO4liJ4yfBuZfUhxY.1&omn=73004658196
Meeting ID: 580 862 3059 Passcode: wcs@2024

- 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 WCS2024 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

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 du cause.

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 12th World Construction Symposium 2024

I am honored to be part of one of the major symposiums in Sri Lanka, now in its 12th consecutive year. This year, we are especially blessed to gather in person after a long pause. The event is organized with the esteemed patronage of the Ceylon Institute of Builders (CIOB) and the Building Economics and Management Research Unit (BEMRU) at the Department of Building Economics, University of Moratuwa.

The 12th World Construction Symposium is a pivotal gathering that unites experts, innovators, and practitioners from across the globe to explore the theme of "Empowering the Construction Industry: Towards Sustainable Development Goals." As we convene this year, we acknowledge the construction industry’s vital role in shaping a sustainable future, addressing complex challenges, and fostering economic, environmental, and social well-being.

The construction sector has a unique opportunity to drive transformative change by adopting sustainable practices, integrating innovative technologies, and promoting ethical standards. Together, we can forge pathways that not only meet today’s infrastructural demands but also ensure a better tomorrow for future generations.

I extend my heartfelt gratitude to our sponsors, partners, and organizing committee for their unwavering support and dedication. Their commitment has been instrumental in facilitating meaningful exchanges that undoubtedly lead to actionable outcomes.

Let us harness our collective expertise and creativity to empower the construction industry, contributing to a sustainable, resilient, and inclusive world. Thank you for joining us at the 12th World Construction Symposium. I look forward to the engaging sessions and fruitful dialogues that await us.

MESSAGE FROM THE PRESIDENT, CIOB

Dr. Rohan Karunaratne

President
The Ceylon Institute of Builders (CIOB)

I am pleased to welcome you to the 12th World Construction Symposium, 2024 held during the period 9th and 10th August, 2024 in Colombo. It gives me immense pleasure to inform you that our institute, 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 at the Symposium. Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, Sri Lanka is the joint organizer of this Symposium. I would like to express gratitude to them for their firm commitment and backing. I am also thankful to the Associate Partners of the Symposium.

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

It is indeed an honour to have a renowned 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.

My best wishes to all of you who have joined the conference for gaining and spreading knowledge.

MESSAGE FROM THE HONY. SECRETARY, CIOB

Eng. Saliya Kaluarachchi

Hon. Secretary
The Ceylon Institute of Builders (CIOB)

I take great pleasure in welcoming all the delegates to the 12th World Construction Symposium 2024 on the theme "Empowering Construction Industry: Towards Sustainable Development Goals" to be held on the 9th and 10th August 2024 in Colombo. CIOBWCS is an exciting annual venture organized jointly by the Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, Sri Lanka.

The purpose and vision of this symposium is the promotion of academic and research activities in the field of Sustainable Construction. The Symposium will bring all like-minded individuals on a single platform to discuss new trends and challenges in the field of Sustainable Construction. In the Symposium, Sri Lankan academics, research scholars and practitioners will get the opportunity to interact with eminent experts from overseas on sustainable construction and new trends in global built environment.

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 SYMPOSIUM CO-CHAIRPERSONS

Mr. Kalana Alwis

Mr. Sagara Gunawardena

Co-Chairpersons
Organizing Committee
The 12th World Construction Symposium

On behalf of Ceylon Institute of Builders (CIOB) we take great pleasure in welcoming you to the 12th World Construction Symposium to be held on the 9th and 10th August 2024 in Colombo. As you already know, this annual symposium has been jointly organized by the Ceylon Institute of Builders and Department of Building Economics, University of Moratuwa since the year 2012.

The theme for the symposium will be “Empowering Construction Industry: Towards Sustainable Development Goals” by keeping in line with the global position and the sustainable goals in the construction industry.

As you know CIOB’s initiatives with the University of Moratuwa through the highly acknowledged event, the WCS, play a leading role in the sustainable development process for the construction industry. This has further strengthened integrated multidisciplinary teams to develop a number of appropriate technologies in the field of research and development Recognition of such outstanding research achievements among 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. Moreover, over the years gaining the Scopus indexed accomplishment is a significant achievement for the WCS by the University of Moratuwa.

While congratulating and appreciating the work done by the global and local participants of the 12th WCS for the enhancement of the Construction Industry through this important global event, we wish the WCS2024 every success in all its endeavors.

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

Prof. Anuradha Waidyasekara

Head of the Department
Department of Building Economics
University of Moratuwa

It is a great pleasure and honour to send this message to express my warmest wishes for the 12th World Construction Symposium 2024. This is a remarkable venture jointly organized by the Ceylon Institute of Builders (CIOB) and the Building Economics and Management Research Unit (BEMRU), Department of Building Economics, University of Moratuwa, Sri Lanka for the twelfth consecutive year successfully. Several national and international partners are joining hands for the symposium including 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 and University of Adelaide, Australia.

The Sri Lankan construction industry is experiencing a significant downturn in projects, driven by rising raw material costs and an economic crisis. As a result, a sector that has previously contributed greatly to the country's economic growth has collapsed. In response, the industry recognises the urgent need to focus on sustainability and resilience to better withstand such challenges in the built environment. In this context, the 12th World Construction Symposium is themed "Empowering the Construction Industry: Towards Sustainable Development Goals," highlighting its relevance and timeliness.

The 12th World Construction Symposium 2024 allows local and international delegates to showcase their knowledge, experiences, innovative ideas, and research findings related to Empowering the Construction Industry: Towards Sustainable Development Goals. Accordingly, I expect all delegates would yield this opportunity to share their knowledge and perceptions on the theme of the year.

I wish all the success for the 12th World Construction Symposium 2024.

CONTENTS

SYMPOSIUM AGENDA

FRIDAY, 09 AUGUST 2024 – DAY ONE	
12.30 pm - 01.30 pm	Symposium Registration
01.30 pm - 01.45 pm	Symposium Inauguration
01.45 pm - 01.55 pm	Welcome address by President, CIOB **Dr. Rohan Karunaratne**
01.55 pm - 02.05 pm	Address by Conference Chairperson **Prof. Chitra Weddikkara**
02.05 pm - 02.15 pm	Address by Deputy Vice Chancellor, University of Moratuwa **Dr. D.P. Chandrasekara**
02.15 pm - 02.30 pm	Address by the Chief Guest **Prof. Ranjith Dissanayake**
02.30 pm - 03.00 pm	Keynote Address 1 **Prof. Charles Egbu**
03.00 pm - 03.10 pm	Sponsors Video 1
03.10 pm - 03.30 pm	Address by Editor-in-Chief, BEPAM Journal **Prof. Mohan Kumaraswamy**
03.30 pm - 04.00 pm	Keynote Address 2 **Prof. Narein Perera**
04.00 pm - 04.10 pm	Sponsors Video 2
04.10 pm - 04.20 pm	Symposium Participants Screenshot Photo
04.20 pm - 04.30 pm	Vote of Thanks by Hony. Secretary, CIOB **Eng. Saliya Kaluarachchi**
04.30 pm - 05.00 pm	Refreshments
05.00 pm - 07.00 pm	Parallel Sessions 1
07.00 pm	End of Day 1

SATURDAY, 10 AUGUST 2024 – DAY TWO	
08.30 am - 10.30 am	Parallel Sessions 2
10.30 am - 11.00 am	Refreshments
11.00 am - 12.30 pm	Parallel Sessions 3
12.30 pm - 01.30 pm	Lunch
01.30 pm - 03.00 pm	Parallel Sessions 4
03.00 pm - 03.30 pm	Refreshments
03.30 pm - 05.00 pm	Panel Discussion on ***"Optimising Use and Minimising Misuse of Public Private Partnerships in Developing Countries"*** ***Introduction-Background:*** Prof. Mohan Kumaraswamy, Prof. Akintola Akintoye, Prof. Giovanni Migliaccio: *Joint Co-ordinators, CIB W122 on PPP* ***Panelists:*** Research Prof. Andreas Wibowo Associate Prof. Yongjian Ke Eng. Nissanka Wijeratne Mr. Chanaka De Silva (President's Counsel, Sri Lanka) ***Moderators:*** Prof. Mohan Kumaraswamy and Dr. Suranga Jayasena
05.00 pm - 05.10 pm	Break
05.10 pm - 05.20 pm	Announcing the Award Winners **Prof. Mohan Kumaraswamy** **Prof. Yasangika Sandanayake**
05.20 pm - 05.30 pm	Vote of Thanks by Scientific Committee Co-Chairperson **Prof. Anuradha Waidyasekara**
05.30 pm	End of Day 2
07.00 pm Onwards	**SYMPOSIUM DINNER**

SYMPOSIUM SESSION PLAN AT-A-GLANCE					
Friday , 9th August 2024 – Day One					
12.30 pm - 01.30 pm	**Symposium Registration**				
01.30 pm - 04.30 pm	**Symposium Inauguration**				
04.30 pm - 05.00 pm	**Break**				
05.00 pm - 07.00 pm	**Session 1A - Online**	**Session 1B**	**Session 1C**	**Session 1D**	
	S16024	T16009	S16084	S16132	
	S16031	T16015	S16092	S16021	
	S16138	S16080	S16091	S16052	
	S16103	S16011	S16083	S16056	
		S16020	S16109	S16120	
	Q&A	Q&A	Q&A	Q&A	
07.00 pm	**End of Day 1**				
Saturday, 10th August 2024 – Day Two					
08.15 am - 08.30 am	**Symposium Registration**				
08.30 am - 10.30 am	**Session 2A - Online**	**Session 2B**	**Session 2C**	**Session 2D**	**Session 2E**
	S16005	S16046	S16033	S16042	S16129
	S16006	S16055	S16053	S16047	S16073
	S16087	S16086	S16085	S16041	S16076
	S16036	S16035	S16140	S16067	S16034
	S16004	S16133	S16130	S16128	S16117
	Q&A	Q&A	Q&A	Q&A	Q&A
10.30 am - 11.00 am	**Break**				
11.00 am - 12.30 pm	**Session 3A - Online**	**Session 3B**	**Session 3C**	**Session 3D**	**Session 3E**
	S16010	S16088	S16074	S16043	S16066
	S16049	S16100	S16090	S16044	S16037
	S16139	S16111	S16110	S16045	S16113
	S16039	S16008	S16131	S16027	S16136
			S16114	S16054	S16102
	Q&A	Q&A	Q&A	Q&A	Q&A

12.30 pm - 01.30 pm	**Break**				
01.30 pm - 03.00 pm	**Session 4A - Online**	**Session 4B**	**Session 4C**	**Session 4D**	**Session 4E**
	S16023	S16094	S16019	S16050	S16115
	S16032	S16108	S16029	S16105	S16068
	S16093	S16101	S16106	S16112	S16126
		S16082	S16025	T16122	S16137
				S16107	
	Q&A	Q&A	Q&A	Q&A	Q&A
03.00 pm - 03.30 pm	**Break**				
03.30 pm - 05.00 pm	**Panel Discussion**				
05.00 pm - 05.10 pm	**Break**				
05.10 pm – 05.30 pm	**Symposium Sum-Up**				
05.30 pm	**End of Day 2**				
07.00 pm onwards	**Fellowship and Awards Night at Taj Samudra, Colombo**				

DETAILED SESSION PLAN

FRIDAY, 09 AUGUST 2024

SESSION 1A (Online)	
Theme	**Cultural Implications of Built Environment Sustainability**
Session Chair	**A/ Prof. Nirodha Fernando**
Time	**05.00 PM - 07.00 PM**
Virtual	**Breakout Room - Session A**

Time	**Paper ID, Title and Author(s)**
05.00 PM - 05.15 PM	**S16024: 'Plan Of Action' for organisational change: A case study of Indian public sector construction organisation** *S.R. Shahu, A. Iyer and A.G. Tawalare,*
05.15 PM - 05.30 PM	**S16031: Impact of corruption on achieving sustainable development goals within Africa's construction industry** *Abiola Aderibigbe, Nnedinma Umeokafor, Tariq Umar and Yog Upadhyay*
05.30 PM - 05.45 PM	**S16138: 5S principles for sustainable resource and waste management in Sri Lankan construction projects** *E.D.A.T. Wijesinghe, T.S. Jayawickrama, Gihan Anuradha Tennakoon and M.K.C.S. Wijewickrama*
05.45 PM - 06.00 PM	**S16103: Mitigation measures for conflicting situations on Indian construction sites** *Uttam Singh Chauhan, Sudarshan Saikia and Sparsh Johari*
06.00 PM - 07.00 PM	**Q&A**

Session Coordinator: Mr. Dilan Weerasooriya

FRIDAY, 09 AUGUST 2024

SESSION 1B

Theme	**Green Solutions for Construction**
Session Chair	**Prof. Lalith De Silva**
Venue/Time	**Crystal Ballroom - 05.00 PM - 07.00 PM**
Virtual	**Breakout Room - Session B**

Time	Paper ID, Title and Author(s)
05.00 PM - 05.15 PM	**T16009: Design and development of a green roof substrate for the tropics** *G.K.P. John, A.M.M.G. Munasinghe, K.G.N.H. Weerasinghe and R.U. Halwatura*
05.15 PM - 05.30 PM	**T16015: Lifecycle carbon emissions: Adaptive reuse vs new buildings in Sri Lanka** *M.K.M. Prabodani, S.S. Ranasinghe and R.U. Halwathura*
05.30 PM - 05.45 PM	**S16080: Adaptation of green building concept to existing government office buildings in Sri Lanka** *T.H.S. Jayoda, K.A.D.M. Natasha and U. Rathnayake*
05.45 PM - 06.00 PM	**S16011: Internet Of Things (IOT) enabled carbon emission monitoring in residential buildings: A bibliometric analysis** *J.A.D.K.S. Jayakodi, B.H. Mallawaarachchi and Y.J.M. Yatawatta*
06.00 PM - 06.15 PM	**S16020: Analysing people's behaviour towards indoor air quality management: A case study in Kandy, Kurunagala and Hambanthota** *K.A.S.H. Wijayasenaratne, R.M.D.I. Rathnayake, A.G.H.M. Rajakaruna, W.K.T. Dulanjana, R.A.K.S. Ranasinghe and R.T.K. Ariyawansha*
06.15 PM - 07.00 PM	**Q&A**

Session Coordinator: Ms. Indrani Wimalaratne

FRIDAY, 09 AUGUST 2024

SESSION 1C	
Theme	**Sustainable and Resilient Built Facilities**
Session Chair	**Dr. Mohan Siriwardena**
Venue/Time	**Grand Crystal Ballroom - 05.00 PM - 07.00 PM**
Virtual	**Breakout Room - Session C**

Time	**Paper ID, Title and Author(s)**
05.00 PM - 05.15 PM	**S16084: Investigating community-based participatory design approaches in planning and constructing public community facilities: A scoping review** *S. Malintha H. Fernando, Y. Inodee Fernando and U. Kulatunga*
05.15 PM - 05.30 PM	**S16092: Revisiting the notion of 'public spaces': Professional and community perspectives** *W.S.D. Perera, U. Kulatunga, M.C.K. De Silva, N. Dias*
05.30 PM - 05.45 PM	**S16091: Assessment of community disaster resilience in Sri Lanka: Methodological approach in developing an index** *K.H.K. Dharmadasa, U. Kulatunga, M. Thayaparan and K.P. Keraminiyage*
05.45 PM - 06.00 PM	**S16083: Building community resilience to economic impacts of climate change on livelihoods: The methodological perspective** *Malsha Buddha Koralage, Udayangani Kulatunga and Bingunath Ingirige*
06.00 PM - 06.15 PM	**S16109: Harnessing nature's blueprint: Biomimicry in urban building design for sustainable and resilient cities** *Ashen Rahubadda and Udayangani Kulatunga*
06.15 PM - 07.00 PM	**Q&A**

Session Coordinator: Mr. Lakshitha Fernando

FRIDAY, 09 AUGUST 2024

SESSION 1D	
Theme	**Facilities Management Strategies for Enhancing Sustainability in the Built Environment**
Session Chair	**Prof. Nayanthara De Silva**
Venue/Time	**Regency Room - 05.00 PM - 07.00 PM**
Virtual	**Breakout Room - Session D**

Time	**Paper ID, Title and Author(s)**
05.00 PM - 05.15 PM	**S16132: Influence of behavioural constructs on building practitioner's minimal compliance with residential building energy performance standards in Australia** *Yi Lu, Gayani Karunasena and Chunlu Liu*
05.15 PM - 05.30 PM	**S16021: A comparative analysis of operational energy by simulation study between modern buildings and adaptive reuse of historic buildings in Sri Lanka** *N. Thirukumaran, M.K.M. Prabodani, S.S. Ranasinghe, G.Y. Jayasinghe and R.U. Halwathura*
05.30 PM - 05.45 PM	**S16052: The need for a climate database for facilities managers to mitigate the climate change implications on buildings** *M.N.U. Maddakandage and P. Sridarran*
05.45 PM - 06.00 PM	**S16056: Misconceptions in heating, ventilation and air conditioning - airside strategy implementation of commercial buildings in Sri Lanka** *P.A.P.Y. Gajaba and Piumi Dissanayake*
06.00 PM - 06.15 PM	**S16120: Fire under control: Enhancing warehouse safety through strategic fire prevention and risk management** *S. Nadarajah, U. Kulatunga, D. Weerasooriya and A.P. Rathnasinghe*
06.15 PM - 07.00 PM	**Q&A**

Session Coordinator: Ms. Diyana Ranasinghe

SATURDAY, 10 AUGUST 2024	
SESSION 2A (Online)	
Theme	**Innovative Approaches and Technologies for Improving Construction Project Performance**
Session Chair	**A/Prof. Gajendran Thayaparan**
Time	**08.30 AM - 10.30 AM**
Virtual	**Breakout Room - Session A**

Time	Paper ID, Title and Author(s)
08.30 PM - 08.45 PM	**S16005: BIM and blockchain integrated construction management: A review** *Rhijul Sood, Nandini Sharma and Boeing Laishram*
08.45 PM - 09.00 AM	**S16006: Evaluation of the benefits of the implementation of digital twins in sustainable construction projects** *AbdulLateef Olanrewaju, Shalini Sanmargaraja, Seong Yeow Tan and Hui Chen Chu*
09.00 AM - 09.15 AM	**S16087: Exploring opportunities and challenges in integrating industry 4.0 for advancements in the Sri Lankan construction sector** *Hasara Sendanayake, Amalka Nawarathna and Nirodha Fernando*
09.15 AM - 09.30 AM	**S16036: A conceptual framework to manage circular economy knowledge in construction projects** *Malsha Buddha Koralage, Nilupa Udawatta and Gayani Karunasena*
09.30 AM - 09.45 AM	**S16004: Sustaining concrete structural integrity: S framework for defect identification and rectification methods** *Kripal Kanakan and Argaw Gurmu*
09.45 AM - 10.30 AM	**Q&A**

Session Coordinator: Mr. Lakshitha Bandaranayake

SATURDAY, 10 AUGUST 2024

SESSION 2B

Theme	**Sustainable Solutions for Construction**
Session Chair	**Prof. Udayangani Kulatunga**
Venue/Time	**Crystal Ballroom - 08.30 AM - 10.30 AM**
Virtual	**Breakout Room - Session B**

Time	Paper ID, Title and Author(s)
08.30 PM - 08.45 PM	**S16046: Assessment of effective waste recycling practices to minimise construction and demolition waste in Sri Lankan construction industry** *M.R.O.V. Amararathne and K.P.S.P.K. Bandara*
08.45 PM - 09.00 AM	**S16055: feasibility assessment of smart grid technology for the Sri Lankan urban areas** *E.G.L.S. Rajapaksha, U. Rathnayake and A.S.W. Karunarathna*
09.00 AM - 09.15 AM	**S16086: Exploratory study on adaptability of wall-mounted solar panels for high-rise buildings in Sri Lanka** *Ravindu Yahanpath, W.M.C.L.K. Wijekoon and Janani Uvasara Kumarathunga*
09.15 AM - 09.30 AM	**S16035: Application of biomimicry concept to improve the sustainability of the construction industry: A literature review** *F.H.Y.D. Silva, B.A.K.S. Perera, A.M.D.S. Atapattu, J.K.D.D.T. Jayanetti and M.K.C.S. Wijewickrama*
09.30 AM - 09.45 AM	**S16133: Revamping the land acquisition process for infrastructure projects in Sri Lanka: Strategies for streamlining the existing process** *U.D.R.E. Ruwanpura, B.A.K.S. Perera and K.A.T.O. Ranadewa*
09.45 AM - 10.30 AM	**Q&A**

Session Coordinator: Ms. Dewmini Wijerathne

SATURDAY, 10 AUGUST 2024

SESSION 2C

Theme	**Modernising Construction Human Resource Management**
Session Chair	**Dr. Sachie Gunathilake**
Venue/Time	**Longdon Room - 08.30 AM - 10.30 AM**
Virtual	**Breakout Room - Session C**

Time	Paper ID, Title and Author(s)
08.30 PM - 08.45 PM	**S16033: Addressing traditional HRM challenges in the construction industry: insights from modern hrm literature** *J.D.S.S. Jayasinghe, C. Hadiwattege and I.W.M.A.D. Ilangakoon*
08.45 PM - 09.00 AM	**S16053: Compare VR vs. conventional training for construction workers' safety awareness** *S.H. Hewagarusinghe and P. Sridarran*
09.00 AM - 09.15 AM	**S16085: Assessing the importance of implementing wearable technologies for construction employees in the Sri Lankan context** *K. Dilani, M.M.I.S. Mapa, Gayani Konara and W.K.U.R.M.K.P.K. Samarakoon*
09.15 AM - 09.30 AM	**S16140: Symptoms of occupational stress in construction professionals: A systematic literature review** *K.A. Gunasekara, B.A.K.S. Perera and K.A.T.O. Ranadewa*
09.30 AM - 09.45 AM	**S16130: Training and development strategies to enhance the use of modern software in quantity surveying practice in Sri Lanka** *W. Pradeep, M. Thayaparan and N.B. Nanayakkara*
09.45 AM - 10.30 AM	**Q&A**

Session Coordinator: Ms. Dasuni Kodithuwakku

SATURDAY, 10 AUGUST 2024

<u>SESSION 2D</u>	
Theme	**Design for Human Wellbeing**
Session Chair	**Dr. Pournima Sridaran**
Venue/Time	**Regency Room - 08.30 AM - 10.30 AM**
Virtual	**Breakout Room - Session D**

Time	**Paper ID, Title and Author(s)**
08.30 PM - 08.45 PM	**S16042: Design tolerance as a pedagogical tactic: The possible role of architectural design in facilitating on-site labour training** *Gayathmi Hettiarachchi and Milinda Pathiraja*
08.45 PM - 09.00 AM	**S16047: The impact of design changes on apartment projects' feasibility and project performances in Sri Lanka** *N.A.R. Sithumina, B.K.C. Perera, T. Wijesinghe and D.D. Hettiarachchi*
09.00 AM - 09.15 AM	**S16041: An examination of green space exposure for well-being: A case study of Colombo City** *H.S.A.J. Samaranayake and S.B.A. Coorey*
09.15 AM - 09.30 AM	**S16067: Incorporating smart interior design concepts in Sri Lankan apartment construction** *Rashmika Rasanjalee Karunanayaka, Janani Uvasara Kumarathunga and Iresha Gamage*
09.30 AM - 09.45 AM	**S16128: Implementation of biophilic design concept in leisure industry: Benefits and challenges** *W.D.R.P. Wickrama, K.G.A.S. Waidyasekara and H.C. Victar*
09.45 AM - 10.30 AM	**Q&A**

Session Coordinator: Ms. Ashinsana Ilangakoon

SATURDAY, 10 AUGUST 2024

SESSION 2E

Theme	**Process Improvement Strategies for Construction Management**
Session Chairs	**Prof. Kanchana Perera**
Venue/Time	**Gregory Room - 08.30 AM - 10.30 AM**
Virtual	**Breakout Room - Session E**

Time	**Paper ID, Title and Author(s)**
08.30 PM - 08.45 PM	**S16129: Feasibility of web-based microservices architecture for contract document drafting** *T.P. Dalugoda, S.D. Gallage and D.M.L.N. Bandaranayake*
08.45 PM - 09.00 AM	**S16073: Pinpointing project pitfalls: A study of critical risk factors in building construction projects in Sri Lanka** *Samindi Perera, K.V.P. Madushan and G.H.S.P. De Silva*
09.00 AM - 09.15 AM	**S16076: Investigating the challenges of implementing covid-19 preventive practices in the construction industry in Sri Lanka** *J. Thiruna, U. Kulatunga, H.F.K. AL-Dahash and M.L.S.S. Fernando*
09.15 AM - 09.30 AM	**S16034: The necessity and opportunity for upgrading quantity surveying practices based on the lessons learned during the covid-19 pandemic: A literature review** *H.S.N. Wanigasinghe, C. Hadiwattage and I.W.M.A.D. Ilangakoon*
09.30 AM - 09.45 AM	**S16117: Comparative analysis of challenges in manual and automated construction progress monitoring in Sri Lanka** *S. Dilaksha, K.A.T.O. Ranadewa, D. Weerasooriya, Agana Parameswaran and Panchali Weerakoon*
09.45 AM - 10.30 AM	**Q&A**

Session Coordinator: Ms. Vithusha Lingasabesan

SATURDAY, 10 AUGUST 2024

SESSION 3A (Online)	
Theme	**Human Contribution to Sustainable Construction**
Session Chair	**Dr. Jessica Siva**
Time	**11.00 AM - 12.30 PM**
Virtual	**Breakout Room - Session A**

Time	**Paper ID, Title and Author(s)**
11.00 AM - 11.15 AM	**S16010: Issues on foreign labourers productivity on green buildings in Selangor, Malaysia** *Shalini Sanmargaraja, Jagadish Rau Bandirau, AbdulLateef Olanrewaju, Vignes Ponniah, Anselm Dass Mathalamuthu and Gunavathy Kanniyapan*
11.15 AM - 11.30 AM	**S16049: Addressing the skilled professional shortage in Indian sustainable construction: A focus on awareness, education, training, and policy interventions** *Talari Naganarasimhulu and Abhay Tawalare*
11.30 AM - 11.45 AM	**S16139: Challenges and solutions for women in construction industry related disciplines: A literature review** *Navodana Rodrigo, M.K.C.S. Wijewickrama, Nirusika Rajenthiran, Wimarshi Jayathilaka and Ruidong Chang*
11.45 AM - 12.00 NOON	**S16039: Lean techniques for project delivery: Assessing construction professionals' level of awareness** *Matthew Ikuabe, Douglas Aghimien, Clinton Aigbavboa, Ayodeji Oke and Pretty Ramaru*
12.00 NOON - 12.30 PM	**Q&A**

Session Coordinator: Mr. Yasith Sandaruwan

SATURDAY, 10 AUGUST 2024

SESSION 3B

Theme	**Circular Economy for Sustainable Construction**
Session Chair	**Dr. Menaha Thayaparan**
Venue/Time	**Crystal Ballroom - 11.00 AM - 12.30 PM**
Virtual	**Breakout Room - Session B**

Time	**Paper ID, Title and Author(s)**
11.00 AM - 11.15 AM	**S16088: Unveiling the potential of design for deconstruction in the circular economy** *Kavini Guruge, K.G.A.S. Waidyasekara, H.S. Jayasena and R.M.A.S. Manewa*
11.15 AM - 11.30 AM	**S16100: Application of circular economy principles into tropical building designs: A literature review** *K.A.C.S. Kalu Arachchi, B.A.K.S. Perera, R.A. Dinithi Piyumra and Sajani Jayasuriya*
11.30 AM - 11.45 AM	**S16111: Adopting circular economy practices in major building materials and elements to minimise waste in Sri Lanka** *K.D.M. Bimsara, D.N. Abenayake, Vithusha Lingasabesan and V.G. Shanika*
11.45 AM - 12.00 NOON	**S16008: Taxonomy of circular economy terminologies** *Sepani Senaratne, Iresha Gamage, Shashini Jayakodi and Srinath Perera*
12.15 PM - 12.30 PM	**Q&A**

Session Coordinator: Ms. Thilini Liyanwatta

SATURDAY, 10 AUGUST 2024

SESSION 3C

Theme	**Optimizing Construction Efficiency Through Lean Methods and Strategic Procurement**
Session Chair	**Dr. Chandanie Hediwattage**
Venue/Time	**Longdon Room - 11.00 AM - 12.30 PM**
Virtual	**Breakout Room - Session C**

Time	**Paper ID, Title and Author(s)**
11.00 AM - 11.15 AM	**S16074: Issues with supply chain management documents that contribute to project delays** *Jananjaya Ekanayake, Chamari Allis, Sathya Jayasinghe and Angel Lokuge*
11.15 AM - 11.30 AM	**S16090: Key parameters of lean construction maturity: A delphi study** *J.K.D.D.T. Jayanetti, B.A.K.S. Perera and K.G.A.S. Waidyasekara*
11.30 AM - 11.45 AM	**S16110: State-of-the-art lean learning practices in construction: A case study in Sri Lanka** *Agana Parameswaran, K.A.T.O. Ranadewa, P.A.D. Rajini and J.K.D.D.T. Jayanetti*
11.45 AM - 12.00 NOON	**S16131: Challenges for commercial management in the construction industry: Case for Sri Lanka** *K.D. Sepalage, K.A.T.O. Ranadewa, M.R.D.P. Wijerathna, A. Parameswaran and D. Weerasooriya*
12.00 NOON - 12.15 PM	**S16114: Challenges for project selection and execution of public-private partnership projects in Sri Lanka** *S.A.C. Kavinda and S.D. Gallage*
12.15 PM - 12.30 PM	**Q&A**

Session Coordinator: Ms. Mathanky Sachchithananthan

SATURDAY, 10 AUGUST 2024

<u>SESSION 3D</u>	
Theme	**Smart Digitalisation for Sustainable Construction**
Session Chairs	**Dr. Suranga Jayasena**
Venue/Time	**Regency Room - 11.00 AM - 12.30 PM**
Virtual	**Breakout Room - Session D**

Time	**Paper ID, Title and Author(s)**
11.00 AM - 11.15 AM	**S16043: Navigating sustainability and digitalisation in the construction industry: A literature review** *W.K.R. Prasadinee, C. Hadiwattage and I.W.M.A.D. Ilangakoon*
11.15 AM - 11.30 AM	**S16044: Potential of virtual reality (VR) technology for safety training and accident prevention in construction** *Maheesha Silva, Chamari Allis and Chanuth De Silva*
11.30 AM - 11.45 AM	**S16045: Advancing digital technology adaptation in Sri Lankan construction firms** *D.M.U.S. Bandara, J.A.S.K Jayasinghe and P. Coomasaru*
11.45 AM - 12.00 NOON	**S16027: Unveiling the benefits of Radio Frequency Identification (RFID) technology for enhancing technological applications in Sri Lankan construction industry** *M.R.D.P. Wijerathna, K.G.A.S. Waidyasekara and A.M.D.S. Atapattu*
12.00 NOON - 12.15 PM	**S16054: The impacts of computer vision technology in construction: Investigating applications and challenges** *M.D. Dulshan Costa, M.R. Ransika Costa, M. Thayaparan*
12.15 PM - 12.30 PM	**Q&A**

Session Coordinator: Mr. Dilshan Akalanka

SATURDAY, 10 AUGUST 2024

SESSION 3E	
Theme	**Strategies to Enhancing Process Management in Construction Organisations**
Session Chair	**Ch.QS. Indunil Senavirathne**
Venue/Time	**Gregory Room - 11.00 AM - 12.30 PM**
Virtual	**Breakout Room - Session E**

Time	**Paper ID, Title and Author(s)**
11.00 AM - 11.15 AM	**S16066: Survival challenges faced by the small-scale building contractors in Sri Lanka** *R.M.K.K. Nuwandhara, A.S. Perera and G.H.S.P. De Silva*
11.15 AM - 11.30 AM	**S16037: A maturity model for digitalisation of small and medium enterprise contractors in the Sri Lankan construction industry: A focus on client and technology dimensions** *D.P.A.L.C. Devapriya and R. Palliyaguru*
11.30 AM - 11.45 AM	**S16113: Risk management in Sri Lankan SME construction sector: Identifying barriers and enablers** *B.B. Bandaranaike, S.D. Gallage and S. Sivanraj*
11.45 AM - 12.00 NOON	**S16136: Integrated project delivery implementation among construction SMEs in Sri Lanka: Barriers and strategies** *E. Edman Lukson, K.A.T.O. Ranadewa, Agana Parameswaran, M.R.D.P. Wijerathna and Dasuni Kodituwakku*
12.00 NOON - 12.15 PM	**S16102: The role of stakeholders in business model innovation in construction organisations in Sri Lanka** *D.S.I. Wijayawardena, Y.G. Sandanayake and D.M.L.N. Bandaranayake*
12.15 PM - 12.30 PM	**Q&A**

Session Coordinator: Ms. Piumi Tennakoon

SATURDAY, 10 AUGUST 2024

SESSION 4A (Online)	
Theme	**Project Financing and Construction Cost Management**
Session Chair	**Dr. Navodana Rodrigo**
Time	**01.30 PM – 03.00 PM**
Virtual	**Breakout Room - Session A**

Time	**Paper ID, Title and Author(s)**
01.30 PM - 01.45 PM	**S16023: Financing scheme for the transit-oriented development projects in Indonesia** *Mohammed Ali Berawi, Pradhana Listio Wicaksono, Gunawan Saroji, Mustika Sari and Perdana Miraj*
01.45 PM - 02.00 PM	**S16032: Making a case for foreign direct investments in the South African construction industry** *Matthew Ikuabe, Clinton Aigbavboa, Andrew Ebekozien and Samuel Adekunle*
02.00 PM - 02.15 PM	**S16093: Mapping global trends in cost of quality dynamics: A bibliometric study** *Nandini Sharma, Rhijul Sood and Boeing Laishram*
02.15 PM - 03.00 PM	**Q&A**

Session Coordinator: Mr. Dilshan Akalanka

SATURDAY, 10 AUGUST 2024

SESSION 4B

Theme	**Smart Building Innovations towards Sustainability**
Session Chair	**A/Prof. Sepani Senaratne**
Venue/Time	**Crystal Ballroom - 01.30 PM – 03.00 PM**
Virtual	**Breakout Room - Session B**

Time	Paper ID, Title and Author(s)
01.30 PM - 01.45 PM	**S16094: Enhancing data security in smart buildings leveraging blockchain technology** *D. Rashmitha Divaneth, M.M.I.S. Mapa, Gayani Konara and W.K.U.R.M.K.P.K. Samarakoon*
01.45 PM - 02.00 PM	**S16108: O2E2: A framework for evolving cost estimation in BIM workflow** *Himal Suranga Jayasena*
02.00 PM - 02.15 PM	**S16101: Augmenting performance of prefabricated MEP modular systems via BIM integration** *J.D.R. Ranathunga, C. Hadiwattege and T.M.P.N. Thennakoon*
02.15 PM - 02.30 PM	**S16082: Integrating 5D-BIM approach optimising quantity calculation efficiency in the Sri Lankan construction industry** *P. Kanimaruthan, U. Kulatunga and T.M.P.N. Thennakoon*
02.30 PM - 03.00 PM	**Q&A**

Session Coordinator: Ms. Nishadi Nanayakkara

SATURDAY, 10 AUGUST 2024

<u>SESSION 4C</u>	
Theme	**Sustainable Construction Technologies**
Session Chair	**Dr. Nandun Madhusanka**
Venue/Time	**Longdon Room - 01.30 PM – 03.00 PM**
Virtual	**Breakout Room - Session C**

Time	**Paper ID, Title and Author(s)**
01.30 PM - 01.45 PM	**S16019: Prototyping a coating based on ancient technology: A case study in Sigiriya, Sri Lanka** *K.M.K.D. Weerasekara, R.M.K.M. Rathnayake, M.S. Mendis, H. Galabada, G.Y. Jayasinghe and R.U. Halwatura*
01.45 PM - 02.00 PM	**S16029: Challenges in chemical anchoring carried out in the Sri Lankan context** *G.A.P.C.S.M. Pathiraja, R.A. Dinithi Piyumra and P.A.P.V.D.S. Disaratna*
02.00 PM - 02.15 PM	**S16106: Role of prefabricated prefinished volumetric construction in enhancing construction productivity: Sri Lankan perspective** *F. Madushan, M.D.T.E. Abeynayake and I.E. Illeperuma*
02.15 PM - 02.30 PM	**S16025: Applicability of the atmospheric water generation: The case of hotel industry in Sri Lanka** *P.M. Wijesundara, Chandanie Hadiwattage and G.G.N. Chandani*
02.30 PM - 03.00 PM	**Q&A**

Session Coordinator: Mr. Hasith Victar

SATURDAY, 10 AUGUST 2024

SESSION 4D	
Theme	**Smart Technologies for Resolving Construction Disputes**
Session Chairs	**Dr. KAK Devapriya/ Dr. Dilani Abeynayake**
Venue/Time	**Regency Room - 01.30 PM – 03.00 PM**
Virtual	**Breakout Room - Session D**

Time	Paper ID, Title and Author(s)
01.30 PM - 01.45 PM	**S16050: Smart contract applications for mitigating disputes in the construction industry** *R.M.O.H. Bandara, M.D.T.E. Abeynayake, I.E. Illeperuma and B.A.I. Eranga*
01.45 PM - 02.00 PM	**S16105: Blueprint for a natural language processing powered nexus for regulatory and legal landscape in construction** *P.V.I.N. Saparamadu, H.S. Jayasena and B.A.I. Eranga*
02.00 PM - 02.15 PM	**S16112: Incorporating digital technologies for alternative dispute resolution in the Sri Lankan construction industry** *A.P.T.M. Abeywickrama, M.D.T.E. Abeynayake, B.A.I. Eranga and I.E. Illeperuma*
02.15 PM - 02.30 PM	**T16122: AI models for predicting construction disputes in Sri Lanka** *Y.M.W.H.M.R.R.L.J.B. Kiridana, M.D.T.E. Abeynayake and B.A.I. Eranga*
02.30 PM - 02.45 PM	**S16107: Barriers for collaboration among built environment higher education: Undergraduate perspectives** *R.L. Opanayake, M. Thayaparan and K.A.L. Dasuni*
02.45 PM – 03.00 PM	**Q&A**

Session Coordinator: Mr. Lakshitha Bandaranayake

SATURDAY, 10 AUGUST 2024

<u>SESSION 4E</u>	
Theme	**Sustainable Solutions for Residential Buildings**
Session Chairs	**Prof. Samitha Manawadu**
Venue/Time	**Gregory Room - 01.30 PM – 03.00 PM**
Virtual	**Breakout Room - Session E**

Time	**Paper ID, Title and Author(s)**
01.30 PM - 01.45 PM	**S16115: Influence of BOI approvals on cost and time aspect of apartment construction in Sri Lanka** *H.R. Gurusinghe, S.D. Gallage, T.P. Dalugoda*
01.45 PM - 02.00 PM	**S16068: Behavioural adaptations and housing modification: A case study of a low-income high-rise housing estate in Sri Lanka** *G.Y.D. Warakapitiya, S.B.A. Coorey, N.G.R. Perera and R. Giridharan*
02.00 PM - 02.15 PM	**S16126: Role of micro-housing in fulfilling middle-income housing demand in urban areas: Sri Lankan perspective** *M.M.N. Mannapperuma, P.A.P.V.D.S. Disaratna and I.E. Illeperuma*
02.15 PM - 02.30 PM	**S16137: A simplified guide towards incentivising embodied carbon assessment: A case of high-rise residential building** *M. Sachchithananthan, T. Ramachandra and D. Geekiyanage*
02.30 PM - 02.45 PM	**Q&A**

Session Coordinator: Mr. Yasith Sandaruwan

KEYNOTE SPEAKERS

Prof. Charles Egbu

Vice Chancellor,
Leeds Trinity University, United Kingdom

Keynote on 'Empowering a Sustainable Future – The Role, Place, and Interconnections in Construction & The Built Environment'.

Professor Egbu joined Leeds Trinity University as Vice-Chancellor on 1 November 2020. He leads the University on all strategic matters; ensuring financial sustainability to allow the delivery of the University's Strategic Plan, including the overall vision and values of the University. He represents the University externally at various groups including Universities UK (UUK), Million Plus, the Cathedral's Group of Universities, University Vocational Awards Council (UVAC), Yorkshire Universities, and Leeds Learning Alliance (LLA). He works closely with industry and professional bodies, especially in the Built Environment sector, and with local communities. He was formerly the President of The Chartered Institute of Building (CIOB – 2019/2020). He was admitted to the Worshipful Company of Constructors in May 2017 and received the Freedom of the City of London in 2017. He was formerly Pro-Vice Chancellor (Education & Experience, University of East London), and Dean of School of the Built Environment & Architecture (London South Bank University).

Professor Egbu's research interests focus on project management, construction management, knowledge management, sustainable development, social justice, equality, diversity and inclusion; subjects about which he has written 15 books and contributed to more than 350 publications in various international journals and conferences. He has supervised over 30 PhD students and examined over 100 PhD candidates world-wide. In addition, he has led many construction industry commissions and working groups and acted as an external examiner to many undergraduate and postgraduate programmes in universities all over the world.

KEYNOTE SPEAKERS

Prof. Narein Perera

Senior Lecturer,
Faculty of Architecture,
University of Moratuwa, Sri Lanka

Keynote on 'Towards a Place Specific Response – Placemaking through Climate-sensitive Interventions in the Tropical Climate of Sri Lanka'.

Professor Narein Perera is a Professor in Architecture at the Department of Architecture, University of Moratuwa, and holds a PhD in climate-sensitive design. His research expertise primarily encompasses urban-scale studies with a focus on the tropical climatic context. He is dedicated to exploring the impacts of rapid and unplanned development on tropical cities, including a "Local Climate Zone" based approach to urban planning in Colombo, Sri Lanka. At the building scale, Professor Perera's work emphasises passive design strategies for the building envelope to ensure daylight integration, thermal comfort, and overall energy efficiency. He strives to apply the 'lessons learned' from his research to his architectural practice.

Professor Perera's architectural practice is distinguished for its innovation and holistic approach to architectural solutions. Each project is approached with consideration for its specific social, climatic, contextual, and technological nuances, resulting in unique outcomes. The practice places a strong emphasis on 'placemaking' through a conscious and meticulous exploration of material and texture. Over its twenty-year history, his practice has achieved significant recognition for design excellence, both locally and internationally.

PANEL DISCUSSION

Panel Discussion on "Optimising Use and Minimising Misuse of Public Private Partnerships in Developing Countries"

Joint Co-ordinators	**:**	Prof. Mohan Kumaraswamy
CIB W122 on PPP		Prof. Akintola Akintoye
		Prof. Giovanni C. Migliaccio
Panellists	**:**	Research Prof. Andreas Wibowo
		Associate Prof. Yongjian Ke
		Eng. Nissanka Wijeratne
		Chanaka De Silva PC
Moderator	**:**	Prof. Mohan Kumaraswamy
		Dr. Suranga Jayasena

Joint Co-ordinator
CIB W122 on PPP/
Panel Discussion Moderator

Prof. Mohan Kumaraswamy

D.Sc. (UK), Ph.D. (UK), M.Sc. (UK), B.Sc. Engineering. (Hons.) Civil Eng.

Honorary Professor at the University of Hong Kong & the University of Moratuwa
Joint Coordinator, CIB W122 on PPP
Editor-in-Chief, BEPAM Journal

Mohan Kumaraswamy is an Honorary Professor at the University of Hong Kong and the University of Moratuwa, Sri Lanka. He has been a Visiting Professor at Universities in Singapore, Australia and India and also a Consultant to the World Bank. Before joining academia, he worked on designs, construction and project management, including as a Construction Manager of a 5-star hotel in Colombo and a Director of the pioneering construction project management company in Sri Lanka.

His contributions to academia-industry-link bodies include those as Sri Lanka representative of CIOB (UK) until 1992; Vice-Chairman of CIOB Hong Kong in 1996-97; Chairman of the Civil Division of Hong Kong Institution of Engineers in 1997-98; and as a member of the Institution of Engineers Sri Lanka Accreditation Board from 2014. Prof. Kumaraswamy is also the Founding Director of the Centre for Innovation in Construction & Infrastructure Development, Hong Kong and the Editor-in-Chief of one of the three CIB recognised journals, the Journal of Built Environment Project and Asset Management (BEPAM. Besides, he is the Editor-in-Chief of the Book Series on Domain-Specific Bodies of Knowledge in Project Management under World Scientific Publishing, Singapore.

Furthermore, Prof. Kumaraswamy is a Joint Co-ordinator of the international CIB Working Commission TG72 from 2008 and W122 from 2017, on ‘Public-Private Partnership’ at the International Council for Research & Innovation in Building and Construction. He also serves as an Arbitrator and Adjudicator in several construction project disputes.

Joint Co-ordinator
CIB W122 on PPP

Prof. Akintola Akintoye

Ph.D., M.Sc., B.Sc. (Hons.), FRICS, FCIOB, FInstCM

Dean of School of Built Environment and Engineering, Leeds Beckett University, United Kingdom
Joint Coordinator, CIB W122 on PPP

Professor Akintola Akintoye is a distinguished academic in the field of construction economics and management. He currently serves as the Dean of the School of Built Environment and Engineering at Leeds Beckett University. His academic journey includes earning a PhD in Construction Economics from the University of Salford, UK. Before his tenure at Leeds Beckett, he was a Professor of Construction Economics and Management at the University of Central Lancashire, where he significantly contributed to the academic community.

In addition to his academic achievements, Professor Akintoye has made substantial professional contributions. He serves on the editorial boards of several prestigious journals in construction management and has provided consultancy services to various government and private sector organizations. His expertise in construction procurement and risk management is widely recognized. Furthermore, he is a frequent speaker at international conferences and has organized numerous workshops and seminars to foster knowledge exchange in the construction industry.

Professor Akintoye's excellence has been acknowledged through various awards and recognitions. He is a Fellow of the Royal Institution of Chartered Surveyors (RICS) and the Chartered Institute of Building (CIOB). His contributions to research and education in construction management have earned him several accolades, underscoring his influence and leadership in the field.

Joint Co-ordinator
CIB W122 on PPP

Prof. Giovanni C. Migliaccio

Ph.D. (USA), M.S. (USA), B.S. (Italy)

Professor at University of Washington, Joint Coordinator, CIB W122 on PPP

Giovanni C. Migliaccio holds a Howard S. Wright Endowed Professorship, he is the current Chair of the Department of Construction Management, and he has served as the Executive Director of the Center for Education and Research in Construction (CERC) for the past 3 years. He joined the CM department in August 2010. Previously, he was a faculty member with the Department of Civil Engineering at the University of New Mexico at Albuquerque. He holds an M.S. and a Ph.D. in Civil Engineering from the University of Texas at Austin and a master-level degree from Politecnico di Bari in Italy. Prior to moving to the U.S., he worked in Italy in the construction management of telecommunication projects under Nortel Networks, Nokia Networks, and IPSE 2000. At UW, Giovanni is active in all three pillars of academic life, including service to the university and the industry, teaching, and research.

Panel Discussion Moderator

Ch. QS. Dr. Suranga Jayasena

Ph.D. University of Moratuwa, M.Sc. (Building), National University of Singapore B.Sc. (Hons) QS University of Moratuwa, F.I.Q.S.SL, MCIOB, UK

Senior Lecturer, Department of Building Economics, University of Moratuwa

Ch. QS. Dr. Suranga Jayasena is a former head of the Department of Building Economics, University of Moratuwa and currently serving as a senior lecturer of the department. He obtained a B.Sc. (Hons) degree in Quantity Surveying from the University of Moratuwa and an M.Sc. in Building from the National University of Singapore. In 2023, Dr. Jayasena completed his PhD at the University of Moratuwa, Sri Lanka.

He is a Fellow member, of the Institute of Quantity Surveyors, Sri Lanka and a member of the Ceylon Institute of Builders. Dr. Jayasena is an excellent academic professional who is sharing his expert knowledge at several institutions. His exceptional career as a researcher has been awarded on multiple occasions. Dr. Jayasena won the Outstanding Research Performance Awards of the University of Moratuwa in 2008, 2009, 2010, 2012, 2013, 2014, and 2016. Also, he was the winner of CIOB Best Paper Award at The World Construction Symposium 2016 and the Emerald Highly Commended Paper Award at the 4th World Construction Symposium.

Panel Member

Research Prof. Andreas Wibowo

Ph.D. (Germany), M.Sc. (Indonesia), B.Sc. (Indonesia)

Senior lecturer at Parahyangan Catholic University, Indonesia
Director of Business Management Innovation and Entrepreneurship

Dr. Wibowo is a research professor and senior lecturer in construction management at the Department of Civil Engineering of Parahyangan Catholic University, Indonesia. He previously served as the Head of the Secretariat for the Agency for Promoting Water Supply Systems and as a principal researcher at the Agency for Research and Development, Ministry of Public Works and Housing, Indonesia. His specialty areas include public-private partnerships (PPP) in infrastructure development, financial engineering, risk modeling, simulation and analysis, and construction economics. Dr. Wibowo obtained his Habilitation degree (a German postdoctoral qualification leading to a professorship) from Bauhaus Universitaet Weimar (2016), a doctoral degree from Technische Universitaet Berlin (2005), and bachelor's and master's degrees from the Institute of Technology Bandung (1995, 1998), all in civil engineering. In addition to his academic activities, he is actively involved in consultancy projects, particularly PPP projects in Indonesia. He also serves as a research advisor at the Indonesia Infrastructure Guarantee Fund Institute. Dr. Wibowo has received several renowned scholarships and awards, including the Alexander von Humboldt re-invitation postdoctoral fellowship (2018), the Emerald Literati Award (2016), the Georg Forster Research Fellowship for Experienced Researchers (2011-2014), the DAAD Long-term Doctoral Scholarship (2001-2005) and Re-invitation Scholarship (2009), the Australia-Indonesia Governance Research Partnership (2007), and the URGE World Bank Scholarship (1996-1998).

Panel Member

Associate Prof. Yongjian Ke

Ph.D. (China), B.Sc. (China)

Associate Professor, University of Technology Sydney, Australia
Department Editor for the Project Management Journal

Dr. Yongjian Ke is an Associate Professor of Project Management in the School of Built Environment at the University of Technology Sydney (UTS), Australia. His research addresses various challenges in delivering infrastructure projects, focusing on risk allocation, contracting behaviours, social acceptance, and social sustainability. Dr. Ke is particularly interested in sustainable infrastructure development and public-private partnerships (PPP), exploring their potential to foster new investment and collaboration opportunities between Australia and China. He has made significant contributions to the field of PPPs, being recognized as one of the most influential and cited authors in this area. With over 140 publications and more than 7,200 citations, Dr. Ke's work has been widely recognized, earning him a place among the world's top 2% scientists. He has received funding from various academic and industry organizations, including the Australia-China Relations Institute, the Project Governance Control Symposium, and the Project Management Institute. Dr. Ke serves as a Department Editor for the Project Management Journal, a Guest Professor at Chang'an University in China, and a member of Standards Australia Committees (MB012 – Project, Programme and Portfolio Management). Dr. Ke holds a PhD in Management Science and Engineering and a Bachelor of Engineering from Tsinghua University in China.

Panel Member

Eng. Nissanka Wijeratne

M.Sc. (UK), B.Sc. Eng (Sri Lanka), C.Eng, M.I.C.E.

Secretary General and Chief Executive Officer (CEO) of the Chamber of Construction Industry of Sri Lanka

Eng. Nissanka N Wijeratne, B.Sc(Eng) Sri Lanka. M.Sc(Construction Management) Loughborough, M.I.C.E, C.Eng has held several appointments during his career spanning 55 years. This includes 8 years as Secretary to the Cabinet Ministries of Housing & Construction and Foreign Employment Promotion & Welfare from 2007 to 2015. In addition, as Chairman of Institute of Construction Training & Development (now CIDA), Ceylon Fishery Harbours Corporation and Sri Lanka Foreign Employment Bureau for a total of 5 years. He also served as Project Director of Southern Expressway under the Ministry of Highways during 2004 – 2007. Apart from above he has also served the Sri Lanka Army Engineers as a Commissioned Officer in different capacities and retired as a Colonel in 1997. Since 2015 to date, he is functioning as the Secretary General/ CEO of the Chamber of Construction Industry of Sri Lanka, which is positioned as the apex representative body of all involved in the construction sector by a statute. Further, he had been engaged as a director of Link Engineering Ltd, a leading construction company, for a long period and served in Nigeria for 2 stints with Jos Metropolitan Development Board, Bepco Ltd. and Standard Construction Ltd. spanning 5 years. Other organizations he had served in different capacities are State Engineering Corporation of Sri Lanka, State Graphite Corporation of Sri Lanka, River Valleys Development Board and Highways Department.

Panel Member

Chanaka De Silva PC

Attorneys-at-Law (Sri Lanka)

President's Counsel
Founder Partner of Nithya Partners
Head of the project finance and dispute resolution practices, Nithya Partners
Senior Legal Consultant to the Bureau of Infrastructure Investment

Mr. Chanaka de Silva P.C. is considered one of the foremost legal experts in the field of project finance transactions and negotiations in Sri Lanka. He is a Founder Partner of Nithya Partners and heads the project finance and dispute resolution practices of the Firm. For over 35 years, Mr. De Silva has been involved in advising, negotiating, and structuring major infrastructure projects in Sri Lanka, spanning a multitude of sectors such as electricity, telecommunication, petroleum, roadways, ports, and mining. He advised on structuring and implementing the earliest public private partnerships in Sri Lanka and was the Senior Legal Consultant to the Bureau of Infrastructure Investment and its predecessor, the Secretariat for Infrastructure Development and Investment. He was also the legal advisor in most major privatizations of state entities by the Government of Sri Lanka. Mr. De Silva advised the Government of Sri Lanka and government agencies on transactions involving infrastructure development, project finance, restructuring and corporatisation and continues advising the Government, the private sector, and lending institutions on such transactions up to date. Mr. De Silva has been consecutively ranked as a leading individual in the field of Projects and Energy and Dispute Resolution by the Legal 500 Asia Pacific, since 2010 and was inducted to the Hall of Fame of the Legal 500 in 2020. He is ranked in Band 1 by Chambers & Partners and is endorsed as an Elite Practitioner by AsiaLaw, in the field of Dispute Resolution. He is also listed as Highly Regarded by IFLR 1000 in the fields of Banking, Energy, Infrastructure and Project Finance. Expert Guides published by Euromoney lists Mr. De Silva as one of the world's leading practitioners in Project Finance. He is a Visiting Lecturer in Commercial Law at the Sri Lanka Law College and at the Master of Laws program of the University of Colombo. He is a Member of the Law Commission of Sri Lanka.

WCS 2024

12th WORLD CONSTRUCTION SYMPOSIUM

9th - 10th August 2024

CIB Working Commission W122 on PPP, University of Moratuwa and the Ceylon Institute of Builders (CIOB)

PANEL DISCUSSION

"OPTIMISING USE AND MINIMISING MISUSE OF PUBLIC PRIVATE PARTNERSHIPS IN DEVELOPING COUNTRIES"

INTRODUCTION-BACKGROUND

Joint Co-ordinators
CIB W122 on Public Private Partnership

Prof. Mohan Kumaraswamy

Prof. Akintola Akintoye

Prof. Giovanni C. Migliaccio

PANELISTS

Research Prof.
Andreas Wibowo

"Issues, Challenges, and Recommendations in Value for Money Assessment for PPP Projects in Developing Countries: Insights from Indonesia's Experience"

Associate Prof.
Yongjian Ke

"Transforming China's PPP Landscape: Key Changes and Strategic Implications from 2023 Onwards"

Eng.
Nissanka Wijeratne

"Construction Procurement Landscape in Sri Lanka and current deterrents to Private Investments"

Chanaka De Silva
PC

"PPPs: The Sri Lanka experience"

MODERATORS

Prof. Mohan Kumaraswamy

Dr. Suranga Jayasena

Saturday 10 August 2024 – 3.30 to 5.00 PM (Sri Lanka time)

Taj Samudra Hotel, Colombo, Sri Lanka

View: VIDEO RECORDING of PANEL DISCUSSION:
https://youtu.be/rLknWZ0LL7w

CONTENTS OF PAPERS

Wijesinghe, E.D.A.T., Jayawickrama, T.S., Tennakoon, G.A. and Wijewickrama, M.K.C.S., 2024. 5S principles for sustainable resource and waste management in Sri Lankan construction projects. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1-14. DOI: https://doi.org/10.31705/WCS.2024.1. Available from: https://ciobwcs.com/papers/

5S PRINCIPLES FOR SUSTAINABLE RESOURCE AND WASTE MANAGEMENT IN SRI LANKAN CONSTRUCTION PROJECTS

E.D.A.T. Wijesinghe[1], T.S. Jayawickrama[2], Gihan Anuradha Tennakoon[3] and M.K.C.S. Wijewickrama[4]

ABSTRACT

The significant resource consumption and waste generation in the construction sector highlights the imperative for sustainable management of resources and waste, particularly in Sri Lanka. Over time, various techniques have emerged as potential solutions to address this challenge, with the 5S technique standing out as a widely discussed approach. This technique is focused on producing high-quality outputs with minimal wastage and high productivity, making it well-suited for sustainable resource and waste management. However, despite its potential, there is limited research exploring its application in this context within the construction domain, specifically in Sri Lanka. Therefore, this study aimed to investigate the applicability of 5S principles for sustainable resource and waste management in Sri Lankan construction projects. Initially, a comprehensive literature review was conducted on the 5S principles and the concept of sustainable resource and waste management, which led to the development of a conceptual framework for the application of 5S principles for sustainable resource and waste management. Following this, a pilot study using interviews was conducted to investigate the specific activities that could be implemented under the individual 5S principles for sustainable resource and waste management. Integrating these activities within construction projects could help mitigate the negative environmental impacts associated with resource consumption and waste generation in the industry.

Keywords: *5S Principles; Construction; Resource Management; Sustainability; Sri Lanka; Waste Management.*

1. INTRODUCTION

The construction sector, known for its high resource intensity, utilises around half of all natural materials extracted (Norouzi et al., 2021). This substantial extraction of natural materials, fuelled by the ever-growing construction demand, carries significant ecological impacts, including resource depletion, environmental contamination, biodiversity loss, increased greenhouse gas emissions, and adverse climate impacts (Bell, 2018; Oyedele et

[1] Chief Quantity Surveyor, Buhaleeba Contracting LLC, United Arab Emirates, achinitwijesinghe@gmail.com

[2] Senior Lecturer, UniSA STEM, University of South Australia, Australia, thilini.jayawickrama@unisa.edu.au

[3] Casual Academic, UniSA STEM, University of South Australia, Australia, gihan.tennakoon@mymail.unisa.edu.au

[4] Lecturer, School of Architecture and Civil Engineering, Faculty of Sciences, Engineering and Technology, The University of Adelaide, Australia, chamitha.wijewickrama@adelaide.edu.au

al., 2014). Furthermore, construction ranks among the leading industries in terms of waste generation, with research showing that construction-related waste accounts for approximately 30-40% of the total global solid waste, a percentage that continues to increase steadily (Purchase et al., 2022; Tennakoon et al., 2022). This high resource intensiveness and waste generation emphasises the need for sustainable resource and waste management within the construction industry.

Over time, various concepts have emerged as potential solutions to address the need for sustainable resource and waste management, with lean management standing out as a key approach (Tasdemir & Gazo, 2018). At its core, lean management focuses on creating customer value using fewer resources and minimising waste (Bhamu & Singh Sangwan, 2014; Tasdemir & Gazo, 2018). It consists of a range of techniques and principles, including Just-in-Time, Kaizen, 5S, Kanban, Six Sigma, value stream mapping (VSM) and total preventive maintenance (Tasdemir & Gazo, 2018). Among these techniques, the 5S technique has been commonly used to achieve different sustainability outcomes (Tasdemir & Gazo, 2018). With the principles of *seiri, seiton, seiso, seiketsu*, and *shitsuke*, the 5S technique aims to instil the values of organisation, neatness, cleanliness, standardisation, and discipline into the management of any activity (Gapp et al., 2008; Randhawa & Ahuja, 2017). This technique is focused on producing high-quality outputs with minimal wastage and high productivity (Randhawa & Ahuja, 2017), making it well-suited for sustainable resource and waste management.

Recent studies have shown that prevailing construction management practices in Sri Lanka prioritise traditional project management objectives, such as timely project completion, cost control, and adherence to quality standards, while giving minimal attention to sustainable resource and waste management (Victar & Waidyasekara, 2023). There are limited efforts targeted at managing resources and wastage, leading to notable inefficiencies in construction projects (Liyanage et al., 2019). Emerging initiatives, such as promoting sustainable material choices, improving construction and demolition waste management, and adopting green building standards, are beginning to gain traction but have not yet become mainstream topics (Victar & Waidyasekara, 2023). Considering the Sri Lankan context, research on the application of the 5S technique has also predominantly focused on the manufacturing and service sectors, with limited attention given to its implementation within the construction sector. For instance, in the manufacturing sector, Suraweera and Jayasena (2016) examined the factors influencing the long-term sustenance of 5S practices, using the Sri Lankan stationery industry as a case study. Similarly, Bandara et al. (2023) investigated how the 5S technique, as a quality assurance method, could enhance employee productivity in Sri Lanka's apparel sector. From a service sector perspective, Withanachchi et al. (2004) conducted a best-practice case study on a Sri Lankan public hospital, exploring how adopting the 5S technique improved the hospital's service delivery quality. It was also noted that these studies primarily regard 5S as a quality management technique rather than considering its applicability for effective waste and resource management. Although the application of lean construction techniques, which is closely related to 5S, has been the subject of previous studies in the Sri Lankan construction sector (Senanayake et al., 2024), they have not explored how the 5S principles, specifically, could be used for managing resources and wastage in construction projects. In these studies, 5S is merely identified as one of the various lean techniques available to reduce wastage, without delving into the practical application of the technique to achieve this goal.

Within this background, undertaking research with a particular focus on exploring the practical applications of the 5S principles, which are conducive to achieving sustainable resource and waste management goals, could be viewed as a forward step in driving sustainability initiatives in Sri Lankan construction projects. Therefore, this study aims to investigate the applicability of 5S principles for sustainable resource and waste management in Sri Lankan construction projects. In order to achieve this aim, two objectives were developed as follows:

1. Review the literature on 5S principles and the concept of sustainable resource and waste management to develop a conceptual framework on applying 5S principles for sustainable resource and waste management.
2. Examine the activities related to 5S principles in achieving sustainable resource and waste management in Sri Lankan construction projects.

2. METHODOLOGY

The study's methodology included a comprehensive literature review to achieve the first objective. Subsequently, a pilot study was conducted via expert interviews to address the second objective. This design builds on prior studies that have integrated literature reviews and qualitative interviews to translate theoretical knowledge into practice (Bellamy et al., 2006; Brown et al., 2019). An overview of the research methodology is shown in Figure 1, followed by a detailed explanation of the individual stages.

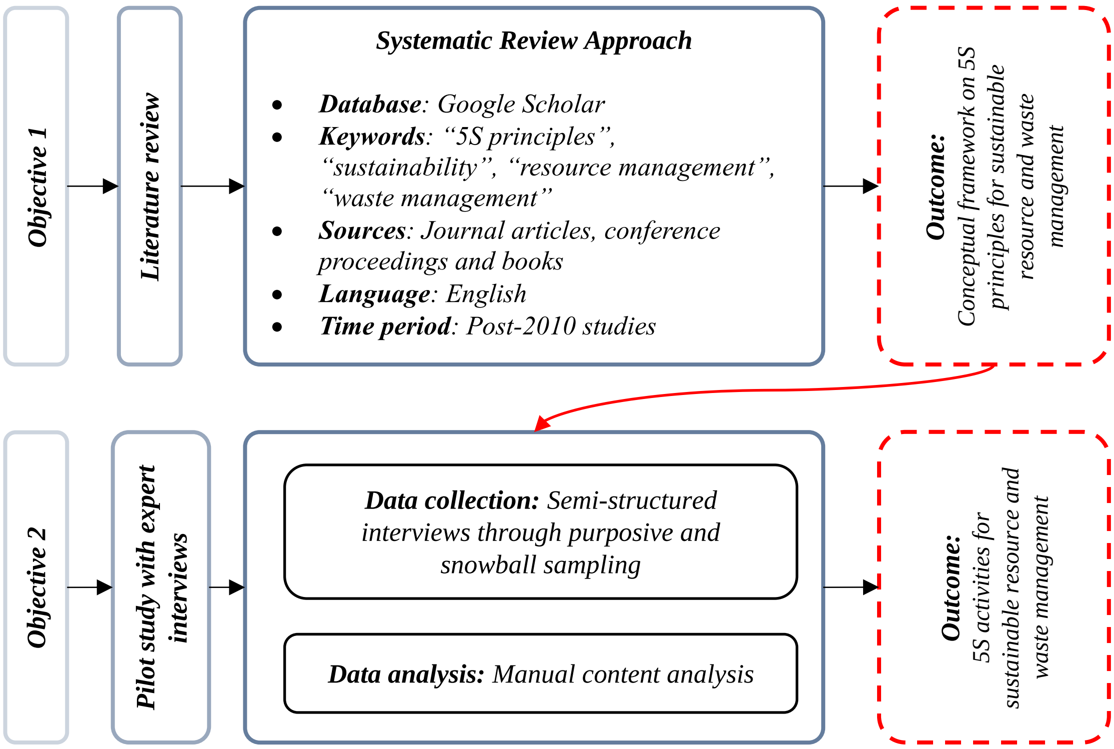


Figure 1: An overview of the research methodology

The literature review focused on exploring extant literature on the 5S principles and related activities, as well as the concepts of sustainable resource and waste management. A systematic approach was followed in undertaking the review. Google Scholar was selected as the primary database considering its comprehensive coverage on a wide range of areas and ease of access while “5S principles”, “sustainability”, “resource management”, and “waste management” were used as keywords to locate relevant studies. The sources considered for the study were limited to journal articles, conference proceedings and books published in the English language. Moreover, emphasis was placed on post-2010 publications with the aim of gathering current insights on the topic. However, some earlier seminal studies were also included considering their significance to the study area. Based on the literature review, a conceptual framework was developed for applying the 5S principles for sustainable resource and waste management in construction projects.

The literature review was followed by a pilot study targeted at investigating the activities that could be implemented under the individual 5S principles for sustainable resource and waste management, specifically in Sri Lankan construction projects. Expert interviews were chosen for the pilot study due to limited local expertise in the study areas. Following the classification of interviews by Saunders et al. (2019), semi-structured interviews were selected since they facilitated the collection of specific data, while also exploring additional insights that arose during data collection. Moreover, the use of semi-structured interviews was also suitable, because the pilot study was guided by pre-determined themes/key questions developed based on the outcomes of the literature review. Considering limitations with expertise available in the study area, a combination of purposive and snowball sampling techniques was used to connect with experienced interviewees. Accordingly, interviews were conducted with seven experts who are well-qualified and experienced in the domains of environmental sustainability and 5S principles in relation to the construction industry. The profile of the interviewees is shown in Table 1.

Table 1: Profile of interviewees for the pilot study

Name	Designation	Experience
E1	Project Manager	22
E2	Environmental Manager	18
E3	Planning Manager	16
E4	Planning Engineer	20
E5	Construction Manager	21
E6	Environmental Officer	15
E7	Planning Engineer	18

The interview guideline comprised of two sections: Section 1 targeted the demographic information of the interviewees while Section 2 looked at the 5S activities for sustainable resource and waste management. Interview questions were developed guided by the conceptual framework and the findings of the literature review. Each interview lasted between 30-60 minutes, recorded with the consent of the interviewees, and transcribed verbatim before the analysis. Considering the qualitative nature of the data collected and the relatively manageable volume of data, manual content analysis was selected as the most appropriate data analysis method for the study. Herein, a directed content analysis approach was followed with the analysis being directed by the literature review findings. Findings from the literature review and the pilot study are elaborated in detail under Sections 3 and 4 of the paper.

3. 5S PRINCIPLES AND SUSTAINABLE RESOURCE AND WASTE MANAGEMENT

The literature review was focused on exploring the 5S principles as well as the key areas of sustainable resource and waste management. The outcomes of the literature review led to the development of a conceptual framework for applying the 5S principles for sustainable resource and waste management.

3.1 THE 5S PRINCIPLES

The 5S principles were introduced in Japan in the early 1980s by Takashi Osada as a technique for establishing and maintaining a quality environment within an organisation (Jiménez et al., 2015). These principles highlight the basic requirements for producing high-quality products and services with little to no wastage, while sustaining high productivity levels. The name 5S comes from the first five letters of the Japanese terms *seiri, seiton, seiso, seiketsu* and *shitsuke*, which, when translated to English, means organisation, neatness, cleanliness, standardisation, and discipline, respectively (Randhawa & Ahuja, 2017). According to Gapp et al. (2008), the 5S principles reflect the Japanese way of thinking of "doing the right things in everyday life in the right way." These five principles are elaborated in detail in the following sections:

- *Organisation (Seiri)*: This is the first "S" and focuses on distinguishing between necessary and unnecessary goods/items, to eliminate the latter (Jiménez et al., 2015; Randhawa & Ahuja, 2017). *Seiri* calls for effective workplace utilisation and suggests that goods/items should be categorised based on their relevance and frequency of use with the objective of creating an efficient workplace (Randhawa & Ahuja, 2017). This ultimately leads to fewer hazards and less clutter that could interfere productivity (Michalska & Szewieczek, 2007). The benefits of adopting this principle include savings in the use of space, minimising searching times, making damage detection easy and creating a safe and comfortable workplace (Sorooshian et al., 2012).
- *Neatness (Seiton)*: Neatness focuses on workplace efficiency and is generally analysed by the time taken for getting and putting things back (Randhawa & Ahuja, 2017). It places emphasis on creating efficient and effective methods to arrange goods/items, facilitating easy accessibility, use, and storage. Further, it highlights the significance of a well-defined workplace layout to enable seamless and safe operations (Low & Ang, 2003). In simple terms, this principle emphasises that "there must be a place for everything, and everything must be in its place" (Michalska & Szewieczek, 2007, p. 212). The benefits of maintaining neatness within the workplace include lowering mistakes, speeding up processes, and fostering better employee morale and creativity (Sorooshian et al., 2012).
- *Cleanliness (Seiso)*: Cleanliness refers to the upkeep of a neat and clean workplace, a responsibility of everyone involved (Randhawa & Ahuja, 2017). This includes three primary activities: cleaning the workplace, maintaining its appearance, and implementing preventive measures to sustain cleanliness. A commitment to effective housekeeping practices inherently addresses safety issues, while assigning responsibility for regular maintenance and providing required resources aids in minimising hazards linked to inefficient operations (Low & Ang, 2003). Maintaining a clean workplace offers numerous benefits, including improving output quality,

minimising equipment failures and creating a safe and pleasant working environment (Sorooshian et al., 2012).

- *Standardisation (Seiketsu)*: Standardisation refers to ongoing and repetitive upkeep of organisation, neatness, and cleanliness, which are synonymous with seiri, seiton, and seiso, within the workplace (Randhawa & Ahuja, 2017). This involves the development of standard operating procedures to establish improved workplace practices, which allows for control and consistency (Michalska & Szewieczek, 2007; Randhawa & Ahuja, 2017). Standardisation offers benefits such as lowering maintenance and overhead expenses while boosting process efficiency (Sorooshian et al., 2012).
- *Discipline (Shitsuke)*: Discipline refers to ingraining the ability to perform tasks the way they are supposed to be done, thereby fostering the development of positive workplace habits (Randhawa & Ahuja, 2017). This aligns with the principle of Kaizen – the Japanese equivalent for repeated improvement. Herein, organisations must consistently analyse their existing practices in order to improve them and ensure their ongoing applicability (Low & Ang, 2003). This principle calls for a proactive change in behaviour among employees at all levels within an organisation (Randhawa & Ahuja, 2017), which, in turn, yields benefits such as enhancing labour productivity, improving output quality, and reducing workplace accidents (Sorooshian et al., 2012).

The literature review also revealed a set of typical activities that could be carried out under each of the 5S principles, as summarised in Table 2.

Table 2: Typical activities carried out under the 5S principles

5S Principles	Definition	Activities
Organisation (Seiri)	Distinguishing between necessary and unnecessary good/items to eliminate the latter	Store unwanted items collected in the workspace Give items a tag (red tagging) Identify and dispose of items that have not been used
Neatness (Seiton)	Creating efficient and effective methods to arrange goods/items facilitating easy accessibility, use and storage	Organise the workspace so that everything has a place Tag and label items with a colour code system Use neat and well-arranged notice boards to identify items Install guidance maps throughout the workspace
Cleanliness (Seiso)	Upkeeping a neat and clean workplace	Implement periodical cleaning Assign a map for cleaning staff and their respective areas Prevent equipment from being exposed to dust and dirt while cleaning Use cleaning checklists and supervision
Standardisation (Seiketsu)	Ongoing and repetitive upkeep of organisation, neatness and cleanliness	Visualisation of slogans in the workplace Use standard colour coding systems Use standardised checklists

5S Principles	Definition	Activities
		Implement supervision to encourage improvement in 5S
Discipline (Shitsuke)	Consistently analysing existing practices to improve and ensure ongoing applicability	Foster improvement of self-discipline and positive attitudes Introduce training programs Develop a checklist as a reminder to sustain all habits Continuous monitoring to identify and refine areas for improvement

3.2 KEY AREAS OF SUSTAINABLE RESOURCE AND WASTE MANAGEMENT

The aim of this study is to investigate the applicability of 5S principles for sustainable resource and waste management in construction projects. To achieve this, it is important to identify the key areas that warrant attention in the pursuit of sustainable resource and waste management. Environmental rating systems serve as a valuable starting point for identifying these specific areas of focus. Following a thorough analysis of different environmental rating systems, six key areas related to sustainable resource and waste management were identified, as shown in Figure 2.

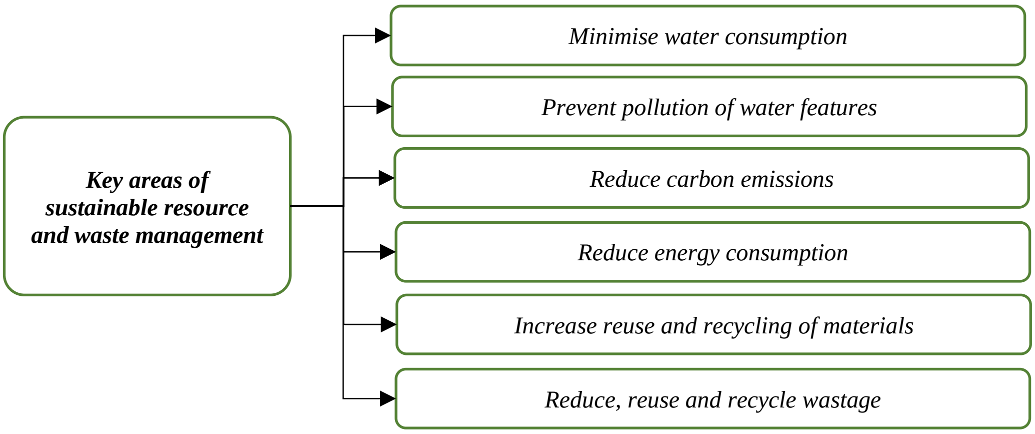


Figure 2: Key areas of sustainable resource and waste management

The identification of these areas was informed by the CEEQUAL (Civil Engineering Environmental Quality Assessment and Award, also known as BREEAM Infrastructure) rating system, considering its robustness, global application, and suitability for projects of different scales. Moreover, CEEQUAL highlights the focus areas for sustainable resource and waste management at a construction site, which aligns closely with the project-level focus of the current study. The current study explored how the 5S principles can be applied to these six key areas of sustainable resource and waste management.

3.3 CONCEPTUAL FRAMEWORK

The literature review led to the development of the conceptual framework, shown in Figure 3, for applying the 5S principles for sustainable resource and waste management. The framework highlights the key areas of sustainable resource and waste management: minimising water consumption, preventing pollution of water features, reducing carbon emissions, reducing energy consumption, increasing reusing and recycling of materials, and reducing, reusing, and recycling wastage. It also outlines the 5S principles: organisation (seiri), orderliness (seiton), cleanliness (seiso), standardisation (seiketsu), and discipline (shitsuke). The aim of this framework is to integrate these two concepts to explore how the 5S principles can be applied to sustainable resource and waste management. This framework formed the basis for conducting the pilot study, which investigated the activities that could be implemented under the individual 5S principles for sustainable resource and waste management in Sri Lankan construction projects.

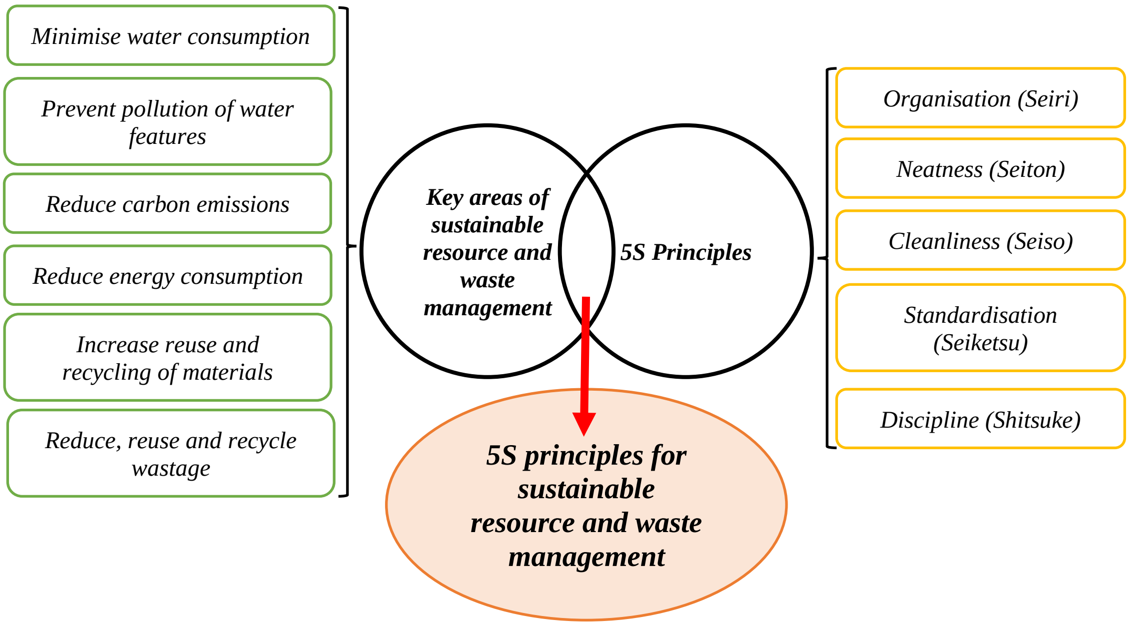


Figure 3: 5S principles for sustainable resource and waste management

4. 5S ACTIVITIES FOR SUSTAINABLE RESOURCE AND WASTE MANAGEMENT

The purpose of conducting the pilot study was to identify the activities that could be implemented under the individual 5S principles for sustainable resource and waste management in Sri Lankan construction projects. During the expert interviews, the typical activities that could be carried out under the 5S principles, identified from the literature review (refer to Table 2), were presented as a guide for the interviewees to suggest activities that could be implemented to achieve sustainable resource and waste management in construction projects.

All interviewees recognised the importance of minimising water consumption and preventing pollution of water features during the construction stage of a project. E2 pointed out that while more attention is typically given to managing water resources during the operational phase, less emphasis is placed on this during construction. The interviewees identified several 5S activities that could be employed to manage water resources and reduce wastage. Initially, the focus should be on reducing water consumption, followed by repurposing or recycling used water for other applications. Interviewee E7 emphasised, "*Our priority should be to reduce water usage where possible; then we can think about how we can collect and reuse the water that we have already used for other applications*". The importance of raising awareness in this area was also highlighted.

Regarding carbon emissions, the interviewees observed that this area has received limited attention in most construction projects. They suggested that a reduction in carbon emissions can be achieved by standardising the use of plant and equipment powered by alternative energy sources (e.g., electric vehicles) and ensuring regular maintenance for efficient operation. Additionally, repurposing waste materials and considering carbon emissions in material selection were identified as strategies to reduce carbon emissions from construction projects. In contrast, more attention has been given to reducing energy consumption in construction projects due to high energy costs. The interviewees mentioned using energy-efficient plant and equipment, low-cost renewable energy sources like solar, and strategic allocation of energy-demanding systems as methods to reduce energy consumption. Interviewee E5 noted, "*We are trying to use solar energy more on our sites; especially our outdoor lighting systems, they are powered by solar energy, it cuts our costs and minimises our environmental footprint as well*". Regular maintenance, monitoring energy consumption, balancing energy demands during peak hours, and raising awareness about responsible energy consumption practices were also recognised as potential activities to reduce energy consumption.

Finally, the interviewees highlighted the increasing focus on reducing, reusing, and recycling materials and waste in construction projects. Storage was identified as a major concern, as improper storage leads to high material wastage. The need for neat and organised material storage was emphasised, and the potential for adopting techniques like Just-In-Time material delivery to eliminate the need for long-term storage was acknowledged. Moreover, the interviewees stressed the importance of standardising the use of reusable and recyclable materials and categorising and segregating waste materials to facilitate alternative uses.

A detailed summary of the findings from the pilot study regarding the 5S activities for sustainable resource and waste management are presented in Table 3.

Table 3: 5S activities for sustainable resource and waste management

5S Principle	Activities to achieve sustainable resource and waste management
Minimise water consumption	
Organisation (Seiri)	• Selection of low water-consuming taps and taps with aerators
Neatness (Seiton)	• Monitor and cut off water taps when not in use • Eliminate unnecessary usage with cups and binding threads • Follow appropriate sequencing of activities
Cleanliness (Seiso)	• Use sand filtration for vegetation • Implement continuous cleaning schemes
Standardisation (Seiketsu)	• Use storm water and recycled wastewater for toilet flushing • Use storm water and recycled wastewater for gardening
Discipline (Shitsuke)	• Conduct toolbox meetings • Undertake proper education • Conduct awareness programs • Create a degradation chart for maintaining water resources
Prevent pollution of water features	
Organisation (Seiri)	• Systematic disposal of wastewater
Neatness (Seiton)	• Use sedimentation tanks

5S Principle	Activities to achieve sustainable resource and waste management
	• Isolate contaminated water before being released to water channels
Cleanliness (Seiso)	• Filter storm water through siltation • Purify contaminated water before being sent out • Ensure contaminated water is not mixed with potable water
Standardisation (Seiketsu)	• Analyse water contamination
Discipline (Shitsuke)	• Use silt traps • Install wastewater treatment plants • Conduct awareness programs
Reduce carbon emissions	
Organisation (Seiri)	• Use electrical vehicles rather than those using fossil fuels • Separate debris without setting fire to them
Neatness (Seiton)	• Undertake timely maintenance of plant and equipment • Maintain adequate material and power for activities (avoid over capacity)
Cleanliness (Seiso)	• Conduct regular maintenance of plant and equipment
Standardisation (Seiketsu)	• Use energy efficient plant and equipment • Proper identification and installation of suitable ventilation and lighting systems • Base material selection decisions on carbon emissions, energy consumption, and impact on eco-system • Undertake preventive maintenance of plant and equipment
Discipline (Shitsuke)	• Create checklists for frequent monitoring
Reduce energy consumption	
Organisation (Seiri)	• Use energy efficiency plant and equipment • Proper identification and installation of suitable ventilation and lighting systems • Use solar energy systems
Neatness (Seiton)	• Proper placing of lighting and ventilation arrangements
Cleanliness (Seiso)	• Undertake preventive maintenance of plant and equipment
Standardisation (Seiketsu)	• Manage peak requirements with respect to grid peak hours • Allocate a daily consumption per person • Regular monitoring of energy consumption • Create work procedures to maximise efficiency of plant and equipment
Discipline (Shitsuke)	• Undertake awareness programs to minimise unnecessary energy usage
Increase reuse and recycling of materials	
Organisation (Seiri)	• Stack/Store materials based on their properties • Use appropriate storage facilities
Neatness (Seiton)	• Orderly storage of materials • Collect materials as per the categorisation
Cleanliness (Seiso)	• Careful usage and proper workstation cleaning and management • Regular housekeeping

5S Principle	Activities to achieve sustainable resource and waste management
Standardisation (Seiketsu)	• Select reusable and recyclable materials • Select storage method as per material type
Discipline (Shitsuke)	• Ensure proper planning and monitoring to reduce material usage, rework and wastage
Reduce, reuse, and recycle wastage	
Organisation (Seiri)	• Categorise root cause for waste generation and take appropriate mitigation measures • Select reusable and recyclable waste and store for future usage
Neatness (Seiton)	• Segregate waste based on recovery potential
Cleanliness (Seiso)	• Implement continuous cleaning to remove any non-recoverable waste
Standardisation (Seiketsu)	• Categorise waste for future use
Discipline (Shitsuke)	• Ensure proper planning and monitoring to reduce material usage, rework and wastage • Adopt Just-in-Time principles

5. DISCUSSION

In exploring the application of 5S principles for sustainable resource and waste management, the first two areas of focus were on minimising water consumption and preventing the pollution of water features. The findings revealed that while these areas are highly regarded during a building's operational phase, they receive less attention during construction. This is consistent with the observations of Waidyasekara et al. (2016), who noted that water use efficiency is often given a low priority during construction. The study also highlighted the importance of reducing water use and implementing techniques for repurposing or recycling used water, aligning with the aforementioned authors' recognition of less water-intensive construction technologies as effective conservation methods. However, it is important to note that some of the activities suggested, such as using filtration systems, sedimentation tanks, and on-site treatment plants, can incur higher costs, potentially making them economically unviable.

The study further revealed that the 5S technique could be used to reduce carbon emissions, an area rarely considered in Sri Lankan construction projects. This corresponds with the work of Ng et al. (2015) who noted that lean techniques like 5S could drive waste reduction and resource efficiency, thereby mitigating environmental impacts, which include the reduction of carbon emissions. Emphasis was placed on the use of alternative energy sources, efficient waste management, and prioritising low-carbon materials. However, here too, further assessment would be needed to assess the viability of some of these measures. For instance, whether it is economically viable to replace fossil fuel-powered vehicles with electric vehicles considering the comparatively higher cost of electricity or whether low carbon emission materials are readily available in the market and can be easily sourced are areas to be considered before undertaking any transition.

Regarding the reduction of energy consumption, the study found that the activities recommended are similar to those for reducing carbon emissions, justified by the significant contribution of energy consumption to carbon emissions. Tasdemir and Gazo (2018) corroborated these findings, recognising that standardised and neat work practices, as advocated by the 5S principles, can lead to reduced energy consumption. The authors have also emphasised the importance of continuous improvement, recognised in the current study through the necessity of undertaking awareness programs as an area of significance.

Aligned with previous research by Morales-Plaza et al. (2020) and Senanayake et al. (2024), the current study recognised that the 5S principles could be used to effectively minimise wastage while simultaneously driving alternative uses for waste materials. As noted in the current study and supported by Morales-Plaza et al. (2020), adopting 5S principles introduces greater orderliness to the construction process, which minimises waste generation in the first place while also ensuring that any generated waste is managed and reused efficiently. The findings also suggested the need for standardising the use of reused or recycled materials, a fact supported by Tennakoon et al. (2024). Importantly, with storage being recognised as a major source of waste, the potential for adopting techniques like Just-In-Time material delivery was recognised. However, the feasibility of such techniques must be further explored, especially considering the wide and sometimes international sourcing of materials.

6. CONCLUSIONS

Recent studies have revealed a lack of emphasis on sustainable resource and waste management in construction projects, particularly in Sri Lanka. Therefore, exploring the practical applications of the 5S principles, which are conducive to achieving sustainable resource and waste management goals, was recognised as an imminent research need since it could, in turn, drive sustainability initiatives in Sri Lankan construction projects. Consequently, this study aimed to investigate the applicability of 5S principles for sustainable resource and waste management in Sri Lankan construction projects. Initially, literature on the 5S principles and the concept of sustainable resource and waste management were reviewed in detail, which led to the development of a conceptual framework for the application of 5S principles for sustainable resource and waste management. Subsequently, an expert interview-based pilot study was conducted building on the conceptual framework to investigate the activities that could be implemented under the individual 5S principles for sustainable resource and waste management, specifically in Sri Lankan construction projects. The interviews revealed fifty-eight activities, categorised into six key areas of sustainable resource and waste management, as defined based on the CEEQUAL rating system.

As a next step in this study, the researchers aim to conduct a Delphi study to prioritise the identified 5S activities for sustainable resource and waste management and develop a practical framework that can be implemented in construction projects to achieve sustainable resource and waste management targets. While this study's qualitative approach does not necessitate statistical generalisation, it acknowledges the limitation in the broad applicability of study findings, paving the way for future quantitative studies with a wider range of participants from the construction industry. However, it is important to note that conducting such quantitative studies may pose challenges in the current Sri Lankan construction landscape due to limited expertise in the study areas.

7. REFERENCES

Bandara, G., Jayasuriya, N., & Dominguhewa, H. (2023). The impact of quality assurance practices on employee productivity in the apparel sector in Sri Lanka: Special reference to three leading apparel manufacturers in Sri Lanka. *SLIIT Business Review, 03*(01), 81-102. doi:10.54389/ACDU9962

Bell, R. G. (2018). Protecting the environment during and after resource extraction. In T. Addison & A. Roe (Eds.), *Extractive Industries: The Management of Resources as a Driver of Sustainable Development* (pp. 318–341). Oxford, UK: Oxford University Press.

Bellamy, J. L., Bledsoe, S. E., & Traube, D. E. (2006). The current state of evidence-based practice in social work: A review of the literature and qualitative analysis of expert interviews. *Journal of Evidence-Based Social Work, 3*(1), 23-48. doi:10.1300/J394v03n01_02

Bhamu, J., & Singh Sangwan, K. (2014). Lean manufacturing: literature review and research issues. *International Journal of Operations & Production Management, 34*(7), 876-940. doi:10.1108/IJOPM-08-2012-0315

Brown, S., Rittenbach, K., Cheung, S., McKean, G., MacMaster, F. P., & Clement, F. (2019). Current and common definitions of treatment-resistant depression: Findings from a systematic review and qualitative interviews. *The Canadian Journal of Psychiatry, 64*(6), 380-387. doi:10.1177/0706743719828965

Gapp, R., Fisher, R., & Kobayashi, K. (2008). Implementing 5S within a Japanese context: An integrated management system. *Management Decision, 46*(4), 565-579. doi:10.1108/00251740810865067

Jiménez, M., Romero, L., Domínguez, M., & Espinosa, M. d. M. (2015). 5S methodology implementation in the laboratories of an industrial engineering university school. *Safety Science, 78*, 163-172. doi:10.1016/j.ssci.2015.04.022

Liyanage, K. L. A. K. T., Waidyasekara, K. G. A. S., Mallawaarachchi, B. H., & Pandithawatta, T. P. W. S. I. (2019, June). Origins of Construction and Demolition Waste Generation in the Sri Lankan Construction Industry. *In Proceedings of the World Conference on Waste Management* (Vol. 1, No. 1, pp. 1-8), Colombo, Sri Lanka.

Low, S. P., & Ang, G. K. (2003). Integrating JIT and 5-S concepts for construction site management: A case study. *International Journal of Construction Management, 3*(1), 31-47. doi:10.1080/15623599.2003.10773034

Michalska, J., & Szewieczek, D. (2007). The 5S methodology as a tool for improving the organization. *Journal of Achievements in Materials and Manufacturing Engineering, 24*(2), 211-214.

Morales-Plaza, A., Vicuña-Izquierdo, R., Pérez-Paredes, M., Raymundo-Ibañez, C., & Moguerza, J. M. (2020, February). Waste management model based on reverse logistics and 5S for the generation of biomass in the fresh fruit industry. *In 2020 9th International Conference on Industrial Technology and Management (ICITM)* (pp. 11-15), Oxford, United Kingdom.

Ng, R., Low, J. S. C., & Song, B. (2015). Integrating and implementing Lean and Green practices based on proposition of Carbon-Value Efficiency metric. *Journal of Cleaner Production, 95*, 242-255. doi:10.1016/j.jclepro.2015.02.043

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering, 44*, 102704. doi:10.1016/j.jobe.2021.102704

Oyedele, L. O., Ajayi, S. O., & Kadiri, K. O. (2014). Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement. *Resources, Conservation and Recycling, 93*, 23-31. doi:10.1016/j.resconrec.2014.09.011

Purchase, C. K., Al Zulayq, D. M., O'Brien, B. T., Kowalewski, M. J., Aydin, B., Tarighaleslami, A. H., & Mostafa, S. (2022). Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. *Materials, 15*(1), 76. doi:10.3390/ma15010076

Randhawa, J. S., & Ahuja, I. S. (2017). 5S – a quality improvement tool for sustainable performance: Literature review and directions. *International Journal of Quality & Reliability Management, 34*(3), 334-361. doi:10.1108/IJQRM-03-2015-0045

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students* (8th ed.). Harlow: Pearson.

Senanayake, A., Seneviratne, I., Ranadewa, K., & Perera, B. (2024). Plumbing waste reduction through lean tools: A case for high-rise building construction. *Journal of the Faculty of Architecture*. doi:10.58278/0.2024.45

Sorooshian, S., Salimi, M., Bavani, S., & Aminattaheri, H. (2012). Case report: Experience of 5S implementation. *Journal of Applied Sciences Research, 8*(7), 3855-3859. https://ssrn.com/abstract=2178780

Suraweera, S., & Jayasena, D. (2016, 27 July). The determinants of sustainability of 5S practices in the stationery industry, Sri Lanka. *Paper presented at the 8th Symposium on Applied Science*, Business & Industrial Research, Faculty of Applied Sciences, Wayamba University of Sri Lanka.

Tasdemir, C., & Gazo, R. (2018). A systematic literature review for better understanding of lean driven sustainability. *Sustainability, 10*(7), 2544. doi:10.3390/su10072544

Tennakoon, G. A., Rameezdeen, R., & Chileshe, N. (2022). Diverting demolition waste toward secondary markets through integrated reverse logistics supply chains: A systematic literature review. *Waste Management & Research, 40*(3), 274-293. doi:10.1177/0734242X211021478

Tennakoon, G. A., Rameezdeen, R., & Chileshe, N. (2024). Walking the talk towards sustainable consumption: interventions to promote the uptake of reprocessed construction materials. Engineering. *Construction and Architectural Management, 31*(7), 2878-2899. doi:10.1108/ECAM-11-2022-1040

Victar, H. C., & Waidyasekara, K. G. A. S. (2023). Circular economy strategies for waste management in Sri Lanka: A focus on demolitions and repurpose and material recovery and production stages. *Waste Management & Research*, 0734242X231206988. doi:10.1177/0734242X231206988

Waidyasekara, K. G. A. S., De Silva, L., & Rameezdeen, R. (2016). Water use efficiency and conservation during construction: drivers, barriers and practices. *Built Environment Project and Asset Management, 6*(5), 553-566. doi:10.1108/BEPAM-09-2015-0052

Withanachchi, N., Karandagoda, W., & Handa, Y. (2004). A performance improvement programme at a public hospital in Sri Lanka: an introduction. *Journal of health organization and management, 18*(5), 361-369. doi:10.1108/14777260410560820

Thirukumaran, N., Prabodani, M.K.M., Ranasinghe, S.S., Jayasinghe, G.Y. and Halwathura, R.U., 2024. A comparative analysis of operational energy by simulation study between modern buildings and adaptive reuse of historic buildings in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 15-26. DOI: https://doi.org/10.31705/WCS.2024.2. Available from: https://ciobwcs.com/papers/

A COMPARATIVE ANALYSIS OF OPERATIONAL ENERGY BY SIMULATION STUDY BETWEEN MODERN BUILDINGS AND ADAPTIVE REUSE OF HISTORIC BUILDINGS IN SRI LANKA

N. Thirukumaran[1], M.K.M. Prabodani[2], S.S. Ranasinghe[3], G.Y. Jayasinghe[4] and R.U. Halwathura[5]

ABSTRACT

The adaptive reuse of buildings is emerging as a sustainable solution within the built environment, addressing global challenges like climate change and greenhouse gas emissions faced by the world's population. Opting to repurpose energy-efficient historic buildings during the operational phase instead of demolishing and constructing new structures is recognized as a protective mechanism for urban cultural heritage. The escalating operational energy consumption in the building sector poses direct and indirect environmental, economic, and social concerns for occupants. This study aimed to compare the operational energy efficiency of adaptive reuse historic buildings and modern structures, seeking to identify the most energy-efficient building type. Energy consumption patterns, especially for air conditioning and lighting in residential houses, were gathered and simulated using DesignBuilder software, considering building materials as variables in both the old and new phases of the buildings. Ten Dutch-era residential dwellings were selected, and a specific schedule was analysed for energy simulations. The average Energy Use Intensity (EUI) value for old buildings in the scheduled case was lower than the newly modelled buildings. The research concludes that old historic buildings are comparatively more energy-efficient and environmentally friendly than new buildings for operational use based on the building envelope in the selected study area.

Keywords: *Adaptive Reuse; Design Builder; Energy Use Intensity; Operational Energy; Residential Buildings.*

---

[1] Graduate, Department of Agricultural Engineering and Environmental Technology, University of Ruhuna, Sri Lanka, nilakshikathiru@gmail.com
[2] Postgraduate student, Department of Civil Engineering, University of Moratuwa, Sri Lanka, methsi.praba@gmail.com
[3] Graduate, Department of Agricultural Engineering and Environmental Technology, University of Ruhuna, Sri Lanka, subasharanasinghe@gmail.com
[4] Senior Professor, Department of Agricultural Engineering and Environmental Technology, University of Ruhuna, Sri Lanka, victorlion3000@gmail.com
[5] Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka, rangika@uom.lk

1. INTRODUCTION

The construction industry is essential for all nations as it is one of the condemnatory constituents of sustainable economic, social, and national development. From the total world's energy, buildings solely account for 40% of the energy consumption (Romani et al., 2015). Nearly 35% of all building energy is utilised for the building's operations, such as heating, ventilation, air conditioning, and equipment (Yang et al., 2016). The operational energy consumption patterns of buildings are different from each building by the functions they perform and the type of building they belongs to. Those factors are climate or temperature, the kind of building envelope, and the effectiveness of the electrical systems in operation. The implementable strategy that can be followed to attain a high comfort level while using less energy in buildings is to enhance the thermal performance of the building envelope and significantly the walling material and insulations (Meng et al., 2018). The composition of the construction materials and their properties influence the operational energy utilisations in the building. Incorporating eco-friendly materials and older construction materials in building envelopes can help to lower the demand for both energy and cost.

The cost for the operation and maintenance of buildings seems to be increasing day by day. Adaptive reuse can be considered a resourceful, innovative approach that can be applied to achieve the goal of an ecologically sustainable built environment while preserving valuable heritage ethics by focusing on existing different structures (Abdulameer & Abbas, 2020). Computer simulations are helpful for deriving conclusions based on vast projects of various building systems. They provide accurate and predictable simulation results for circumstances that have not yet been tested in reality. They help forecast how these changes will influence energy balance and comfort levels inside the buildings. DesignBuilder software is one of the Building Energy Simulation (BES) tools that includes a variety of uploaded data templates for a range of building simulation inputs, such envelope construction components, lighting systems, and occupancy schedules (Wasilowski & Reinhart, 2009).

The research gap identified is the limited extent of studies focusing on operational energy consumption within Sri Lankan residential buildings. This gap suggests a lack of comprehensive understanding regarding the energy usage patterns, efficiency levels, and potential areas for improvement within the residential sector of Sri Lanka. This emphasises an important concern that global attention has been put in minimising the energy consumption of residential buildings by improving the building architectural and structural designs. In this study, the operational energy (OE) consumption patterns among dwellings belonging to historic buildings and modern buildings in Sri Lanka were compared and analysed using DesignBuilder software. The objective of this study is to compare the operational energy of adaptive reuse historic buildings (ARHB) with that of modern buildings to find the most energy-efficient building type. Ten residential dwellings were selected in the old town of Galle Fort area for research purposes. All ten buildings were modelled using the DesignBuilder software (DBS) using the original construction materials as old buildings and new construction materials as modern buildings with a specific schedule of 6 hours of Air conditioning and 7 hours of lighting for the simulation. Then, the OE need for those two building categories were compared to analyse whether the old historic buildings can be used for adaptive reuse in the modern operational phase. The simulated results showed that there is a significant difference between these two types of buildings. Adaptive reuse is one of the most popular methods for achieving sustainability in the construction industry. Adaptive Reuse of Historic Buildings (ARHB) is a relatively new idea introduced by the educationalist as a sustainable approach. The scope of this study is to ensure the sustainability of utilising historical buildings over constructing new ones, particularly in terms of operational phase energy consumption. By conducting simulation studies that account for building materials, researchers can evaluate the efficiency and viability of repurposing old-era structures, thereby contributing to informed decision-making and sustainable urban development.

2. LITERATURE REVIEW

2.1 OPERATIONAL ENERGY CONSUMPTION IN BUILDINGS

A typical building's life cycle energy is comprised of a trio of components: the energy the building itself comprises (Embodied energy), the energy it uses to operate throughout its lifetime (Operational energy), and the energy required to demolish the building and dispose of its waste. The typology "operational energy" means the magnitude of energy utilized during an object's functional use (Li et al., 2020). It specifically refers to the energy needed for the functioning of lighting systems, cooling and heating systems like HVAC, and other electrical appliances like refrigerators, dishwashing machines, and washing machines in a building. The four most common end uses can be stated as lighting, space heating, cooling, and water heaters, which account for approximately 70% of the energy used on the building property (Cao et al., 2016). According to Koezjakov et al. (2018), buildings' operational energy usage, or the energy needed to heat and cool them, accounts for around 33% of the total final energy demand of the globe and 30% of the carbon dioxide emissions related to energy use. The analysis of operational energy, particularly for residential situations, is a challenging task since it involves the intrinsic personal traits of each user, making the actual consumption profile of each residence unique. The operating phase's activity-wise energy split demonstrates that area lighting accounts for 29% of operating energy, with space cooling accounting for 45% (Ramesh et al., 2014).

Many factors can influence the operational energy of buildings. The design of building envelope, types of HVAC system, the performance of the electrical systems in use, pattern or behaviour of occupancy, energy management mechanisms and climate factors. Operational energy intensity relies on tenant behaviour in addition to location (climate zones) (Koezjakov et al., 2018). The authors found that, the Dutch building typology' operational energy consumption ranges from 124 to 682 MJ/(m^2.yr). The design of the building and envelope's material composition directly affect the operational energy performance of a building (Umbark et al., 2020). An air-tight construction and proper insulation can reduce the heat transfers within the building (Zilberberg et al., 2021). During the summer season, it neglects heat gains from outside and during the winter season, it reduces the heat loss from the building. Other factors, such as the orientation of the building and the effective design of the fenestration, can also affect the energy use of the buildings (Haase &Amato, 2009).

2.2 ADAPTIVE REUSE OF HERITAGE BUILDINGS (ARHB)

Adaptive reuse, also known as AR, encompasses the procedural endeavour of reconfiguring architectural structures to serve alternative functionalities (Rodrigues &

Freire, 2017). It involves aspects such as reusing components and materials, considering the life cycle of the building, evaluating aspects and making decisions based on multiple criteria as well as adhering to regulatory guidelines and analysing stakeholder's perspectives. Owojori et al., (2021) highlight that AR offers an improved alternative to construction and demolition, addressing challenges faced by the built environment.

Historic buildings can make a significant contribution to the history and culture of a country (Ayçam et al., 2020). AR of urban cultural heritage buildings gives new life to old buildings and has the potential to help future generations understand their genealogies, including a greater understanding of historical change (Bullen & Love, 2011). When thinking about renovating or retrofitting priceless heritage building structures, it is essential to recognize their substantial historical and architectural added value (Owojori et al., 2021). A vital part of regenerating the built environment to meet the demand for new structures is adaptive reuse of buildings (ARB), which preserves the latent prestige of old buildings. The good capacity of the building is not the sole factor for the successful adaptability of the buildings; the other factors like owner's or user's capacity to adapt and any other numerous variable which supports the dynamic interplay among building and context (Cellucci, 2021).

2.3 SIMULATION STUDY

A building is a complicated thermodynamic object that handles dynamic energy shifts between the various temperature zones inside and outside of the structure. According to (Reinhart & Christoph, 2009), the building energy simulation model control is made up of two primary parts. They are the building fabric contents and plant components. Since simulation tools may be applied at any stage of the life cycle and employ more general notions, computer simulations can assess the effects of many Energy Conservation Measures (ECMs) and their complex interactions more effectively, thoroughly, and correctly than any other method because of the complex nature a building model is (Coakley et al., 2014).

The simulation program has to execute the simulation utilizing hourly values of climate data, such as temperature, humidity, solar radiation, and wind speed and direction from representative climate data, for the location where the proposed design would be deployed (Jentsch et al., 2013). When compared to the standalone EnergyPlus engine, "DesignBuilder" has quality control mechanisms in place to ensure the findings are accurate. EnergyPlus is a ready-to-use program for a dynamic building energy simulation engine for modelling building’s heating, cooling, lighting, ventilation, and other energy flows (Crawley et al., 2001).

Numerous parameters affect and impact the building's energy systems. These parameters can be broadly categorized as enclosure factors, which refer to the thermal characteristics of the construction materials, climatic variables, and occupancy factors (Yu et al., 2015). According to Al-ajmi and Hanby (2008), the following elements could influence a building's energy needs in a simulation study: Location of the building (height, latitude, longitude, and direction) and weather in an area. Albatayneh (2021) ran a sensitivity analysis on 12 design variables in DesignBuilder to determine how they affect the heating and cooling loads to reduce the energy consumed for heating and cooling loads in household buildings in 'Ma'an City. The variables he used are the building envelope's window-to-wall percentage, local shading type, infiltration rate (ac/h), glazing type, flat roof construction, natural airflow rate, window blind type, window shading control schedule, partition construction, site orientation, external wall construction. Motuziene and Vilutiene (2013) demonstrated the simulation findings of the impact of domestic occupancy profiles on the energy efficiency of a Lithuanian home. To demonstrate his findings, he mentioned that the parameters must take into account the age, behaviour, and number of residents.

The DesignBuilder software is a sophisticated and advanced graphical user interface. It was created specifically to run EnergyPlus simulations and can assess how well a structure performs in terms of energy, carbon dioxide emissions, lighting and comfort (Reinhart & Christoph, 2009). According to Harish and Kumar (2016) the applications of DesignBuilder are Building energy simulation, visualisation, CO_2 emissions, solar shading, natural ventilation, daylighting, comfort studies, Computational Fluid Dynamics (CFD), HVAC simulation, pre-design, early-stage design, checking for compliance with building energy codes, OpenGL EnergyPlus interface, building stock modelling, hourly weather data, and sizing of heating and cooling equipment are all topics covered by this (An-Naggar et al., 2017). Wasilowski and Reinhart (2009) utilized the DesignBuilder interface for the energy plus simulation engine by constructing and assessing a model of Gund Hall. It was a complex building and he simulated the energy consumption pattern in it using customized internal loads and weather data. Ismail et al. (2015), calibrated the DesignBuilder and found that the acceptable error rate was 3.17% when calibrating with that software.

3. METHODOLOGY

3.1 DESCRIPTION OF STUDY AREA AND SAMPLE SELECTION

The old town of Galle and its fortifications are listed in UNESCO World Heritage Sites (Jinadasa, 2020). Dwellings belonging to the Dutch period were selected for the study as the adaptive phase of the buildings. The selection criteria were grounded in identifying buildings intended primarily for residential habitation. Employing a purposive sampling methodology, Dutch-era dwellings located in Galle were specifically chosen. So, in selecting the samples, they were chosen with care, considering their period and the current state of the building use. For the study 10 buildings were selected from the study area. Figure 1 shows the location of selected dwellings.

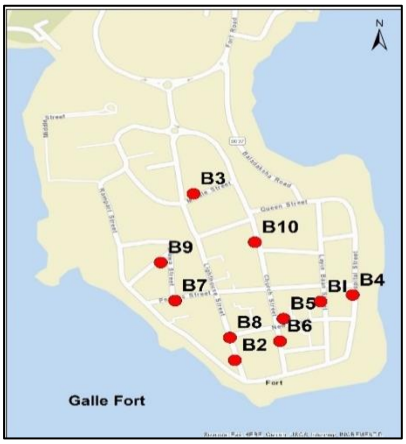


Figure 1: Location of selected ten buildings in Galle fort area

The selected buildings were visited, and the construction materials, the thickness of the walls, and their specifications were clarified during the site visit. Further information regarding the buildings, including floor plans, measurements, architectural specifications and history, were obtained from the Galle Heritage Information Centre**.** Table 1 shows the summary of construction materials used in the modelling.

Table 1: Details of building construction material

	Building Construction Materials	
Components	**Old Dutch Era Building**	**Modern Buildings**
External walls	Clay, Limestone, Granite mix (470 mm)	Brick wall (225 mm) + Plasters
Internal walls	Clay, Limestone, Granite mix (470 mm)	Brick wall (115 mm) + Plasters
Floor	Granite	Tile, Plaster, RC slab
Wall plaster	Clay, sand, Lime (15 mm +15 mm)	Cement/Sand plaster (15 mm +15 mm)
Columns	Clay, Limestone, Granite mix	Concrete
Doors	Timber	Timber
Staircases	Timber	Concrete + Tile
Windows	Timber + Glass	Aluminum + Glass
Roofs	Sinhala clay tiles +Timber	Clay tiles +Timber
Foundation	Concrete	Random rubble

3.2 THE SURVEY

An online questionnaire survey was prepared and circulated throughout different parts of the country, mainly focusing on the urban residential houses in all twenty-five districts of Sri Lanka. After filtering, 400 responses from the participants were included in the analysis of the survey. The main aim of the conducted survey was to find out the prevailing energy usage patterns in the household in Sri Lankan houses to find out the operational energy usage patterns for air conditioning and lighting. Those two are the main energy consumers in a household of tropical countries. Typical building' energy consumption for air conditioning and lighting is 56% and 16%, respectively, in tropical countries (Katili et al., 2015). There are evidences with booming economic report showing that, countries including Sri Lanka has high growth of sales of room air conditioners. This shows the increased usage of air conditioning in households (Mahlia & Saidur, 2010). Figure 2 shows the summary of the questionnaire survey.

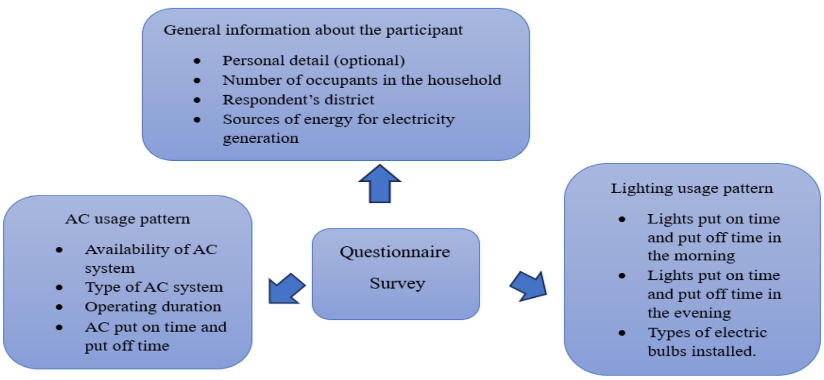


Figure 2: Summary of questionnaire survey

3.3 SIMULATION OF BUILDINGS

For simulating the operational energy consumption of the chosen ten buildings, the DBS (version 6.1.0.006) software was employed. Known for its user-friendly interface and flexibility, DBS adheres to ASHRAE 90.1 guidelines and utilizes EnergyPlus for accurate energy simulations. Input data utilised in the DesignBuilder software are outlined in Table 2.

Table 2: Input data into the DBS

Function Of Building	Residential
Working Profile	07 days per week
Clothing Value	0.665
Metabolic Factor	0.925
Occupancy	4 people per dwelling
HVAC	Split Air conditioning system.
Lux Level	150 lux
Cooling setback Temperature	26 degree C
Lighting Power Density	8 W / m^2

The DesignBuilder's "LKA _ COLOMBO _ KATUNAYAKE _ SWERA" was set as the simulation weather data file as it is similar to the Galle fort climatic conditions. The building's construction material was considered the primary input variable factor for the energy simulation for the selected buildings in the DBS. The Dutch-era buildings with their original construction materials as it is, being considered old buildings and the same buildings with similar dimensions, orientations, purposes and other functional factors, except building construction materials are considered as modern buildings. The selected ten buildings were developed in the DBS according to the actual dimensions of the building materials, heights and thickness, which were gathered during the site visit. A specific schedule, which was analysed from the survey data, was used for the simulation. The bedrooms in each dwelling were simulated with 6 hours of AC, and the whole building was simulated with 7 hours of lighting.

4. RESULTS AND DISCUSSION

The functional purpose of the selected ten buildings was to serve as residential buildings. The energy consumption and the adaptability of using the old historic buildings with the present operational energy consumption with the modern buildings were modelled using the DesignBuilder simulation under the specific schedule individually. The average simulated EUI values for the overall old buildings and new buildings are 50.37 kWh/m^2/yr and 56.42 kWh/m^2/yr respectively. The following Figure 3 shows the DBS simulated total EUI values for the selected buildings.

Here, new buildings show a relatively higher EUI value than older buildings, which indicates lower OE efficiency. Shabunko et al. (2018) did a research study regarding EUI per year in Brunei for residential buildings using EnergyPlus models and obtained the values ranging from 47.8 kWh/m^2 to 64.2 kWh/m^2. A door-to-door survey was conducted among 400 residential buildings to gather details on energy consumption.

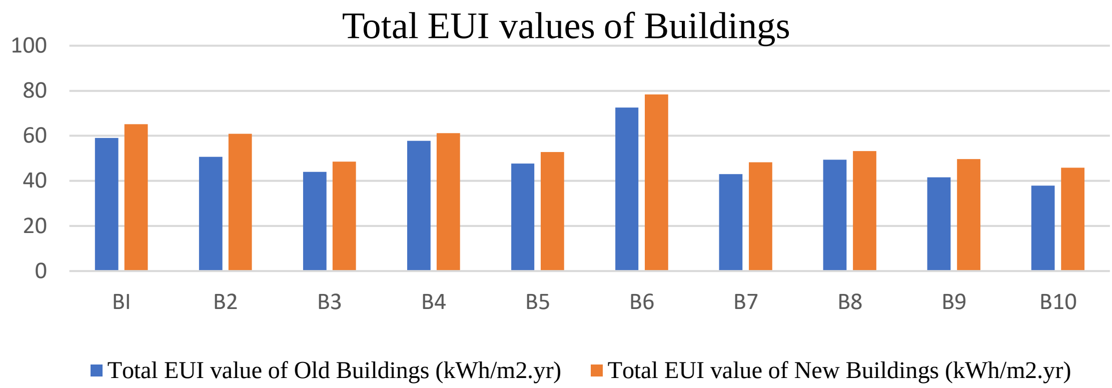


Figure 3: DBS simulated Total EUI values for buildings

These findings can be correlated with the results obtained from simulations conducted using our DBS, as Brunei is located in a tropical equatorial climate, and over 60% of electric load is contributed to HVAC operations. According to Boehme et al. (2015), the EUI values for residential landed housing range between 52.15 kWh/m^2/year to 65.19 kWh/m^2/yr. The findings of EUI were gained from the calculation results by considering building database and electricity consumption statistics, and it can be relatable to our findings as this study was also done in a tropical city – Singapore.

Figures 4 and 5 show the operational EUI values. The average EUI for the cooling in the old and new buildings are 21.41 kWh/m^2/yr and 31.10 kWh/m^2/yr, respectively. The average EUI need for the lighting in the old and new buildings are 28.96 kWh/m^2/yr and 25.33 kWh/m^2/yr, respectively.

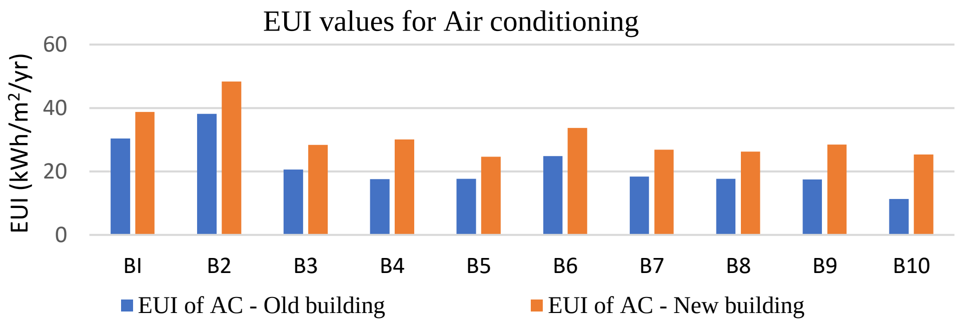


Figure 4: EUI values for AC

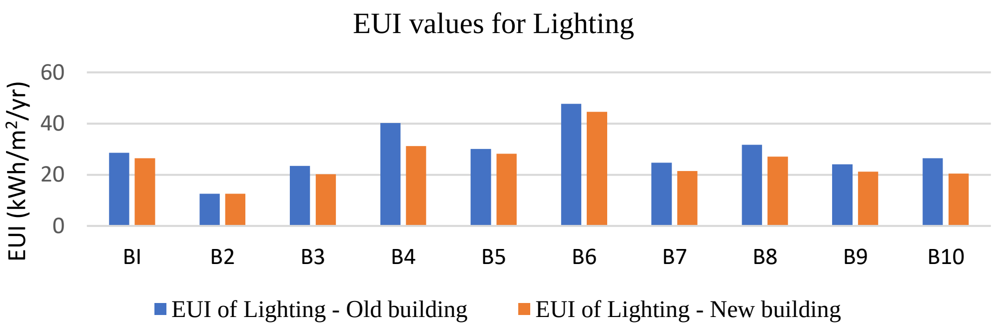


Figure 5: EUI values for Lighting

The specific reason for the simulated result is that cooling energy can be used with the construction materials and the thickness of the walling materials because all the other factors were kept constant during the simulations for the modern buildings. The thermal mass and the insulation properties of older buildings are often high (Reilly & Kinnane, 2017). Because they have thicker wall, and the walling materials are denser. The walls of the Dutch houses are around 0.35 m -1 m, and materials such as limestone, clay and granite have higher thermal mass properties (Waltham, 2002). This property reduces the temperature fluctuations by absorbing and releasing the heat inside the building slowly and contributing to stabilize the indoor temperature (Al-Homoud, 2005). By these features, a favourable comfortable internal environment was created, and it has the potential to reduce the need for frequent cooling.

The DBS simulated result shows that Dutch-era buildings require more energy for lighting compared to their modern counterparts. The reasons behind this can be validated with building design and material properties of the construction: Dutch-era buildings may have darker interior finishes, that comprises of wood panelling which can absorb higher percentage of light (Pajchrowski et al., 2014). Modern buildings with sophisticated designs often incorporate lighter colours and reflective surfaces to enhance and improve the reflection and distribution of light (Santamouris et al., 2011). Modern design principles emphasize open and flexible spaces that allow for better light distribution.

All the simulated results of the study were done in a Tropical climate – Sri Lanka. There are some limitations to the study that was conducted due to the availability of literature sources in the Sri Lankan context (Ariyarathna et al., 2023). The available literatures are regarding the different climatic zones, and this can impact the simulation in a big manner. This study is a significant approach to analyse the operational energy comparison for the adaptive reuse of historic buildings and modern buildings in Sri Lanka.

5. CONCLUSIONS

This research examined the simulated operational energy consumption of Dutch era historic buildings in Galle, which rely on construction materials for the old phase and new phase of the building with present energy usage, to find out the most energy efficient building type for the adaptive reuse of building purposes.

The simulated results validate that the modelled historic buildings are more energy efficient than the modelled new buildings, as the EUI values of new buildings are higher than the EUI values of the old buildings. In the specified schedule the total EUI of new buildings were higher than the total EUI of old buildings. The average EUI values for old buildings and new buildings were 50.37 kWh/m^2/yr and 56.42 kWh/m^2/yr respectively. The results of statistical analysis show an overall significant difference among the EUI values of two building types. That is, the old Dutch-era buildings are more energy efficient than the modern buildings in the selected buildings and locations. So, the objective of the study is to compare the operational energy of adaptive reuse historic buildings and modern buildings to find out the most energy-efficient building type was achieved. The other important feature observed was a better thermal performance in historical buildings resulted in a lower energy load for cooling than modern buildings in the simulated case for selected buildings based on the paired t-test analysis. The visual efficiency of historical buildings was seemed lower than that of modern buildings, resulting in a higher energy usage for lighting in old historic buildings.

Several methods can improve energy efficiency in residential dwellings, mainly targeting air conditioning (AC) and lighting systems for adopting those buildings. These methods encompass utilizing programmable thermostats and adhering to regular maintenance schedules to optimize Air conditioning usage and diminish energy wastage. Strategic deployment of shading devices and implementation of insulation techniques aid in mitigating heat transfer, thus alleviating the burden on air conditioning systems. Furthermore, the adoption of energy-efficient LED lighting fixtures alongside the integration of occupancy sensors serves to reduce unnecessary lighting consumption. Lastly, educating residents about energy-saving practices and fostering behavioural changes are pivotal for making substantial contributions to overall energy conservation within residential contexts. Difficulties arose during the research process, particularly in the validation of results. Acquiring pertinent operational energy data solely for air conditioning (AC) and lighting proved challenging due to the predominant focus in literature on combined usage, encompassing household appliances and domestic hot water systems alongside air conditioning and lighting. The accuracy of the simulation outcomes was guaranteed through validation against empirical data corresponding to studies of comparable scope and comprehensive input parameters. Moreover, the simulation methodology-maintained rigor by confining its assumptions to operational energy considerations primarily attributed to air conditioning and lighting within the designated residential units.

To enhance the comprehensiveness of this study, additional examination of other OE consumption mechanisms is warranted to corroborate the overall efficiency of adopting ARHB for contemporary purposes. Even though the results show a green flag to the adaptive reuse of historic buildings during the operational phase, the final decisions are relying on the building owners and their preferences in adapting them for operational use.

Future researchers can employ this methodology as a foundation for their investigations into the myriad factors influencing the operational energy of adaptive reuse buildings, with a specific emphasis on enhancing energy efficiency. Additionally, they can extend this conceptual framework across different stages of the building lifecycle to assess efficiency and sustainability comprehensively.

6. REFERENCES

Abdulameer, Z. A., & Sati'Abbas, S. (2020). Adaptive reuse as an approach to sustainability. IOP conference series: *Materials Science and Engineering, 881*(1), 012010. IOP Publishing. https://doi.org/10.1088/1757-899X/881/1/012010

Al-Ajmi, F. F., & Hanby, V. I. (2008). Simulation of energy consumption for Kuwaiti domestic buildings. *Energy and Buildings*, *40*(6), 1101-1109. https://doi.org/10.1016/j.enbuild.2007.10.010

Albatayneh, A. (2021). Optimizing the parameters of a building envelope in the East Mediterranean Saharan, cool climate zone. *Buildings*, *11*(2), 43.https://doi.org/10.3390/buildings11020043

Al-Homoud, M. S. (2005). A systematic approach for the thermal design optimization of building envelopes. *Journal of Building Physics*, *29*(2), 95-119. https://doi.org/10.1177/1744259105056267

An-Naggar, A. S., Ibrahim, M. A., & Khalil, E. E. (2017). Energy performance simulation in residential buildings. *Procedia Engineering*, *205*, 4187-4194. https://doi.org/10.1016/j.proeng.2017.10.177

Ariyarathna, I. S., Kariyakarawana, M., Abeyrathna, W. P., Danilina, N., & Halwatura, R. U. (2023). Analysis of operational energy between adaptive reuse historic buildings (ARHB) and modern office buildings: A case study in Sri Lanka. *Architecture*, *3*(3), 344-357. https://doi.org/10.3390/architecture3030019

Ayçam, I., Akalp, S., & Görgülü, L. S. (2020). The application of courtyard and settlement layouts of the traditional Diyarbakır houses to contemporary houses: A case study on the analysis of energy performance. *Energies*, *13*(3), 587.https://doi.org/10.3390/en13030587.

Boehme, P., Berger, M., & Massier, T. (2015). Estimating the building based energy consumption as an anthropogenic contribution to urban heat islands. *Sustainable Cities and Society*, *19*, 373-384. https://doi.org/10.1016/j.scs.2015.05.006

Bullen, P. A., & Love, P. E. (2011). Adaptive reuse of heritage buildings. *Structural Survey*, *29*(5), 411-421.https://doi.org/10.1108/02630801111182439

Cao, X., Dai, X., & Liu, J. (2016). Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy and Buildings*, *128*, 198-213. https://doi.org/10.1016/j.enbuild.2016.06.089

Cellucci, C. (2021). Circular economy strategies for adaptive reuse of residential building. *Vitruvio*, *6*(1), 111-121. https://doi.org/10.4995/vitruvio-ijats.2021.15404

Coakley, D., Raftery, P., & Keane, M. (2014). A review of methods to match building energy simulation models to measured data. *Renewable and sustainable energy reviews*, *37*, 123-141. https://doi.org/10.1016/j.rser.2014.05.007

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., & Glazer, J. (2001). Energy Plus: creating a new generation building energy simulation program. *Energy and Buildings*, *33*(4), 319-331. https://doi.org/10.1016/S0378-7788(00)00114-6

Haase, M., & Amato, A. (2009). An investigation of the potential for natural ventilation and building orientation to achieve thermal comfort in warm and humid climates. *Solar Energy*, *83*(3), 389-399. https://doi.org/10.1016/j.solener.2008.08.015

Harish, V. S. K. V., & Kumar, A. (2016). A review on modeling and simulation of building energy systems. *Renewable and Sustainable Energy Reviews*, *56*, 1272-1292. https://doi.org/10.1016/j.rser.2015.12.040

Ismail, A. M., Abo Elela, M. M., & Ahmed, E. B. (2015). Calibration of design builder program. *The Journal of American Science*, *11*, 96-102. https://www.researchgate.net/publication/286458880_Calibration_of_Design_Builder_program

Jentsch, M. F., James, P. A., Bourikas, L., & Bahaj, A. S. (2013). Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. *Renewable Energy*, *55*, 514-524. https://doi.org/10.1016/j.renene.2012.12.049

Jinadasa, U. N. (2020). *Changes in the cultural landscape and their impacts on heritage management: A study of Dutch fort at Galle, Sri Lanka*. Archaeological studies Leiden University. Leiden university press. https://www.aup.nl/en/book/9789087283407/changes-in-the-cultural-landscape-and-their-impacts-on-heritage-management

Katili, A. R., Boukhanouf, R., & Wilson, R. (2015). Space cooling in buildings in hot and humid climates—a review of the effect of humidity on the applicability of existing cooling techniques. *14th International conference on sustainable energy technologies –set,* (3, pp.90). The University of Nottingham. https://www.researchgate.net/profile/R-Boukhanouf/publication//Space-Cooling-in-Buildings-in-Hot-and-Humid-Climates-a-Review-of-the-Effect-of-Humidity-on-the-Applicability-of-Existing-Cooling-Techniques.pdf

Koezjakov, A., Urge-Vorsatz, D., Crijns-Graus, W., & Van den Broek, M. (2018). The relationship between operational energy demand and embodied energy in Dutch residential buildings. *Energy and Buildings*, *165*, 233-245. https://doi.org/10.1016/j.enbuild.2018.01.036

Li, Z., Lin, B., Zheng, S., Liu, Y., Wang, Z. and Dai, J., 2020, August. A review of operational energy consumption calculation method for urban buildings. *In Building Simulation* (13, pp. 739-751). Tsinghua University Press. https://doi.org/10.1007/s12273-020-0619-0

Mahlia, T. M. I., & Saidur, R. (2010). A review on test procedure, energy efficiency standards and energy labels for room air conditioners and refrigerator–freezers. *Renewable and Sustainable Energy Reviews*, *14*(7), 1888-1900.https://doi.org/10.1016/j.rser.2010.03.037

Meng, X., Huang, Y., Cao, Y., Gao, Y., Hou, C., Zhang, L., & Shen, Q. (2018). Optimization of the wall thermal insulation characteristics based on the intermittent heating operation. *Case studies in Construction Materials, 9*, e00188. https://doi.org/10.1016/j.cscm.2018.e00188

Motuziene, V., & Vilutiene, T. (2013). Modelling the effect of the domestic occupancy profiles on predicted energy demand of the energy efficient house. *Procedia Engineering*, *57*, 798-807. https://doi.org/10.1016/j.proeng.2013.04.101

Pajchrowski, G., Noskowiak, A., Lewandowska, A., & Strykowski, W. (2014). Wood as a building material in the light of environmental assessment of full life cycle of four buildings. *Construction and Building Materials*, *52*, 428-436. https://doi.org/10.1016/j.conbuildmat.2013.11.066

Owojori, O. M., Okoro, C. S., & Chileshe, N. (2021). Current status and emerging trends on the adaptive reuse of buildings: A bibliometric analysis. *Sustainability*, *13*(21), 11646. https://doi.org/10.3390/su132111646

Reilly, A., & Kinnane, O. (2017). The impact of thermal mass on building energy consumption. *Applied Energy*, *198*, 108-121.https://doi.org/10.1016/j.apenergy.2017.04.024

Ramesh, T., Prakash, R., & Shukla, K. K. (2014). Life cycle energy of low-rise residential buildings in Indian context. *Open Journal of Energy Efficiency*, *3*(04), 108. https://doi.org/ 10.4236/ojee.2014.34012

Reinhart, C. M., & Reinhart, V. R. (2009). Capital flow bonanzas: An encompassing view of the past and present. *In NBER international seminar on macroeconomics*, *5*(1).9-62. Chicago, IL: The University of Chicago Press. https://doi.org/10.1086/595995

Rodrigues, C., & Freire, F. (2017). Adaptive reuse of buildings: Eco-efficiency assessment of retrofit strategies for alternative uses of an historic building. *Journal of Cleaner Production*, *157*, 94-105. https://doi.org/10.1016/j.jclepro.2017.04.104

Romani, Z., Draoui, A., & Allard, F. (2015). Metamodeling the heating and cooling energy needs and simultaneous building envelope optimization for low energy building design in Morocco. *Energy and Buildings*, *102*, 139-148. https://doi.org/10.1016/j.enbuild.2015.04.014

Santamouris, M., Synnefa, A., & Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy*, *85*(12), 3085-3102. https://doi.org/10.1016/j.solener.2010.12.023

Shabunko, V., Lim, C. M., & Mathew, S. (2018). EnergyPlus models for the benchmarking of residential buildings in Brunei Darussalam. *Energy and Buildings*, *169*, 507-516. https://doi.org/10.1016/j.enbuild.2016.03.039

Umbark, M. A., Alghoul, S. K., & Dekam, E. I. (2020). Energy consumption in residential buildings: Comparison between three different building styles. *Sustainable Development Research*, *2*(1), p1-p1. https://doi.org/10.30560/sdr.v2n1p1

Waltham, T. (2002). *Foundations of Engineering Geology*. CRC press. https://doi.org/10.1201/9781482267785

Wasilowski, H., Reinhart, C., & Samuelson, H. W. (2009). Modeling an Existing Building in DesignBuilder/EnergyPlus: Custom Versus Default Inputs. In Eleventh International IBPSA Conference, (pp,1252-1259). Glasgow, Scotland. https://www.researchgate.net/publication/228453444_modelling_an_existing_building_in_designbuilderenergyplus_custom_versus_default_inputs

Yang, Z., Ghahramani, A., & Becerik-Gerber, B. (2016). Building occupancy diversity and HVAC (heating, ventilation, and air conditioning) system energy efficiency. *Energy*, *109*, 641-649. https://doi.org/10.1016/j.energy.2016.04.099

Yu, S., Cui, Y., Xu, X., & Feng, G. (2015). Impact of civil envelope on energy consumption based on EnergyPlus. *Procedia Engineering*, *121*, 1528-1534. https://doi.org/10.1016/j.proeng.2015.09.130

Zilberberg, E., Trapper, P., Meir, I. A., & Isaac, S. (2021). The impact of thermal mass and insulation of building structure on energy efficiency. *Energy and Buildings*, *241*, 110954. https://doi.org/10.1016/j.enbuild.2021.110954

Koralage, M.B., Udawatta, N. and Karunasena, G., 2024. A conceptual framework to manage circular economy knowledge in construction projects. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 27-38. DOI: https://doi.org/10.31705/WCS.2024.3. Available from: https://ciobwcs.com/papers/

A CONCEPTUAL FRAMEWORK TO MANAGE CIRCULAR ECONOMY KNOWLEDGE IN CONSTRUCTION PROJECTS

Malsha Buddha Koralage[1], Nilupa Udawatta[2], and Gayani Karunasena[3]

ABSTRACT

Circular Economy (CE) implementation in the construction industry has gained wider attention worldwide due to its ability to minimise the negative impacts of construction industry practices. However, gaps in CE knowledge have hindered CE implementation in the construction industry. Although the necessity of Knowledge Management (KM) for CE transition has been raised in numerous studies, existing literature has a dearth of CE KM studies, which is further limited in the construction context. Thus, this research aims to develop a conceptual framework to manage CE knowledge in construction projects by investigating required CE knowledge for construction professionals. A comprehensive literature review was undertaken to achieve this aim by analysing the literature using manual content analysis. The findings of this research highlight the overlaying impact of knowledge and KM on financial, market, technology, policy, and culture-related enablers and barriers of CE implementation in the construction industry. Furthermore, the potential of knowledge on addressing context and concept-related barriers to implementing CE was discussed, and a bespoke KM cycle with seven steps has been established, highlighting the importance of the KM cycle for CE KM rather than using the KM process. Finally, a conceptual framework for CE KM of the construction industry has been developed, revealing a shell view of these concepts. These findings will be beneficial for construction practitioners to i). understand areas of knowledge to be improved, and ii). identify KM actions to initiate improvements to ensure the implementation of CE principles.

Keywords: *Circular Economy; Construction Industry; Knowledge Enablers and Barriers; Knowledge Management.*

1. INTRODUCTION

The construction industry is considered one of the highest resource-consuming industries in the world, with substantial emissions and waste generation (Ababio & Lu, 2023; Adams et al., 2017; Munaro & Tavares, 2023). Accordingly, various attempts exist to mitigate the problems of overconsumption of resources, waste generation and harmful

[1] PhD Scholar, School of Architecture and Built Environment, Deakin University, Geelong, Australia, m.buddhakoralage@deakin.edu.au
[2] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Geelong, Australia, nilupa.udawatta@deakin.edu.au
[3] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Geelong, Australia, gayani.karunasena@deakin.edu.au

emissions of construction practices. CE is one of the promising concepts for the construction industry, which offers new opportunities and perspectives to reduce the overconsumption of resources and waste generation by feeding back products to the supply chain and thereby contributing to a reduction in harmful emissions (Bilal et al., 2020). Furthermore, the application of CE in the construction industry contributes to reducing ecological footprint, waste, and resource depletion (Wuni, 2022). CE in the construction context refers to an economic system that helps to create slow, narrow, and close loops of production and consumption of resources (Oluleye et al., 2022), contrary to the traditional “end of life” mindset (Shooshtarian & Maqsood, 2023). It comprises different R principles. These principles have evolved, leading to twelve potential R principles to be adopted in the present context: refuse, rethink, redesign, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover, and regenerate (Collins et al., 2023).

However, despite the diverse approaches to Circular Economy (CE) in the construction industry, such as waste, energy, water, materials, emissions, and general practices (Bilal et al., 2020); the industry remains in the early stages of CE adoption. This situation underscores the need for further action to facilitate the transition to CE within the construction sector (Ababio & Lu, 2023). This transition required a broader diffusion of CE into construction materials, products, processes, philosophies, stakeholders, and organisations in the industry (Wuni, 2022). Being a dynamic, complex, labour-intensive, and changing industry (Charef et al., 2021; Hart et al., 2019) with long-term project-based interactions in supply chains (Senaratne et al., 2021), the construction industry faces the challenge of CE transition (Adams et al., 2017; Munaro & Tavares, 2023; Charef et al., 2021). Numerous barriers impede CE transition in the construction industry, including financial, regulatory, knowledge, organisational, cultural, technology and stakeholders (Ababio & Lu, 2023; Bilal et al., 2020). Similarly, lack of experienced, skilled workers and insufficient knowledge have been portrayed as two of the top five barriers to CE transition in the construction industry, and KM has been proposed as a viable solution to address this barrier (Charef et al., 2021). Furthermore, researchers have highlighted that lack of CE knowledge, the complexity of the CE concept, inadequate skills and awareness of stakeholders, and the complexity of the industry as more specific and significant causes for the lack of CE implementation in the construction industry (Hart et al., 2019; Osei-Tutu et al., 2023; Charef et al., 2021; Wuni, 2022). Accordingly, the absence of CE knowledge and the CE KM system have hindered CE implementation in the construction industry. Henceforth, it is necessary to apply CE KM methodologies in the construction industry (Charef et al., 2021).

Due to its ancient origins, KM comprises well-established principles, practices, tools, and strategies. Furthermore, it has been applied in a wide range of research domains. However, the systematic, continuous, multi-dimensional and complex nature of CE emerges the necessity of organising pertinent information, analysing, applying, and evaluating them properly, defining accurate sources and holistic ideas of workable concepts (Formisano et al., 2021). Further, despite the availability of KM practices, CE KM requires the circulation of knowledge and know-how in the process of CE transition, which requires unique insights into “what knowledge”, “which individuals/groups”, "what methods", and “communication channels” (Chembessi, 2023).

Despite the importance of KM in processing, storing, visualising, and sharing CE data and information regarding products, processes, and stakeholders, CE KM can be considered an under-examined area in current academic literature (Klapalová, 2019). Acerbi et al. (2020) discussed the connection of CE with KM in a lean context and revealed that CE KM is an essential area for waste management and sustainable manufacturing. Nonetheless, the prospective role of KM methods and tools incorporating CE in this context is rarely investigated. Accordingly, Chembessi (2023) has suggested three directions to initiate research in this under-examined area as investigating; i). KM processes for CE, ii). KM methods for CE, and iii). micro-level application of CE KM to ensure a macro-level transition to CE. Additionally, Formisano et al. (2021) highlighted that while a correlation between KM and CE exists, with KM serving as a key pillar in CE implementation, most developed countries have yet to take substantial initiatives to effectively manage knowledge within the context of CE. Similarly, concentrated and specific models, frameworks, methods, tools, and evaluation indicators are urgently needed to assist the transition to CE (Peralta et al., 2020).

Even though many studies have emphasised the importance of CE KM in the construction industry, CE KM studies are further limited in the construction context. Shooshtarian and Maqsood (2023) emphasised the importance of KM through collaborations and partnerships to facilitate the implementation of CE in the Australian construction industry. Moreover, the findings of Senaratne et al. (2021) regarding the trends of KM research in the construction industry have revealed the gaps in CE KM research and identified the importance of developing a generic KM model focusing on connecting stakeholders covering all stages of a construction project to ensure CE using social, economic, and environmental pillars of sustainability. Overall, the findings mentioned above revealed the limited attention on CE KM in academia, which is further limited in the construction context, irrespective of the need for a tailored CE KM model for the construction industry. Thus, the methods of integrating elements of CE and elements of KM in the construction context to ensure CE transition are limited in the literature. Henceforth, this research aims to develop a conceptual framework that can be used to utilise KM for CE transition in the construction industry.

2. RESEARCH METHOD

This study is developed based on a comprehensive literature review in CE, KM, and the construction industry by exploring theories, concepts, and patterns to develop a conceptual framework to manage CE knowledge in construction projects. The studies of Chembessi (2023) and Peralta et al. (2020) have used a similar method of literature review to investigate the role of KM in CE transition. Accordingly, keywords for literature retrieval were established as “circular*”, AND “knowledge*”, AND (“enabler*” OR “benefit*” OR “advantage*” OR “barrier*”, OR “limitation*” OR “disadvantage*”) AND (“construction*” OR “built* environment*” OR “building* industry*”). These keywords were pursued in the "Web of Science", "Scopus", and “Engineering Village” databases, as well as the “Google Scholar” search engine, to identify appropriate results. Consequent to the dearth of studies collectively contributing to these three fields of studies, both distinct and combined search terms were used to identify results. After thoroughly reviewing the search outcomes' titles, abstracts, and keywords, this sample of papers was purposively selected to cover a more comprehensive range of articles on CE enablers and barriers, seminal studies in KM, and current contributions in CE KM.

This study critically reviews: (i) connection of CE and the construction industry, revealing CE principles, practices, benefits, and strategies applicable to the construction industry; (ii) Impact of knowledge as an enabler and a barrier for CE implementation, (iii) the necessity of KM to CE implementation in the construction context, and (iv) KM steps to develop a conceptual framework for CE KM for the construction industry to contribute to CE transition. Manual content analysis was conducted to review and analyse the selected articles, following the author's opportunity to review them extensively.

3. LITERATURE FINDINGS

3.1 CIRCULAR ECONOMY PRINCIPLES, PRACTICES, STRATEGIES AND BENEFITS FOR THE CONSTRUCTION INDUSTRY

The CE principles, practices, and strategies are closely related terms, while principles refer to the fundamental guidelines and concepts that describe procedures for transitioning from a traditional take-make-dispose approach to a circular approach (Adams et al., 2017). The practices or strategies refer to actions taken to reduce waste generation from natural resources and energy consumption and lead to ensure sustainable and cleaner production (Oluleye et al., 2022). Accordingly, CE strategies have been drawn based on CE principles, and many authors have used these two terms collectively to describe the actions for CE transition in the construction industry.

The CE principles keep evolving in the academic literature, and authors have provided different arguments about them. According to the Ellen MacArthur Foundation (2016), which is considered a pioneer organisation researching CE: (i) design out waste and pollution (slow), (ii) keep products and materials in use (narrow), and (iii) regenerating natural systems (close) has been identified as the overview of the fundamental principles for the circularity movement. A recent study by Collins et al. (2023) has identified twelve CE principles as reuse, repair, redesign, remanufacture, refurbishment, recycle, replace, recover, repurpose, rethink, reduce and regeneration. This classification of CE is a substantial guideline of principles for CE implementation, directed to achieve the focus of CE, closing and narrowing the resource loop. A variety of CE strategies have been identified for the construction industry. For instance, Charef et al. (2021) have identified five leading strategies for CE implementation in the construction industry: implementing CE design, developing CE competencies, ensuring the CE value chain, managing CE practices, and tracking CE development. Furthermore, Wuni (2022) identified a set of strategies targeting different clusters of CE barriers, including common strategies of increasing government interference, improving material quality, expanding evidence-based knowledge, professional training, and improving design strategies.

Izquierdo et al. (2024) have mentioned twelve practices for CE implementation in the built environment: (i) material and product selection, (ii) design for modularity, (iii) design for adaptability and flexibility, (iv) design for standardisation, (v) design for disassembly, (vi) design for prefabrication, (vii) built out of waste, (viii) building in layers, (ix) selective demolition, (x) disassembly, (xi) upcycling, and (xii) downcycling. A similar view has been disclosed by Wuni (2022). The author has mentioned that design for waste elimination and value recovery operations are CE practices applicable to the construction industry. Accordingly, it is evident that these practices coincide with CE strategies proposed by Charef et al. (2021), such as implementing CE design, developing CE competencies, ensuring the CE value chain, and managing CE practices. Henceforth, these principles and strategies are developed to ensure attaining R principles and use concurrently in the academic literature. For example, design for adaptability and flexibility contributes to ensuring “reuse”, and the build-out of waste ensures “reduce.”

There are a variety of benefits to implementing CE principles, practices, and strategies for the construction industry, which primarily contribute to sustainable development. CE contributes to minimising energy use, waste generation, and greenhouse gas emissions, ensuring optimal resource usage and, therefore, portraying a prominent step towards sustainability (Illankoon & Vithanage, 2023). Furthermore, as emphasised by Oluleye et al. (2022) and Shooshtarian and Maqsood (2023), the implementation of CE strategies helps innovation and collaboration regarding technologies and best practices, contributing to sustainability in the construction industry and provides prolific ways for implementation of construction activities. In addition, implementing CE practices adds value to construction organisations and makes them reputed for initiating actions, embracing this novel concept. Moreover, though the implementation of CE practices is costly by the construction industry (Charef et al., 2021), it has the potential to save lifecycle costs of construction projects as it reduces transportation costs (Oluleye et al., 2022), increase the durability of products (Collins et al., 2023), promote reusing of components and design for modularity (Izquierdo et al., 2024). Overall, it is evident that CE implementation provides substantial benefits to the construction industry.

3.2 IMPACT OF KNOWLEDGE ON ENABLERS AND BARRIERS TO IMPLEMENT CIRCULAR ECONOMY IN THE CONSTRUCTION INDUSTRY

Considering CE as a promising solution to ensure sustainability in the construction industry, various enablers and barriers to CE implementation can be identified from the literature. Hart et al. (2019) noted that enablers and barriers to implementing CE in the construction industry are two sides of the same coin, as they often relate to the same financial, cultural, political, and sectoral categories. A similar view is presented by Munaro and Tavares (2023), who categorised enablers and barriers into altered economic, technological, organisational, political, and informational classifications. In addition, Charef et al. (2021), Osei-Tutu et al. (2023), and Wuni (2022) revealed categorisations for barriers of CE, which include categories of economic, technical, technological, cultural, organisational, political, market, knowledge, supply chain, management, stakeholders, social, and environmental.

A significant aspect revealed in these studies is the necessity and relationship of knowledge with all the categorised barriers being one of the overlaying forces to enable CE (Adams et al., 2017; Illankoon & Vithanage, 2023; Oluleye et al., 2022). Thus, many studies have identified CE knowledge as an enabler and barrier (Bilal et al., 2020b; Shooshtarian & Maqsood, 2023). According to Izquierdo et al. (2024), most of the identified enablers and barriers of CE are significant in the linear economy context, and the difference is customising them to ensure the goals of CE. Accordingly, the authors reveal and argue the importance of special accreditation on CE knowledge and KM to reinforce enablers and mitigate barriers to CE implementation in the construction industry (Izquierdo et al., 2024). Furthermore, according to Wuni (2022), knowledge, awareness and skills are directly related to ensuring CE transition in the construction industry. This knowledge requirement can be identified from different viewpoints, as shown in Figure 1.

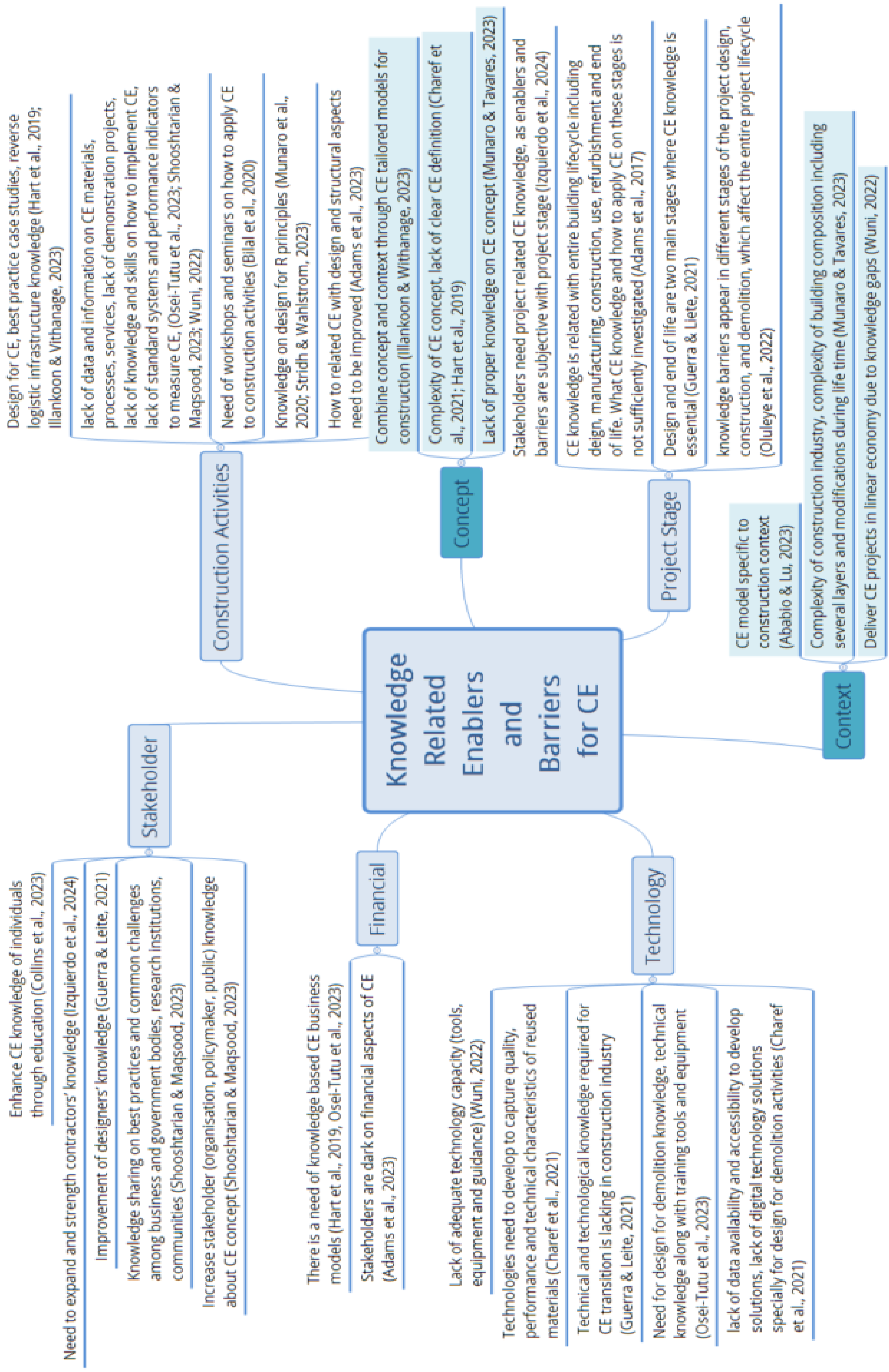


Figure 1: Circular economy knowledge enablers and barriers in the construction industry

According to Figure 1, CE knowledge is required for the construction industry from the viewpoints of stakeholders, project stage, construction activity, technology, financial, concept and context, being an enabler and a barrier for CE implementation. For instance, Izquierdo et al. (2024) emphasised that improving stakeholders' knowledge ensures the quality of CE implementation, being an enabler. Furthermore, Charef et al. (2021) conveyed that a lack of information on the quality, performance and technical characteristics of the reused materials is a barrier that hinders CE implementation. After an extensive review of existing literature, this study identified two less revealed, significant areas of knowledge barriers i.e., (i) concept, and (ii) context barriers. Even though they have been less revealed as categories of enablers or barriers, related aspects to these two factors have been highlighted in existing studies, as mentioned in Figure 1. Overall, knowledge can be argued as an overlaying force for enablers, and barriers revealed in existing studies, including finance (business models), materials, products, and processes (construction activity and technology), supply chain (project stage and stakeholders), and delivering CE in the linear economy (concept and context).

3.3 KNOWLEDGE MANAGEMENT FOR CIRCULAR ECONOMY IMPLEMENTATION IN THE CONSTRUCTION INDUSTRY

Despite the dearth of comprehensive, systematic KM strategies, the need for KM has been revealed in existing studies, which align with the steps of the KM cycle. As per the enablers and barriers of CE, the absence of adequate knowledge and KM methods have been associated with the frequently emerged barriers to CE implementation in the construction industry (Oluleye et al., 2022; Shooshtarian et al., 2023; Charef et al., 2021, 2023; Wuni, 2022). Similarly, Charef et al. (2021) have identified KM as a suitable approach to addressing CE implementation issues of the construction companies as the construction industry requires changing working methods, training, skills building and access to additional data to enable CE. This need is because of the nature of the construction industry being conservative, uncollaborative and adversarial (Hart et al., 2019), providing complex building compositions, including several layers and modifications during the lifespan (Illankoon & Vithanage, 2023; Munaro & Tavares, 2023).

Accordingly, Collins et al. (2023) communicate the necessity of individuals' CE knowledge for successful CE transition and convey the role of education for that. This education relates to the entire KM cycle, as education on "how to" is a crucial activity in every stage of the KM cycle. Similarly, KM actions revealed in studies of Illankoon and Vithanage (2023) and Izquierdo et al. (2024), which to provide CE guidance and to develop a CE model specific to construction could help to overcome the identified context and concept knowledge barriers, which requires efforts from entire KM cycle. Moreover, Wuni (2022) mentioned the need for “knowledge evaluation”, highlighting the need for CE-friendly technologies. Further, the lack of data availability and accessibility to develop technologies and the lack of digital technology solutions for CE, especially for “design for demolition stage activities” (Charef et al., 2021; Osei-Tutu et al., 2023) can be mitigated by enhancing "design for demolition" knowledge, and technology knowledge through evidence-based projects, which is related with “knowledge application and evaluation”.

Shooshtarian and Maqsood (2023) mention knowledge sharing on best practices as a vital step in CE implementation in the construction industry. Further, the need to promote stakeholder awareness through education, developing a CE model specific to construction, developing collaborative information-sharing tools (Ababio & Lu, 2023;

Munaro & Tavares, 2023), and conducting seminars and workshops (Bilal et al., 2020) are knowledge-sharing steps to increase knowledge regarding construction activities to foster CE transition. Moreover, Bilal et al. (2020) state that the above barriers can be addressed by educating the public on CE and conducting seminars and workshops to increase CE awareness. Thus, KM plays a vital role in the CE transition of the construction industry, which is consequent to the nature of the construction industry, which has lengthy supply chains and requires extensive stakeholder collaborations (Senaratne et al., 2021). Henceforth, the next section of this study investigates the concept of KM, identifying its steps.

3.4 KNOWLEDGE MANAGEMENT CYCLE

The KM can be considered a source of innovation and a powerful engine of production, which provides the entire basis for the proper functioning of any industry and helps to gain a competitive advantage (Nakamori, 2020). Different terminologies have been used to explain the KM process; principally, it involves the creation, organisation, distribution, and application of knowledge (Klapalová, 2019; Marinho & Couto, 2022; Nakamori, 2020). In contrast, some studies have highlighted the cyclic nature of the KM, (Fard & Selseleh, 2010; Mohapatra et al., 2016) and this cycle includes the same steps of the KM process. Accordingly, Table 1 describes the different terminologies associated with the KM process/cycle.

Table 1: Different terminologies used in literature for steps of knowledge management.

KM steps terminologies	Context	Source
Create, Capture, Refine, Store, Manage, Disseminate	General	Bose (2004)
Collection, Accumulation, Utilisation, Dissemination	General	Nakamori (2020)
Identify, Create, Store, Share, Use, Learn, Improve *	General	Evans et al. (2014)
Capturing, Coding, Publishing, Sharing, Accessing, Application *	General	Mohapatra et al. (2016)
Generation, Acquisition, Sharing, Use, Generate Value	Construction	Yepes and López (2021)
Creation, Acquisition, Sharing, Integration, Application	Construction	Yu and Yang (2018)
Acquire, Capture, Analyse, Utilise, Store, Share	CE	Klapalová (2019)
Acquire, Design, Manage, Share	CE	Chembessi (2023)
Generation, Using, Transferring, Sharing	CE	Formisano et al. (2021)

*- set of terminologies used in the KM cycle and remainders stand for the terminologies in the KM process.

By acknowledging the iterative nature of knowledge, this study considered KM as a cycle rather than a sequential process. Henceforth, Figure 2 depicts the KM model tailored for this study following the KM process of Bose (2004) and the KM cycles of Evans et al. (2014) and Mohapatra et al. (2016), considering their comprehensive explanation of KM steps.

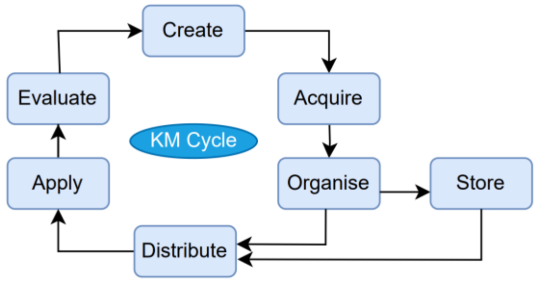


Figure 2: Knowledge management cycle

Figure 2 depicts a seven-step KM cycle covering the key actions used to manage knowledge in different contexts. Following the view of Evans et al. (2014), who have identified the possibility of having double loops in the KM cycle, a double loop has been identified for this cycle at the step of "organise". CE knowledge must be managed to ensure CE implementation in the construction industry (Charef et al., 2021; Munaro & Tavares, 2023a; Oluleye et al., 2022b) through (i) Creation of CE knowledge for the construction industry regarding the materials, processes, techniques, technologies, principles, and best practices that align with CE; (ii) Obtaining (acquiring) the created knowledge from reliable sources, (iii) Organising the knowledge to generate easily retrievable meaningful outcomes, (iv) Storing and/or distributing the organised outcomes to internal and external stakeholders of the construction industry, relevant cross-industries (e.g., manufacturing), policymakers and business innovators, (v) applying the identified CE knowledge in their contexts to enhance CE implementation, and finally, (vi) learn from applying knowledge, improve it, and feed the lessons learned from application to knowledge creation. The next section of this study reveals the conceptual framework developed for CE KM.

3.5 CONCEPTUAL FRAMEWORK

This section explains the conceptual framework developed for CE KM in the construction industry, which explains the necessity of CE transition in the construction sector, as conveyed in Figure 3.

Accordingly, two fundamental areas of CE and KM should be combined, identifying the critical areas of CE knowledge to be managed to ensure transition. Thus, the three main objectives of CE (Ellen MacArthur Foundation, 2016) and 12R CE principles (Collins et al., 2023) can be considered as the critical reinforcing knowledge to contemporise initiating solutions to current limitations of CE transition in the construction industry as discussed in Section 3.1. This information serves as inner layers of the conceptual framework, and this knowledge helps to manage enablers and barriers of CE implementation (Ababio & Lu, 2023) and formulate practices and strategies for improving CE in the construction industry. Steps of the KM cycle discussed in Section 3.3 have been integrated as the outermost layer of the conceptual framework, which is an effective procedure to synchronise information to address CE knowledge-led barriers for the construction industry and improve CE knowledge-led enablers for the construction industry as it includes all the steps of creating, acquiring, organising, storing, distributing, applying, and evaluating required knowledge for the implementation of CE practices in the construction projects and thereby transforming to a circular construction industry. This outer layer can be expanded with tailored and detailed CE KM strategies targeting different stakeholder groups, different project stages and different types of construction projects. While this framework does not replace all the existing KM studies, it will contribute to the KM domain by offering targeted and focused CE KM initiatives. Further, the outcomes of this study will assist in rendering current KM practices feasible.

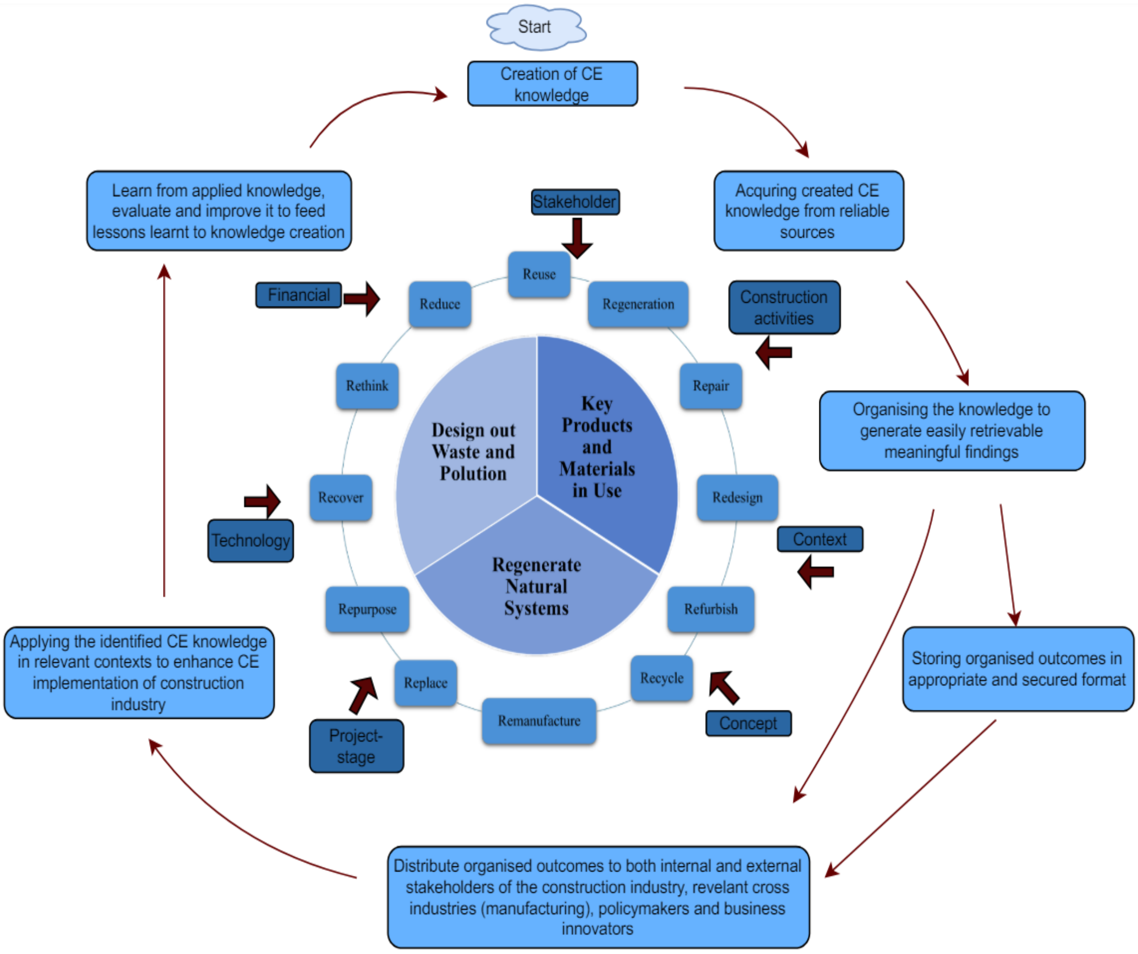


Figure 3: Circular economy knowledge management conceptual framework for the construction industry.

4. CONCLUSIONS

The construction industry, being resource-intensive, faces several challenges in the CE transition. CE knowledge has been acting as an overlaying force for these challenges, being related to different stakeholders, various stages of a project, activities of the construction process, and required technologies. Thus, a comprehensive literature review proposes a conceptual framework for CE KM by integrating CE principles, practices, and the KM cycle.

The findings highlighted that even though CE enablers and barriers have been categorised into distinct groups, knowledge serves as the primary link between them all. However, despite the extensive need highlighted in existing "CE in construction literature" to enhance CE knowledge, "how to do that" is rarely investigated. Although existing literature on CE and KM emphasises the importance of KM processes, it often lacks clarity in specifying their interconnections, thereby impeding the systematic and continuous adoption of CE. Hence, this study argues the suitability of the KM cycle over the KM process for CE transition in the construction industry.

The proposed conceptual framework insists on the shell view of CE principles, practices and KM. Accordingly, the execution of an outer shell requires inputs from the adjacent inner shell to tailor the context. This framework can be used as a basis to develop the CE KM model for the construction industry, targeting different stakeholders and various stages of the construction process. Moreover, this framework can be applied to targeting a particular category of enabler(s) or barrier(s) and/or R principle(s). This study has a few limitations. First, this literature review has not been limited to any geographical area, where some alterations may be needed to apply this framework to a particular country. Moreover, this framework needs to be validated with primary data which will be a limitation and a future research avenue.

5. REFERENCES

Ababio, B. K., & Lu, W. (2023). Barriers and enablers of circular economy in construction: a multi-system perspective towards the development of a practical framework. *Construction Management and Economics*, *41*(1), 3–21. https://doi.org/10.1080/01446193.2022.2135750

Acerbi, F., Sassanelli, C., Terzi, S., & Taisch, M. (2020). Towards a data-based circular economy: exploring opportunities from digital knowledge management. *Lecture Notes in Networks and Systems*, *122*, 331–339. https://doi.org/10.1007/978-3-030-41429-0_33

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Bilal, M., Khan, K. I. A., Thaheem, M. J., & Nasir, A. R. (2020). Current state and barriers to the circular economy in the building sector: Towards a mitigation framework. *Journal of Cleaner Production*, *276*, 123250. https://doi.org/10.1016/j.jclepro.2020.123250

Bose, R. (2004). Knowledge management metrics. *Industrial Management and Data Systems*, *104*(6), 457–468. https://doi.org/10.1108/02635570410543771

Charef, R., Morel, J. C., & Rakhshan, K. (2021). Barriers to implementing the circular economy in the construction industry: A critical review. *Sustainability (Switzerland)*, *13*(23), 1–18. https://doi.org/10.3390/su132312989

Chembessi, C. (2023). Learning and knowledge management in the transition to circular economy (CE): Roots and research avenues. *Journal of Circular Economy.1*(3), 1-14. https://doi.org/10.55845/FJWU9610

Collins, R., Laws, C., & Wadhwani, T. (2023). *Circularity in Australian Business 2023*. From Pollution to Solution. https://www.frompollutiontosolution.org/circularsteel

Ellen MacArthur Foundation. (2016). *What is a circular economy*? . Ellen MacArthur Foundation https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Evans, M., Dalkir, K., & Bidian, C. (2014). A holistic view of the knowledge life cycle: The knowledge management cycle (KMC) model. *Electronic Journal of Knowledge Management*, *12*(2), 85–97. https://academic-publishing.org/index.php/ejkm/article/view/1015/978

Fard, H. D., & Selseleh, M. (2010). Measuring knowledge management cycle: Evidence from Iran. *European Journal of Scientific Research*, *41*(2), 297–309.http://www.eurojournals.com/ejsr.html

Formisano, V., Fedele, M., & Bonab, A. B. (2021). Knowledge management and circular economy: Novel solutions to cope with uncertain times. Managing knowledge in uncertain times, *16th International Forum on Knowledge Asset Dynamics*, (pp. 183–206). https://www.researchgate.net/publication/355131843_Knowledge_Management_and_Circular_Economy_Novel_Solutions_to_Cope_with_Uncertain_Times

Hart, J., Adams, K., Giesekam, J., Tingley, D. D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: The case of the built environment. *Procedia CIRP*, *80*(March), 619–624. https://doi.org/10.1016/j.procir.2018.12.015

Illankoon, C., & Vithanage, S. C. (2023). Closing the loop in the construction industry: A systematic literature review on the development of circular economy. *Journal of Building Engineering*, *76*(July), 107362. https://doi.org/10.1016/j.jobe.2023.107362

Izquierdo, R. S., Soliu, I., & Migliaccio, G. C. (2024). Enablers and barriers to implementation of circular economy practices in the built environment: An exploratory study. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *16*(2), 1–11. https://doi.org/10.1061/jladah.ladr-1094

Klapalová, A. (2019). How knowledge management is approached in circular economy academic research. *Proceedings IFKAD, March*. (pp. 653–663). https://www.researchgate.net/profile/Alena-Klapalova/publication/339474321_How_Knowledge_Management_is_Approached_in_Circular_Economy_Academic_Research.pdf

Marinho, A. J. C., & Couto, J. (2022). Contribution to improvement of knowledge management in the construction industry - Stakeholders' perspective on implementation in the largest construction companies. *Cogent Engineering*, *9*(1). https://doi.org/10.1080/23311916.2022.2132652

Mohapatra, S., Agrawal, A., & Satpathy, A. (2016). Knowledge management cycles. In *In Management for professionals.* (pp. 13–29). https://doi.org/10.1007/978-3-319-33894-1_2

Munaro, M. R., & Tavares, S. F. (2023). A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Cleaner and Responsible Consumption*, *8*(February), 1-14. https://doi.org/10.1016/j.clrc.2023.100107

Nakamori, Y. (2020). *Knowledge construction methodology*. Springer. https://doi.org/10.1007/978-981-13-9887-2_5

Oluleye, B. I., Chan, D. W. M. M., Saka, A. B., & Olawumi, T. O. (2022). Circular economy research on building construction and demolition waste: A review of current trends and future research directions. *Journal of Cleaner Production*, *357*(2022), 1–18. https://doi.org/10.1016/j.jclepro.2022.131927

Osei-Tutu, S., Ayarkwa, J., Osei-Asibey, D., Nani, G., & Afful, A. E. (2023). Barriers impeding circular economy (CE) uptake in the construction industry. *Smart and Sustainable Built Environment*, *12*(4), 892–918. https://doi.org/10.1108/SASBE-03-2022-0049

Peralta, M. E., Luna, P., & Soltero, V. M. (2020). Towards standards-based of circular economy: knowledge available and sufficient for transition? *International Journal of Sustainable Development and World Ecology*, *27*(4), 369–386. https://doi.org/10.1080/13504509.2019.1701581

Senaratne, S., Rodrigo, M. N. N., Jin, X., & Perera, S. (2021). Current trends and future directions in knowledge management in construction research using social network analysis. *Buildings*, *11*(12). https://doi.org/10.3390/buildings11120599

Shooshtarian, S., Hosseini, M. R., Kocaturk, T., Arnel, T., & Garofano, N. T. (2023). Circular economy in the Australian AEC industry: investigation of barriers and enablers. *Building Research and Information*, *51*(1), 56–68. https://doi.org/10.1080/09613218.2022.2099788

Shooshtarian, S., & Maqsood, T. (2023). Circularity in the Australian Built Environment Sector. *Australian Environment Review*, *37*(8), 161–163. https://www.researchgate.net/profile/Salman_Shooshtarian/publication/Circularity-in-the-Australian-Built-Environment-Sector.pdf

Wuni, I. Y. (2022). Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map. *Building and Environment*, *223*(July), 109453. https://doi.org/10.1016/j.buildenv.2022.109453

Yepes, V., & López, S. (2021). Knowledge management in the construction industry: Current state of knowledge and future research. *Journal of Civil Engineering and Management*, *27*(8), 671–680. https://doi.org/10.3846/jcem.2021.16006

Yu, D., & Yang, J. (2018). Knowledge management research in the construction industry: A review. *Journal of the Knowledge Economy*, *9*(3), 782–803. https://doi.org/10.1007/s13132-016-0375-7

Devapriya, D.P.A.L.C. and Palliyaguru, R., 2024. A maturity model for digitalisation of small and medium enterprise contractors in the Sri Lankan construction industry: A focus on client and technology dimensions. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp.39-53. DOI: https://doi.org/10.31705/WCS.2024.4. Available from: https://ciobwcs.com/papers/

A MATURITY MODEL FOR DIGITALISATION OF SMALL AND MEDIUM ENTERPRISE CONTRACTORS IN THE SRI LANKAN CONSTRUCTION INDUSTRY: A FOCUS ON CLIENT AND TECHNOLOGY DIMENSIONS

D.P.A.L.C. Devapriya[1] and R. Palliyaguru[2]

ABSTRACT

Small and Medium-Scale Enterprises (SMEs) tremendously contribute to Sri Lanka's economy, providing employment opportunities and contributing to the total Gross Domestic Product of the country. However, many SMEs underperform due to limited digital technology use. The COVID-19 pandemic accelerated digital adoption, highlighting the potential for significant competitive advantages through digital transformation. This research aimed to identify key digitalisation aspects relevant to small and medium-scale construction firms and establish a mechanism for assessing the maturity of digitalisation by proposing a digitalisation maturity model tailored to SMEs operating within the Sri Lankan construction industry. The maturity model was derived based on the findings from a comprehensive literature review and a focus group discussion that was composed of ten construction professionals. The primary dimensions of the model include Client, Technology, Operations, Organisation and Culture. However, this manuscript presents a detailed study carried out for Client and Technology dimensions only. Within these two dimensions, nine sub-dimensions and 41 digital criteria were identified, which can be employed for the assessment of digital maturity within organisations.

Keywords: *Digital Maturity Model; Digitalisation; SME Enterprise Contractors; Sri Lankan Construction Industry.*

1. INTRODUCTION

The construction industry, which is a major contributor to the economies of countries across the globe, was affected by the COVID-19 pandemic due to numerous restrictions imposed, such as social distancing, curfews and travel restrictions. leading to delays, disruptions, and uncertainty on construction projects, while forcing the industries to adopt more sophisticated technologies to tackle the reduced workforce on job sites (Adhikari &

[1]Undergraduate, Department of Quantity Surveying, University of Vocational Technology, Sri Lanka, lindyadevapriya@gmail.com

[2]Senior Lecturer, School of the Built Environment, Oxford Brookes University, United Kingdom, rpalliyaguru@brookes.ac.uk

Poudyal, 2020). In the business world, the main sufferers of the COVID-19 outbreak were Micro and Small Enterprises, especially in developing countries like Sri Lanka due to the limited use of digital technologies (Bai, et al., 2021). Hence, the disruptive nature of COVID-19 has compelled many industries to promptly transform their business processes and operational practices using digital technologies, communication platforms, and information systems (Bartik et al., 2020; Watermeyer et al., 2020). Conversely, the employees had to adapt to new technology within a short period of time to perform their work. For example, work-from-home setup, video conferencing, digital payments, new computer applications, likely software were needed to be adopted.

Digital transformation offers numerous benefits in construction sector. According to Parusheva (2019), these include enhanced productivity and efficiency, accelerated construction activities, shortened project deadlines, and improved adherence to schedules. Aghimien et al. (2018) emphasise that digital transformation also enhances quality, safety and the precision of construction documentation, alongside improved building design. Furthermore, digitalisation reduces construction costs and given that the construction industry is a major consumer of raw materials, digitalisation plays a crucial role in optimising global resource use through digital platforms for material supply and smart logistics and maintenance of construction sites (Schober et al., 2016). Additionally, construction workers spend approximately 30% of their time on core tasks, with the remaining 70% allocated to tasks such as material handling, site cleaning, and equipment retrieval. Utilising digital tools such as supply management software can significantly improve efficiency by ensuring timely material delivery, thereby reducing the need for storage and rearrangement efforts (Schober et al., 2016).

However, the ability of SME construction firms in Sri Lanka to mobilise around and sustain digital transformation is questionable. It is essential to identify the specific aspects of digitalisation available to these firms and categorise them into maturity levels to assess their digital maturity. Furthermore, understanding the current digital maturity level of an SME construction firm is crucial for guiding its development towards higher levels of digital transformation. Therefore, this research aims to fill this gap by identifying the key aspects of digitalisation in SME construction firms in Sri Lanka and establishing a mechanism to assess and understand their digital maturity through a Digital Maturity Model. This model will be focused on 2 dimensions: Client and Technology dimensions. Ultimately, this will help enhance the performance and productivity of the construction industry.

2. LITERATURE REVIEW

2.1 SMALL AND MEDIUM-SCALE ENTERPRISES (SMES)

As per the National Human Resources and Employment Policy published by the Secretariat for Senior Ministers, SMEs account for 80% of all businesses. SMEs are established in all sectors of the economy, primary, secondary, and tertiary and provide employment for persons under skilled, semi-skilled and unskilled categories. The SME sector is considered the core segment of economic development in Sri Lanka. More than 75% of the total number of enterprises falls within the SME sector, providing employment opportunities of 45% and contributing to the total Gross Domestic Product of the country by 52% (Ministry of Industry and Commerce, 2015)

The SMEs can be defined considering parameters like the number of people employed, the amount of capital invested, and the amount of annual turnover. Bolton (1971, as cited in Ranadewa, et al., 2018) also stated the parameters that can be used to define SMEs qualitatively/economically, namely, having a relatively small share of its market, being managed by its owners or part-owners in a personalised way, not being part of a larger enterprise, and being free from outside control in taking their principal decisions. In Sri Lanka, a business is considered an SME if its number of employees does not exceed 300 individuals and if its revenue does not exceed 750 million LKR (Export Development Board, 2021). According to the National Policy Framework for Small Medium Enterprise Development published by the Ministry of Industry and Commerce as indicated in Table 1, medium-scale enterprises in the manufacturing sector are made up of 51-300 employees, whereas in the service sector it is 51-200 employees. Furthermore, small scale enterprises, both in manufacturing and service sectors, are made up of 11-50 employees.

Table 1: Defining SME enterprises
(Source: National Policy Framework for Small Medium Enterprise Development by the Ministry of Industry and Commerce, 2015)

Sector	**Size**		
	Criteria	**Medium**	**Small**
Manufacturing Sector	Annual Turnover	Rs. Mn. 251 - 750	Rs. Mn. 16 - 250
	No. of Employees	51 - 300	11 - 50
Service Sector	Annual Turnover	Rs. Mn. 251 - 750	Rs. Mn. 16 - 250
	No. of Employees	51 - 200	11 - 50

According to Table 1, C2, C3 graded contractors under CIDA grading can be considered medium scale enterprise contractors while C4, C5, and C6 graded contractors can be considered small scale enterprise contractors (Ranadewa, et al., 2018).

2.1.1 Characteristics and Challenges Faced by Construction SMEs

Agwu and Emeti (2014) identified that in developed and developing countries, SMEs employ most of the workforce and are responsible for income-generating opportunities while declining poverty. With the construction industry being one of the riskiest business environments in the world, the SMEs face many difficulties and challenges. Ofori and Toor (2012) explain that the risks faced by SMEs in developing countries are the lack of job continuity due to the project-based nature of the industry, the competition generated by a large number of similar enterprises offering the same service, the expectations of stakeholders. In addition to these, Rymaszewska (2014) identifies inadequate financial resources, low levels of technology, shortage of skilled labour, the lack of entrance to international markets, and uncooperative government laws as some other problems faced by SMEs. The barriers for small enterprises in the Sri Lankan construction industry to survive in the competitive construction industry have been identified as employee turnover, application of new technology, government regulations, financing, contractor responsiveness to environmental issues, project management, and knowledge transfer. Hence, these firms need support from the government or any outsiders to upgrade existing technology, improve product quality, improve managerial skills and explore market opportunities (Ramawickrama, 2016).

2.2 DIGITALISATION

Digitalisation (digital transformation), a significant topic for companies in all industries, has become a critical element due to the development of technology. Digital transformation is the integration of digital tools to enhance processes and make them more efficient. The technologies have advanced significantly over the last few years to support digital transformation and have been designed to encounter specific construction requirements. The five key trends that reinforce digital transformation in the construction industry currently are BIM, digital documentation, mobile-first tools, process automation, and data software (McManus, 2022). Moreover, McKinsey Global Institute also identifies five trends that will shape construction and capital projects, as indicated in Figure 1, which are more similar to what McManus (2022) has identified.

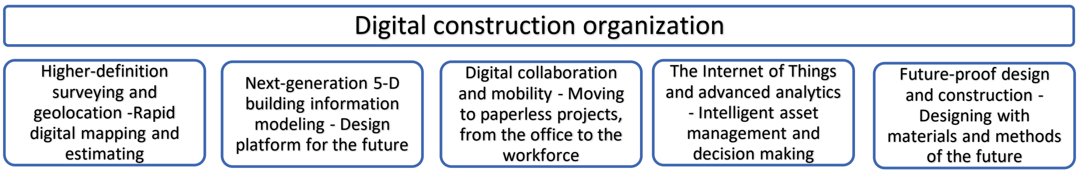


Figure 1: 5 trends that will shape construction and capital projects: McKinsey Global Institute (2016)

Relevant to the above, Walch (2020) also identifies the usage of AI-based technologies in construction work, like AI and machine learning systems to process data to make future predictions to assist in bidding on new projects. Additionally, within construction sites, autonomous drones and rovers equipped with high-quality cameras can be used to take photographs, scan the sites, and transport materials. The scanned images can then be compared with BIM models, 3D rendered drawings, project schedules, specifications, and estimates to inspect the quality of work and to assure the process adheres to the expected standard (McManus, 2022). Likewise, with advanced software, deep-learning algorithms can be used to identify and report errors in work executed, and technologies, such as Telematics, Internet of Things (IoT), Virtual Reality (VR), Augmented Reality (AR) and 3D printing can be identified as new approaches for digitalisation (Adhikari & Poudyal, 2021). Moreover, Schober et al. (2016) identified additional technological advancements in the construction sector, such as the utilisation of digital platforms for raw material procurement, the deployment of digital tools for efficient logistics, and site maintenance that facilitate just-in-time material delivery and reduce storage and rearrangement efforts. With the help of related sensors and signals within intelligently connected construction machines, the time for the coordination of equipment like hoists, cranes, vehicles can be optimised. Hence, it is crucial for construction contractors to consider digitising their organisations by developing digital road maps and also partnering with technology firms (Agarwal, et al., 2016).

2.3 DIGITAL MATURITY

Lahrmann et al. (2011) defines the term '*Maturity' as "a state of being complete, perfect or ready and is the result of progress in the development of a system*". Further, Chanias and Hess (as cited in Teichert, 2019) describes digital maturity specifically reflects the status of a company's digital transformation. Hence, this describes a company's efforts in achievement of transformation and the preparation of the system to be more competitive in further development of the digital environment. The study on digital maturity and corporate performance of companies by Eremina et al. (2019) identified factors such as technology, computers and software represent the fundamentals of the digitisation process and further digital maturing.

2.4 MATURITY MODELS (MM)

A maturity model described by Succar (as cited in Adekunle, et al, (2022) is said to be a collection of process maturity levels from the starting point of "immaturity" to highly mature. MMs are further elaborated by Adekunle, et al, (2022), "*an assessment tool to identify the effective level of a system and suggest the solutions by recognising the required capabilities to encounter the optimum effectiveness*". Moreover, Lasrado (2015) identifies five components in a maturity model as maturity levels, dimensions, sub-categories, path to maturity, and assessment questions which are usually directly linked to the sub-categories with the maturity score or level visualised usually as a graphical representation.

2.4.1 Digital Maturity Models (DMM)

DMMs aid organisations in understanding the status quo in order to achieve digital transformation in a systematic way. As Berghaus and Back (2016) describe, DMMs are composed of dimensions and criteria that describe areas of action and measures to be taken at several levels of maturity. A dimension, as described by Bruin et al. (2015) is a specific, measurable, and independent component reflecting a key aspect of digital maturity and defines an area of action. Most importantly, Teichert (2019) has identified common digital maturity areas of the existing MMs in their study as: Digital Culture, Technology, Operations & Processes, Digital Strategy, Organisation, Digital Skills, Innovation, Customer Insight & Experience, Governance, Vision, Digital Ecosystem, Leadership, Compliance & Security, Products & Services, and Business Model.

2.4.2 Requirements of SME for Digital Maturity Models

The research conducted by Schallmo et al., (2020) has identified various dimensions from the responses given by SMEs to develop a maturity model as represented in Table 2. Accordingly, the most required dimensions are processes, digital strategy, products and services, technology and customer respectively. Therefore, Technology and customer/ client dimensions will be focused in the digital maturity model due to the limited time frame for the research.

Table 2: The dimensions required in digital maturity models agreed by SMEs (Schallmo, et al., 2020)

Requirements / Dimensions	SME1	SME2	SME3	SME4	SME5
Digital strategy		**		**	**
Partner interface			*	**	**
Company's processes	**		**	**	**
Employees	*	*		*	**
Technologies used		*	*	**	**
customer interface		*	*	**	**
products and services		*	**	**	**

** Strong need for further actions (top priority),
* Need for further actions, (Blank) - No immediate need for further actions

2.4.3 Phases of Developing a Maturity Model for Digitalisation of SMEs

Bruin et al. (2005) implemented a development framework for maturity models and recognised 6 phases for the development of maturity models as:

Figure 2: Model development phases (Bruin, et al., 2005)

2.5 DEVELOPMENT PHASES OF CONCEPTUAL MODEL

2.5.1 Scope

In this phase, the outer boundaries of the digital maturity model were defined by clarifying its purpose and limitations. The audience was identified as SMEs within the Sri Lankan construction industry. Dimensions were defined as Client and Technology. Boundaries were established by excluding non-construction-related SMEs. Rather than overall business maturity, digitalisation aspects were concentrated.

2.5.2 Design

The architecture of the model is determined including the needs of the intended audience and methods for achieving these needs. The specific needs of SMEs in the Sri Lankan construction sector regarding digitalisation were identified. A series of one-dimensional linear stages (Maturity Stages) representing maturity, from basic to advanced digitalisation were developed. Layered Model was developed as indicated in Figure 3, which is composed of Domain, Domain Components (client management and technology adoption) and Sub-components (specific elements within each domain component, informed by literature and expert consensus).

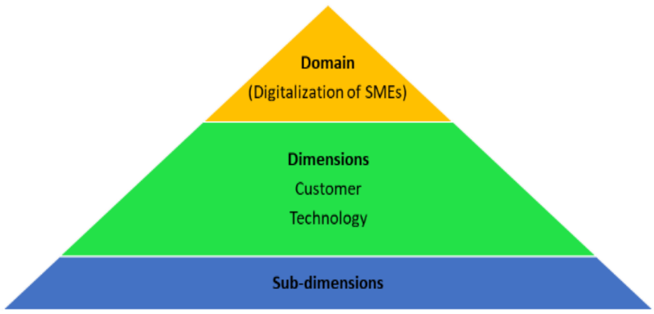


Figure 3: Architecture of the model

As illustrated in Table 3, the dimensions and sub-dimensions for the conceptual model were selected through a literature review and by referring to existing maturity models.

Table 3: Dimensions, Sub-dimensions of Conceptual Model

	Dimension	
	Customer	**Technology**
Sub-dimensions	Customer engagement	Use of modern tools/applications
	Customer experience	Advanced IT infrastructure
	Customer trust and perception	Data management
	Customer insights and behaviour	Connectivity and network
		Security
		Technology architecture
		Application for users

3. RESEARCH METHODOLOGY

Research approaches can be categorised as either qualitative or quantitative, depending on the type of data sought. Research that involves a mixture of these approaches is called the mixed-method approach. While the qualitative approach is useful in identifying new perceptions, concepts, and theories, the quantitative approach can be used to explain and describe phenomena using numerical values derived from observations (Taherdoost, 2022). In this research, to identify the dimensions, sub-dimensions, and criteria for a digitalisation model, the knowledge, ideas, agreement, and criticism of experts in the construction industry were essential. Hence, a qualitative approach was employed, involving the case study strategy and the focus group technique for data collection.

Case Study Design: The case for this study is defined as the development of a digital maturity model for SME contractors in the Sri Lankan construction industry, with a specific focus on the client and technology dimensions. This research aims to address the absence of such a model tailored to the unique needs and challenges of these firms.

Focus Group Technique:

To collect qualitative data within this case study framework, the focus group technique was employed. The focus group consisted of carefully selected participants from the case organisations. This technique involved the participation of a total of 10 participants, representing top-level and middle-level management from the 10 SME construction firms. Participants were chosen using the judgmental sampling technique to ensure they had substantial knowledge and experience with digital technologies in the construction industry. Each participant provided insights and perspectives that contributed to understanding the digitalisation maturity across the selected SME construction firms. Additionally, a comprehensive literature review was conducted to define new terms, identify methods for developing maturity models, compare existing digital maturity models, and develop a conceptual model.

The steps involved in conducting the focus group discussions were as follows:

- Prepared the focus group questions and conceptual model to be presented.
- Recruited the right participants through judgmental sampling.
- Chose a moderator (the researcher).
- Conducted the session and generated focus group transcripts from the recordings.

Detailed information about participants of the focus group is included in Table 4.

Table 4: Profile of the focus group participants

Participant Code	Designation	Experience > 5 years	CIDA grading of organisation	Size	No. of Employees	Industry focus	Years of operation > 10 years	Geographical location
P1	Civil Engineer	Yes	C2	Medium	>50	Building/Roads	Yes	Western Province
P2	Civil Engineer	Yes	C2	Medium	>50	Building	Yes	Western Province
P3	Civil Engineer	Yes	C4	Small	<50	Building	Yes	Noth Western Province
P4	QS	Yes	C5	Small	<50	Building/ Roads	Yes	Western Province
P5	Assistant QS	Yes	C6	Small	<50	Building/ Roads	Yes	Central Province
P6	Assistant QS	Yes	C4	Small	<50	Building	Yes	Western Province
P7	QS	Yes	C3	Medium	>50	Building/ Roads	Yes	Central Province
P8	QS	Yes	C6	Small	<50	Building	Yes	Noth Western Province
P9	Managing Director	Yes	C6	Small	<50	Building/ Roads	Yes	Central Province
P10	Civil Engineer	Yes	C3	Medium	>50	Building	Yes	Noth Western Province

3.1 DATA COLLECTION

The data collection process involved the following steps. The preparation step; focus group questions were prepared and provoke detailed insights were developed on digitalisation aspects. The Conceptual Model was presented to participants for feedback and validation. Participants were recruited through judgmental sampling based on their expertise and experience with digital technologies in the construction industry. The sample included top-level and middle-level management from the ten SME construction firms. The researcher facilitated the sessions to ensure structured and productive discussions. Sessions were conducted with 10 participants in a conducive environment to encourage open and honest discussions. Sessions were recorded with participants' consent to ensure accurate data capture. Detailed precise transcriptions of the discussions were created from the recordings.

3.2 DATA ANALYSIS AND DISCUSSION

The analysis of the primary data followed a systematic approach. All verbal exchanges from the focus group sessions were accurately captured in written form through transcription. The transcribed data were reviewed and initial codes were assigned to segments of the text that related to specific aspects of digitalisation. These codes were based on recurring themes and topics discussed by the participants. The initial codes were grouped into broader categories representing different dimensions and sub-dimensions of digitalisation. This step involved organising the data into meaningful clusters that aligned with the research objectives. The categories were further refined into themes that encapsulated the core aspects of digitalisation identified in the discussions. These themes were used to develop the digital maturity model. The themes and categories were reviewed and validated by comparing them with findings from the literature review. This triangulation ensured the reliability and validity of the data. Based on the manually sorted and analysed data, a digitalisation maturity model was developed.

3.2.1 Dimension – 'Client'

Given the limited literature on digital maturity models for SMEs in the construction industry, the conceptual model required validation by industry professionals and adaptation to industry-specific terminology. The dimension areas, sub-dimensions, criteria under each sub-dimension, and the method of determining maturity levels were thoroughly discussed. The dimension "Client" was defined by the focus group as the "use of digital channels to interact and communicate with the client." Initially, the conceptual model included four sub-dimensions under "Client," but it was expanded to five based on common suggestions as Client experience strategy, Client Engagement, Client Needs Assessment, Client Collaboration & Client Satisfaction.

3.2.2 Sub-Dimensions of 'Client'

Sub-dimensions suggested for the dimension 'Client' by the focus group are indicated tin Table 5.

Table 5: Sub-dimensions for dimension 'Client'

		Sub-dimensions
Group 01	P01, P02, P03	Client Communication, Client Procurement process, Client expectations, Client Engagement and Collaboration, Client Satisfaction
Group 02	P04, P05, P06	Client Engagement – Consider first engagement, Client Needs Assessment, Client Engagement and Collaboration, Client Satisfaction
Group 03	P07, P08, P09, P10	Client experience strategy, Client Engagement, Client Needs Assessment, Client Collaboration, Client Satisfaction
Proposed sub-dimensions		Client experience strategy, Client Engagement, Client Needs Assessment, Client Collaboration, Client Satisfaction

3.2.3 Dimension – 'Technology'

The dimension "Technology" was initially composed of seven sub-dimensions. Given the complexity and significance of this dimension, there was some debate among participants. While some argued for three sub-dimensions (Modern Tools, Applications, Communication) to simplify the model, others proposed a more detailed structure. Eventually, the consensus was to refine the sub-dimensions into four main areas: Modern Tools (Office & Site Operations), Modern Software Applications, Data Management, Connectivity and Network, User Applications.

3.2.4 Sub-Dimensions of 'Technology'

Sub-dimensions that are suggested for the dimension 'Technology' by the focus group are indicated in Table 6 as follows.

Table 6: Sub-dimensions for dimension 'Technology'

		Level of agreement for Sub-dimensions of "Technology"
Group 01	P01, P02, P03	Modern tools, Applications, Communication
Group 02	P04, P05, P06	Use of modern tools & applications, Advanced IT infrastructure, Data management, Connectivity and network, Security, Technology architecture, Application for users, AI tools that works with software's and general computers apps
Group 03	P07, P08, P09, P10	Modern tools in organisation (Office) & site operations & Modern software applications, Data management, Connectivity and network, Application for users
Proposed sub-dimensions by all participants		Modern tools in organisation (Office) & site operations& Modern software applications, Data management, Connectivity and network, Application for users

3.2.5 Criteria Under Sub-dimensions

The criteria or all the available tools under the sub-dimensions were identified as in Table 7. The significance of these criteria is to determine the use of each tool on a scale to find the maturity level of the organisation.

Table 7: Assessment criteria

Dimension	Sub-dimensions	Criteria
Client	Client experience strategy	Methods implemented to understand the Client and requirements.
		A clear customer experience vision has been defined by the organisation.
		Compose a strong team to increase customer experience and provide improved service.
		Use artificial intelligence (AI) for a better customer experience
		Methods implemented to measure customer experience
		Incorporate customer feedback for continuous improvement
		Provide digital customer experience
	Client Engagement	1. Client-to-Company Engagement
		2. Client-to-Content Engagement
	Client Needs Assessment	1. Prepare client priorities appraisal
		2. Clearly defined business case/Client brief of Client
		3. Develop a plan on what has to be achieved
		4. Execute according to the plan
	Client Collaboration	1. Work with cloud-based construction software
		2. Share real-time project data and insights across project team therefore always are up to date with the status of the project.
		3. Use a Single Source of Data
		4. Methods to start collaboration early
	Client Satisfaction	1. Have an effective and efficient complaints-handling process in place oriented to ensure the Project Owner Satisfaction and also to improve the quality of the construction elements being executed.
		2. Measure, evaluate and monitor the Project Owner Satisfaction on regular bases as to be possible to implement the required measures to achieve this goal in real time. (Aleixo, 2015)
Technology	1.Modern tools in organisation (Office)/ site operations/Modern software applications	1. Tools in organisation (Office) / site operations/ Modern software applications.
		Take off and estimating -Manually/Use software
		Bidding platforms - Newspaper/Web sites/e-tendering
		Accounting – Manually/Use software
		Resources planning - Use of proper plan manually/Use of software/Use of ERP system
		Marketing – Newspaper/Website/Social media/Media
		Project management -Use of proper plan manually/ Use of software
		BIM - Use of BIM
		Design & modelling - Manual drawings/ Use of 2D rendering software/ Use of 3D rendering software/ Virtual Reality
		Document management - Manually with paper work/ Cloud storage

Dimension	Sub-dimensions	Criteria
		Progress tracking – Manually/ Use of offline tools like MS office/ Use of software
		Site management – Manually/ Use of offline tools like MS office/ Use of software
		Equipment and plant management - Use of software applications
	2. Data management	Collecting data –Manually/Use of software
		Processing data – Manually/ Use of software
		Validating data – Manually/ Use of software
		Storing data - Printed papers in files / Use of cloud storage
		Access to project stakeholders - Use of apps/software to provide access to data of the project for reference of stakeholders
		Use of methods to secure data and privacy with a digital partnership.
	3. Connectivity and network	Connectivity and network -
		Presence of network of divisions, construction equipment, vehicles, devices, people, to communicate with each other via wireless or digital technology.
		Digitally transfer data and information across regional business units, remote workers, sub-contractors, suppliers and partners. (Gareeb, 2017)
	4. Application for users	Application for users
		Presence of developed application for communication, information sharing with the clients, Presence of Website, Blogs, social media

3.2.6 Determining the Levels of Digital Maturity

The focus group discussion defined each level of digital maturity as in Table 8. The scoring against the usage or not usage of tools listed under sub-dimensions will range the organisations accordingly and assign them a level in the model.

Table 8: Maturity level definitions and score range

Level	Definition	Score range
Unaware	Use manual or analog methods, no vision on digital transformation of the organisation. No understanding of the potential benefits of digital technologies	0
Initiating	Basic digital tools are used such as having a website, email communication, and basic project management tools., initiated methods in adapting to new technology, have a strategic plan for initiation, organisational vision on digital transformation is established, educate the employees on new tools.	0-29
Emerging	Companies at this stage have started adopting construction-specific software for project management, scheduling, and cost estimation.	30-59
Performing	Performing according to the steps of strategic plan for digitalisation, work towards to achieve organisational vision on digital transformation, Use of modern tools and applications, provide training and skill development of employees to perform tasks using digital tools. Advanced utilisation of	60-89

Level	Definition	Score range
	BIM for 4D scheduling, cost estimation, and facilities management. Implementation devices for remote monitoring and data collection.	
Transformed	At the highest level, the company achieves full digitisation and optimisation across its operations. This includes utilising AI. Implementation of robotics and automation for construction processes likes drones for supervision. Advanced tools are used to perform tasks under dimension areas, Cloud based operation, Continuous learning environment in the organisation.	89-100

3.3 RECOMMENDATIONS

3.3.1 Developed Maturity Model

Figure 4 below illustrates the proposed Digital Maturity Model with dimensions and levels of maturity. This model will aid to measure the level of digital maturity in an organisation.

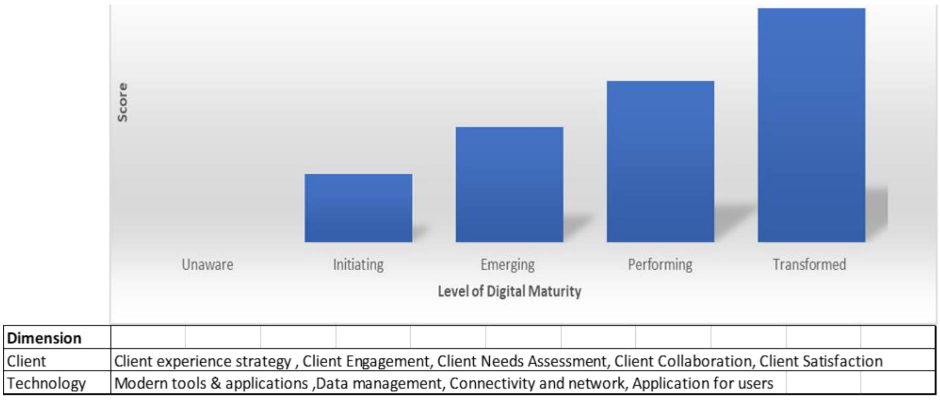


Figure 4: Maturity levels in digital maturity model

4. CONCLUSIONS

The technology is emerging day by day where most of the analogue processes become digitally transformed. Construction being one of the significant industries in Sri Lanka, it is necessary to consider embracing digital transformation in to organisations to be more efficient and productive. When compared to digital transformation in construction industry in other countries, Sri Lanka is far behind owing to several reasons. The digital maturity model developed focusing the SME enterprise contractors in Sri Lanka will enable them to determine their level of digitalisation within their organisation or status quo. Hence the model will enable the organisations to identify the digitally deficiency areas to be developed to reach next level of digital maturity. The common structure of the maturity model was composed of Domain, Dimensions, sub-dimension and maturity criteria. The digital maturity model developed for government of Sri Lanka by ICTA was examined when determining the sub-dimensions for the proposed model, since it was related to Sri Lankan context. But the terminology and definitions in this model were inappropriate for the construction industry. Yet in order to fulfil this objective the conceptual model was developed while reviewing the existing digital maturity models. The professionals from the construction industry contributed their knowledge and expertise in determining the dimensions, sub-dimensions and digital criteria to be assessed in this digital maturity model. The model composed of 2 dimensions, 9 sub-dimensions and 41 digital criteria which will measure the digital maturity of SME enterprise contractors in Sri Lanka. Further researches are encouraged on, developing this model further in other dimensions which were not considered in this research, validation of the digital maturity model in the SME enterprise contractors in Sri Lankan construction industry and develop a digitalisation road map for digital transformation of SME enterprise contractors in Sri Lankan construction industry.

5. REFERENCES

Adekunle, S. A., Aigbavboa, C., Ejohwomu, O., Ikuabe, M., & Ogunbayo, B. (2022). A critical review of maturity model development in the digitisation era. *Buildings*, *12*(6), 858. Retrieved from https://doi.org/10.3390/buildings12060858

Adhikari, K., & Poudyal, L. (2021, April 14). *Future of Construction Industry: COVID-19 and its implications on construction projects and risk management: A review*. Preprints. Retrieved March 18, 2022, from https://doi.org/10.20944/preprints202104.0383.v1

Agarwal, R., Chandrasekaran, S., & Sridhar, M. (2016). *Imagining construction's digital future*. McKinsey Productivity Sciences Center. Retrieved from https://www.mckinsey.com/~/media/mckinsey/business%20functions/operations/our%20insights/imagining%20constructions%20digital%20future/imagining-constructions-digital-future.pdf

Aghimien, D., Aigbavboa, C., & Oke, A. (2020). Critical success factors for digital partnering of construction organisations: A Delphi study. *Engineering, Construction and Architectural Management*. *27*(10), 3171-3188. Retrieved from https://doi.org/10.1108/ECAM-11-2019-0602

Agwu, M. O., & Emeti, C. I. (2014). Issues, challenges and prospects of small and medium scale enterprises (SMEs) in Port-Harcourt City, Nigeria. *European Journal of Sustainable Development, 3*(1), 101-114. Retrieved from https://doi.org/10.14207/ejsd.2014.v3n1p101

Aleixo, L. M. (2015, September 9). *Managing customer satisfaction in construction projects.* LinkedIn. Retrieved July 28, 2024, from https://www.linkedin.com/pulse/managing-customer-satisfaction-construction-projects-aleixo

Bai, C., Quayson, M., & Sarkis, J. (2021). COVID-19 pandemic digitization lessons for sustainable development of micro and small enterprises. *Sustainable Production and Consumption, 27*, 1989-2001. Retrieved from https://doi.org/10.1016/j.spc.2021.09.015

Bartik, A., Cullen, Z., Glaeser, E. L., Luca, M., & Stanton, C. (2020). *What jobs are being done at home during the Covid-19 crisis? Evidence from firm-level surveys* (NBER Working Paper No. w27422). National Bureau of Economic Research. https://doi.org/10.3386/w27422

Berghaus, S., & Back, A. (2016). Stages in digital business transformation: Results of an empirical maturity study. *Proceedings of mediterranean conference on information systems (MCIS) 2016*. Association for Information Systems. AIS Electronic Library (AISeL). Retrieved from https://aisel.aisnet.org/mcis2016/3

Blatz, F., Bulander, R., & Dietel, M. (2018). Maturity model of digitization for SMEs. In *2018 IEEE International conference on engineering, technology and innovation (ICE/ITMC),* 17-20 June 2018. (pp. 1-9). IEE. https://doi.org/10.1109/ICE.2018.8436251

Bruin, T., Rosemann, M., Freeze, R., & Kulkarni, U. (2005). Understanding the main phases of developing a maturity assessment model. In Bunker, D, Campbell, B, & Underwood, J (Eds.) *Proceedings of the 16th Australasian conference on information systems* (pp. 8-19). Australasian Association for Information Systems.

Eremina, Y., Lace, N., & Bistrova, J. (2019). Digital maturity and corporate performance: The case of the Baltic States. *Journal of Open Innovation: Technology, Market, and Complexity, 5*(3), 54. Retrieved from https://doi.org/10.3390/joitmc5030054

Export Development Board (EDB). (2021, August 13). Role of SMEs in Sri Lanka. Sri Lanka Export Development Board. Retrieved July 30, 2024 from https://www.srilankabusiness.com/blog/role-of-smes-sri-lanka.html

Gareeb, P. (2017, February 24). S*ME data network connectivity 101*. LinkedIn. Retrieved July 28, 2024, from https://www.linkedin.com/pulse/sme-data-network-connectivity-101-prashil-gareeb

Haryanti, T., Rakhmawati, N. A., & Subriadi, A. P. (2023). The extended digital maturity model. *Big Data Cognitive Computing, 7*(1), 17. Retrieved from https://doi.org/10.3390/bdcc7010017

Lahrmann, G., Marx, F., Winter, R., & Wortmann, F. (2011, February). *Business Intelligence Maturity: Development and Evaluation of a Theoretical Model*. Paper presented at the 44th Hawaii International Conference on System Sciences (HICSS). https://doi.org/10.1109/HICSS.2011.90

Lasrado, L., Vatrapu, R. K., & Andersen, K. N. (2015). Maturity models development in IS research: A literature review. In N. Iivari, K. Kuutti (Eds.). *IRIS Selected Papers of the Information Systems Research Seminar, Oulu, Finland,* August 9-12, 2015, Retrieved from https://doi.org/10.13140/RG.2.1.3046.3209

Ofori, G., & Toor, S. R. (2012). Leadership development for construction SMEs. In *Engineering Project Organisations Conference, Rheden, The Netherlands,* July 10-12, 2012 (pp. 1-14).

McManus, R. (2022, May 20). *Digital transformation in the construction industry*. FlowForma. Retrieved January 01, 2023, from https://www.flowforma.com/blog/how-to-accelerate-digital-transformation-in-the-construction-industry

Ministry of Industry and Commerce. (2015). *National Policy Framework for SME Development*. Retrieved from http://www.sed.gov.lk/sedweb/en/wp-content/uploads/2017/03/SME-fram-work_eng.pdf

Parusheva, S. (2019). Digitalization and digital transformation in construction: Benefits and challenges. *Proceedings of information and communication technologies in business and education* (pp. 126-134). University publishing house “Science and economics” University of Economics, Varna.

Ramawickrama, G. (2016). Barriers on small scale contractors to enter and survive competitive construction industry in Sri Lanka. [Master thesis, University of Moratuwa]. http://dl.lib.mrt.ac.lk/handle/123/14038

Ranadewa, T., Sandanayake, Y. G., & Siriwardena, M. (2018). *A SWOT analysis for Sri Lankan construction SMEs*. In: Sandanayake, S. Gunatilake Y.G., Waidyasekara, (eds). *Proceedings of the 7th world construction symposium, Sri Lanka.,* 29 June - 01 July 2018. (pp. 1-12).

Rymaszewska, A. D. (2014). The challenges of lean manufacturing implementation in SMEs. *Benchmarking: An International Journal, 21*(6), 987-1002. https://doi.org/10.1108/BIJ-10-2012-0065

Schallmo, D. R. A., Lang, K., Hasler, D., Ehmig-Klassen, K., & Williams, C. A. (2021). An approach for a digital maturity model for SMEs based on their requirements. In D. R. A. Schallmo & J. Tidd (Eds.), *Digitalization (Management for Professionals)*. (pp 87–101) Springer, Cham. https://doi.org/10.1007/978-3-030-69380-0_6

Schober, K.S., Hoff, P., & Sold, K. (2016). Digitization in the construction industry: Building Europe's road to "Construction 4.0". *Think Act*. Roland Berger GMBH, Civil Economics, Energy & Infrastructure Competence Centre.

Taherdoost, H. (2022). What are different research approaches? comprehensive review of qualitative, quantitative, and mixed method research, their applications, types, and limitations. *Journal of Management Science & Engineering Research, 5* (1), 55-63.

Teichert, R. (2019). Digital Transformation Maturity: A Systematic Review of Literature. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 67*, 1673-1687. doi: 10.11118/actaun201967061673

Walch, K. (2020, June 6). *AI transforming the construction industry*. Forbes. Retrieved July 28, 2024, https://www.forbes.com/sites/cognitiveworld/2020/06/06/ai-transforming-the-construction-industry/

Watermeyer, R., Crick, T., Knight, C., & Goodall, J. (2021). COVID-19 and digital disruption in UK universities: Afflictions and affordances of emergency online migration. *Higher Education, 81*(4), 1-19. Retrieved from https://doi.org/10.1007/s10734-020-00561-y

Sachchithananthan, M., Ramachandra, T. and Geekiyanage, D., 2024. A simplified guide towards incentivising embodied carbon assessment: A case of high-rise residential building. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 54-65. DOI: https://doi.org/10.31705/WCS.2024.5. Available from: https://ciobwcs.com/papers/

A SIMPLIFIED GUIDE TOWARDS INCENTIVISING EMBODIED CARBON ASSESSMENT: A CASE OF HIGH-RISE RESIDENTIAL BUILDING

M. Sachchithananthan[1], T. Ramachandra[2] and D. Geekiyanage[3]

ABSTRACT

In recent decades, the increasing threat of global warming has emphasised the importance of reducing carbon emissions within construction sector due to its significant impact. Despite efforts to mitigate climate change, the construction industry faces a critical gap in effectively evaluating the carbon emissions and costing it. The major reasons could be attributed to lack of awareness of carbon performance and commitment, lack of data availability and inconsistent methodologies. Hence, this study aims to develop a simplified guide, as an extension to the typical cost estimation practice towards addressing the above concerns with respect to embodied carbon (EC). This study primarily involved a quantitative assessment of EC emission of a typical high-rise residential building in Sri Lanka. Therefore, BOQ of the selected building and additional information such as material and machinery requirements, EC co-efficient, fuel consumption and transportation distance were obtained from technical specifications, industry practiced norms and databases. Accordingly, the EC emission of the selected building was derived as 873KgCO$_2$/m^2 of GFA. Of this, 94% is due to material production stage, while remaining 6% is in transportation and construction stages. Key materials contributed include: paint, cement and reinforcement. The steps followed in deriving the above estimation is presented as a simplified guide that would promote and account the construction clients for the EC emission of their proposed building constructions. By integrating EC assessment (ECA) into the construction cost estimation process, this guide seeks to empower decision-makers to choose among carbon alternatives and aid in carbon taxation in the Sri Lankan context.

Keywords: *Carbon Taxation; Embodied Carbon Assessment; Residential Buildings.*

1. INTRODUCTION

In recent decades, global warming has emerged as a significant challenge, predominantly driven by greenhouse gases (GHGs), with carbon dioxide (CO_2). According to the United Nations Environment Programme (UNEP, 2021), energy consumption in buildings remained constant and increased embodied carbon (EC) emission to 9.95 giga-tons

[1] Temporary Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, smathanky@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thanujar@uom.lk
[3] Lecturer, School of Science, Engineering and Environment, University of Salford, UK, D.geekiyanage@salford.ac.uk

globally. However, according to UNEP (2022), building energy demand has experienced a notable rise of approximately 4% since 2020, reaching 135 exajoules (EJ), marking the most substantial increase observed in the past decade. Significantly, in 2021, the building sector has shown a 5% surge in operational CO_2 emissions compared to 2020, surpassing the previous peak in 2019 by 2%. Further, buildings utilise a variety of materials that consume energy and emit CO_2 throughout their life cycle, collectively known as embodied energy and EC (Ahmed Ali et al., 2020). The latest study reveals that the built environment stands out as a major contributor, accounting for over 37% of CO_2 emissions linked to global energy consumption (Arenas & Shafique, 2024). Authors further stated that the utilisation of construction materials, already responsible for 9% of total energy-related CO_2 emissions, is projected to double by 2060.

As part of mitigation strategies, evaluating the EC of buildings stands out as a fundamental approach with the potential to significantly reduce carbon footprint. Assessing the carbon emissions associated with the material production, transportation, and construction would enable informed decisions to prioritise low-carbon alternatives (Myint & Shafique, 2024). In addition, a sound environmental tax system would require carbon emission reduction to gain long-term cost benefits in the building sector (Bai et al., 2024). Although the tax is charged from end-users of buildings, it will be distributed among manufacturers and contractors to reverse the cost flow (Bertoldi et al., 2010). Therefore, identification of potential risks in terms of EC emission and its cost is vital throughout the building's lifetime (Pomponi & Moncaster, 2016).

To date, number of studies have aimed to assess the carbon emission in various contexts and concluded, differently. For instance, EC emission assessments conducted for office buildings in UK, Korea, China and Greece reported 595 $kgCO_2eq/m^2$, 674 $kgCO_2eq/m^2$, 715 $kgCO_2eq/m^2$ and 200 $kgCO_2eq/m^2$ of emissions, respectively (Chau et al., 2015; Kumanayake & Luo, 2018b; Victoria et al., 2015). However, it is important to note that while these studies focus on a specific type of building, the emission levels can vary due to differences in location and construction methodology. Additionally, although these studies provide detailed analysis of emission, which lack its reference to derive the carbon emissions of other buildings in future. On a similar note, Kumanayake et al. (2018) concluded that in the Sri Lankan context, the life cycle energy and carbon emission of residential buildings varies depending on the material and utilised construction techniques. Based on the study, authors developed carbon emission estimator tool towards increasing the awareness of low-carbon building construction for a sustainable future (Kumanayake & Luo, 2018a) using MySQL database management software. However, this may pose challenges for users with limited computer literacy. Further, the database comprised of materials contributing to over 85% of the total CO_2 emissions of typical Sri Lankan buildings. Since this is the first attempt to develop a life cycle CO_2 emission estimator tool for Sri Lanka, it lacks flexibility in the assessment of EC. Similarly, Nawarathna et al. (2019) proposed a conceptual methodology to assess EC in Sri Lankan building construction complying with life cycle assessment (LCA) and EC estimation process. While this methodology provides a conceptual framework, its actual adoption and feasibility for carbon assessment may be questionable.

Despite the foregoing study findings, industry practitioners remain hesitant to assess the carbon emissions of buildings (Jackson & Kaesehage, 2020). This reluctance is largely attributed to lack of awareness on the impact of carbon emissions (Abeydeera et al., 2019), commitment to mitigation and absence of comprehensive guidance regarding carbon assessment in construction sector (Jayathilaka et al., 2023). Further, review of 33 construction LCA software found that most ECA tools adopt a process-based LCA (PLCA) method, following ISO 14040/14044 and PAS 2050 standards (Ariyaratne & Moncaster, 2014). While LCA tools vary from Cradle-to-gate to Cradle-to-grave, those focusing on embodied carbon Cradle-to-end of construction can be complex and time-consuming, requiring detailed data and expertise, thus limiting their applicability for quick decision-making in industry settings (Kumanayake et al., 2018; Nawarathna et al., 2019; Victoria et al., 2015). Although some of these tools offer convenience and automation, they may lack transparency regarding underlying assumptions and data sources, leading to uncertainty of results. Hence, industry practitioners perceive such assessment as time-consuming due to the absence of consistent methods and benchmarks (De Wolf et al., 2017).

As one of the party countries in the Paris Agreement, Sri Lanka has signed to combat climatic changes where achieving low-carbon economy is one of the main objectives (De Silva, 2017). Therefore, the Ministry of Environment (2021) set targets introducing national policies to reduce carbon emission, approximately 15% by 2030 targeting the main six sectors namely, power, transport, waste, industry, agriculture, and forestry. To that end, construction practices disregarding carbon emission would impinge the achievement of the set goal. Given that, it is vital to account the potential carbon emission of proposed construction projects and thereby seek low-carbon alternatives towards mitigating carbon emission. In that context, this paper aims to propose a simplified guide that enables assessing the embodied carbon emission from cradle to construction stage, where significant amount of embodied carbon is emitted.

2. RESEARCH METHODOLOGY

This research aims to develop a guide for carbon estimation by analysing EC emission of a typical high-rise residential building to facilitate the carbon costing in future construction. Accordingly, this research employed a quantitative approach to collect required data for the assessment of EC emission and developing the said simplified guide. A high-rise residential apartment with the gross internal floor area (GIFA) of 5,500m^2, located in Colombo was selected as case example. Furthermore, a review was conducted into BOQ, technical specifications, manufacturers' catalogues, and details on construction and industry norms such as NRM1, NRM2, SLS 573 and Building Schedules of Rates (BSR). The emission coefficients were extracted from the Inventory of Carbon and Energy (ICE) database and the Hutchins UK Building Blackbook. In accordance with previous studies, in the absence of specific EC coefficient data for Sri Lanka, a mean location factor of 0.76 extracted from the above sources was employed in this study (Kumanayake et al., 2018; Nawarathna et al., 2019). Using the data collected, EC emissions related to material production & transport, and construction were calculated as per the following steps. According to RICS (2017), EC is emitted in different stages of a construction project; Cradle-to-gate, Cradle-to-site, Cradle-to-end of construction, Cradle-to-grave, and Cradle-to-cradle. When it comes to EC emission, Cradle-to-end of construction is vital, early stages where most of the design and construction decisions are finalised.

Step I: Extract the typical construction activities and respective quantities by referring to selected BOQ

Step II: Derive the appropriate norms for construction activities by referring to norms used by the leading construction companies

Step III: Calculate the quantity of each material used each construction activity and derive the aggregate quantity for each material

Step IV: Derive the total EC emission in material production stage by applying EC coefficient factors on aggregate quantity of each material

Step V: Identify the required vehicle for each material transportation and the average distance of transportation, and EC coefficient of each vehicle. Derive the total EC emission in material transportation stage

Step VI: Derive the EC coefficient factors for each material and calculate the EC emission in construction stage

Step VII: Assess the total carbon emission of the project from cradle to construction stage by aggregating outcomes of steps IV, V and VI.

The above steps have been integrated into an Excel spreadsheet for convenient navigation through the proposed ECA process, as depicted in Figure 1.

A SIMPLIFIED GUIDE FOR EMBODIED CARBON COST ESTIMATION		
STEP 1	Extract typical construction activities and quantities from the chosen BOQ	BOQ
STEP 2	Determine industry norms for each activity from leading construction companies.	Construction Activities
STEP 3	Calculate material quantities for each construction activity based on the BOQ.	Building Norms
STEP 4	Establish EC coefficient factors for materials and calculate EC emissions during production.	EC - Materials Production
STEP 5	Identify required vehicles for material transportation, determine average distances, establish EC coefficients for each vehicle, and calculate EC emissions during transportation.	EC - Materials Transport
STEP 6	Establish EC coefficient factors for materials and calculate EC emissions during construction.	EC - Construction
STEP 7	Assess total carbon emissions of the project from cradle-to-construction stage.	EC - Total

Project Name:	Nine storey residential building for Mr.XYZ
Location:	Colombo - 03
GIFA (Sq.m):	5500

Figure 1: Menu sheet of the proposed simplified ECA guide

Following the steps described, the ECA of the proposed high-rise building was assessed and presented in the subsequent sub-sections.

3. RESULTS

Initially, BOQ of the selected building was referred and the activities involved along with their respective quantities were extracted. Then, appropriate building norms derived by considering norms used by the leading contractors in Sri Lanka were applied to quantities extracted. This process resulted in quantities of each material consumed in the selected activity of the selected building. Based on the materials consumed, the EC in material production, transportation and construction stages was assessed and presented in following sub-sections.

3.1 EC EMISSION DURING THE MATERIAL PRODUCTION PHASE

The material production phase mainly focused on the calculation of material production related EC emission as the EC coefficients cover the scope of cradle to gate. According to the ICE database, the EC coefficient is given for the unit of $kgCO_2e/kg$. Therefore, the average quantity of materials was converted into its volume (m^3) and multiplied by its density to obtain mass (kg) as shown in Equation 1.

$$Mass\ of\ material\ (kg) = Average\ volume\ (m3) \times Density\ (kg/m3) \qquad (Eq.\ 1)$$

After determining the average mass of each material, EC emission was calculated by multiplying the mass by 0.76 to convert the coefficient into the Sri Lankan context. This method was followed to calculate EC emission for each activity. Accordingly, the EC emission in material production related to concrete work was calculated as illustrated in Table 1. Similarly, EC emissions in all activities involved in the construction of selected residential building were calculated and added to Table 1.

Table 1: Activity-based EC emission during the material production phase

Material	Unit	Qty per GIFA	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EC Coefficient ($kgCO_2/kg$)	EC Emission ($kgCO_2/m^2$)
Cement	Bag	7.15			357.55	0.9100	247.28
Sand	Cube	0.10	0.00	1,400.00	4.07	0.0075	0.02
Aggregate	Cube	0.22	0.01	1,600.00	10.09	0.0049	0.04
Water	Gal	71.79	0.29	1,000.00	287.15	0.0003	0.08
Total emission in concrete work							**247.42**

Emission in all construction activities				
Activities	**Unit**	**Quantity**	**Emission ($KgCO_2/m^2$)**	**%**
Painting	sqr	3,961	280.39	34%
Concrete	cube	1282	247.42	30%
Reinforcement	cwt	8,914	213.90	26%
Finishes	sqr	3,775	36.15	4%
Masonry	sqr	906	30.54	4%
Formwork	sqr	3,083	6.63	1%
Waterproofing	sqr	623.90	3.23	0%
Excavation	cube	64	0.00	0%
Total emission in material production (per GIFA)				**820.24**
GIFA (m^2)				**5,500**
Total emission in material production				**4,511,327**

Emission in major construction materials		
Material	**Emission ($KgCO_2/m^2$)**	**%**
Paint	1121.56	68%
Cement	291.12	18%
Reinforcement	213.89	13%
Blocks	27.27	2%
Round Timber 3" dia. (10'-0")	3.96	0.2%
Timber Planks 1" Class 111	1.41	0.1%
Timber 2"x 2" Cl.111	0.80	0.1%
Sand	0.37	0.0%

As shown in the table, the top emitting activity is painting, which is 34% of the total emission of material production. Secondly, concrete and reinforcement activities contributed 30% and 26% of the total material production emission, respectively. In the context of construction materials, paint emerges as a substantial contributor, constituting

68% of total emissions from material production. Cement and reinforcement followed, contributing 18% and 13% respectively to these emissions. Although concrete production is a major contributor to material production emissions, cement is the predominant factor, accounting for 38% of the total emissions, overshadowing the relatively negligible contributions of sand and aggregate.

3.2 EC EMISSION DURING MATERIAL TRANSPORTATION

Materials produced so as explained above, to be used in proposed building, were transported to proposed building site using appropriate vehicles. The vehicles used and their capacities were obtained from the records maintained by the site store. However, due to unavailability of exact details regarding certain material suppliers and factories, the research opted to consider the vehicles used as per the general industry practice and the suppliers who based in close proximity to the selected project site. For each material, the average distance to the site from the suppliers around were calculated, and used to estimate the EC emissions during material transportation. Table 2 presents the calculation of EC emission at the material transportation stage in concrete work. Similarly, EC emissions in all materials transportation were calculated and added to Table 2.

Table 2: Calculation of EC emission from material transportation stage

Material	Vehicle Type	Capacity	Mass per GIFA (kg)	Average Distance (km)	EC Coefficient ($kgCO^2/kg$)	EC Emission ($kgCO^2/m^2$)
Concrete mixing						
Cement	Truck	8 ton	358	0.6	0.241	0.11
Sand	Truck	8 ton	4	13.4	0.241	2.45
Aggregate	Truck	8 ton	10	9.0	0.241	1.65
Concrete placing						
Concrete	Mixture truck	$4m^3$		8.8	1.099	7.35
Total emission in concrete work						**11.56**

Emission in all construction activities		
Activities	**EC Emission ($kgCO_2/m^2$)**	**%**
Concrete	11.56	23%
Masonry	8.17	16%
Earthwork	6.66	13%
Finishes	6.51	13%
Reinforcement	5.26	10%
Waterproofing	5.15	10%
Formwork	3.86	8%
Roof work	3.72	7%
Painting	0.07	0%
Total emission in material transportation (per GIFA)		**50.96**
GIFA (m^2)		**5500**
Total emission in material transportation		**280,301**

As per the table, the concrete work is responsible for 23% of the total emission. Further, masonry, earthwork and finishes contributed significantly, collectively for over 40% of total emission.

3.3 EC EMISSION DURING CONSTRUCTION PHASE

The EC emission in construction phase is limited to activities where heavy machinery involved. Accordingly, amongst the typical construction activities of the proposed high-rise building, concrete, excavation and reinforcing activities were considered as responsible for emission in this stage. Depending on the type of machinery used, fuel-based/electricity-based EC emissions was to be calculated. Therefore, the energy usage rates of each machinery need to be identified along with material quantities to determine the fuel usage in each construction activity. Energy usage factors were extracted from the literature and technical specifications for building construction. Accordingly, 2.68 $kgCO_2/l$ and 0.5845 $kgCO_2/kWh$ were considered as EC coefficients for fuel and electricity, respectively (Kumanayake et al., 2018; Nawarathna et al., 2019; Victoria et al., 2015). Using the above information, EC emissions for the above said activities are calculated and presented in Table 3.

Table 3: EC emission at the construction stage

Machinery	Unit	Quantity per GIFA	Energy Use Rate	EC coefficient	EC emission ($kgCO_2/m^2$)
			Concrete		
Pump Car	m^3	0.66	0.770 l/m^3	2.680 $kgCO_2/l$	1.20
Vibrator	m^3	0.66	0.210 l/m^3	2.680 $kgCO_2/l$	0.34
Material hoisting	kg	0.12	0.003 kwh/kg	0.5845 $kgCO_2/kwh$	0.00
Total EC emission of concrete work					**1.55**
			Excavation		
Pump Car	m^3	0.03	0.770 l/m^3	2.680 $kgCO_2/l$	0.06
Vibrator	m^3	0.03	0.210 l/m^3	2.680 $kgCO_2/l$	0.02
Material hoisting	kg	0.00	0.003 kwh/kg	0.5845 $kgCO_2/kwh$	0.00
Total EC emission of excavation					**0.08**
			Reinforcement		
Rebar processing machine	kg	81.04	0.002 kWh/kg	0.5845 $kgCO_2/kWh$	0.09
Material hoist	kg	81.04	0.003 kWh/kg	0.5845 $kgCO_2/kWh$	0.14
Total EC emission of reinforcement					**0.24**
Total emission in physical construction					**1.86**
GIFA (m^2)					**5,500**
Total emission in physical construction					**10,244**

The highest EC emission was resulted in concrete work due to its higher mass and higher energy capacity of pump cars and other types of machinery like mechanical vibrators. Even though reinforcement has a comparatively higher mass, the lesser energy usage rate of rebar processing machine and material hoisting resulted in the least EC emission in the construction phase. Therefore, above results highlights that the mass and energy usage rate of machinery directly influence the amount of EC emission.

3.4 TOTAL EC EMISSION

The total EC emissions of activities from the cradle to construction include cumulative emission of material production, transportation, and construction stages. Total EC emission from cradle to construction stage of the selected high-rise building is tabulated in Table 4.

Table 4: Total EC emission

Activities	EC Emission ($kgCO_2/m^2$)			Total	Share of total EC Emission
	Production	Transportation	Construction		
Painting work	280.39	0.07	0.00	280.46	32%
Concrete	247.42	11.56	1.55	260.53	30%
Reinforcement	213.90	5.26	0.24	219.39	25%
Finishes	38.14	6.51	0.00	44.64	5%
Masonry	30.54	8.17	0.00	38.71	4%
Formwork	6.63	3.86	0.00	10.50	1%
Waterproofing	3.23	5.15	0.00	8.37	1%
Earthwork	0.00	6.66	0.08	6.74	1%
Roof work	0.00	3.72	0.00	3.72	0%
Total EC per GIFA	**820.24**	**50.96**	**1.86**	**873.07**	**100%**
Total EC	**4,511,327**	**280,301**	**10,244**	**4,801,872**	

As seen from Table 4, of the total EC emission from cradle to construction site, material production stage is responsible for 94% (820 out of 873 $kgCO_2/m^2$) while remaining 6% is attributed to transportation and construction stages. This shows that material production plays a pivotal role in mitigating embodied carbon emission effects.

The above analysis further shows that over 80% of emissions are due to painting, reinforcement and masonry works. Notably, painting work has the highest EC emission of 32% (280.46 out of 873.07) of the total EC emission. The concrete and reinforcement are the next highest contributors with 30% and 25% contributions, respectively. Hence, these activities are recognised as carbon hotspots. Other activities namely, finishes, masonry, formwork, waterproofing, earthwork and roof work have a marginal contribution of less than 5% each to the total EC emission at the material production phase.

3.5 A SIMPLIFIED GUIDE FOR THE ASSESSMENT OF CARBON EMISSION

A simplified guide to assist the EC emission is developed based on the outcome derived from the steps described in section 2 and sections 3.1 to 3.4 and depicted in Figure 2, together with a QR code to access the developed simplified tool for ECA. As seen, the guide requires to pass through 7 simple self-directed steps to derive the total emission in any proposed building construction.

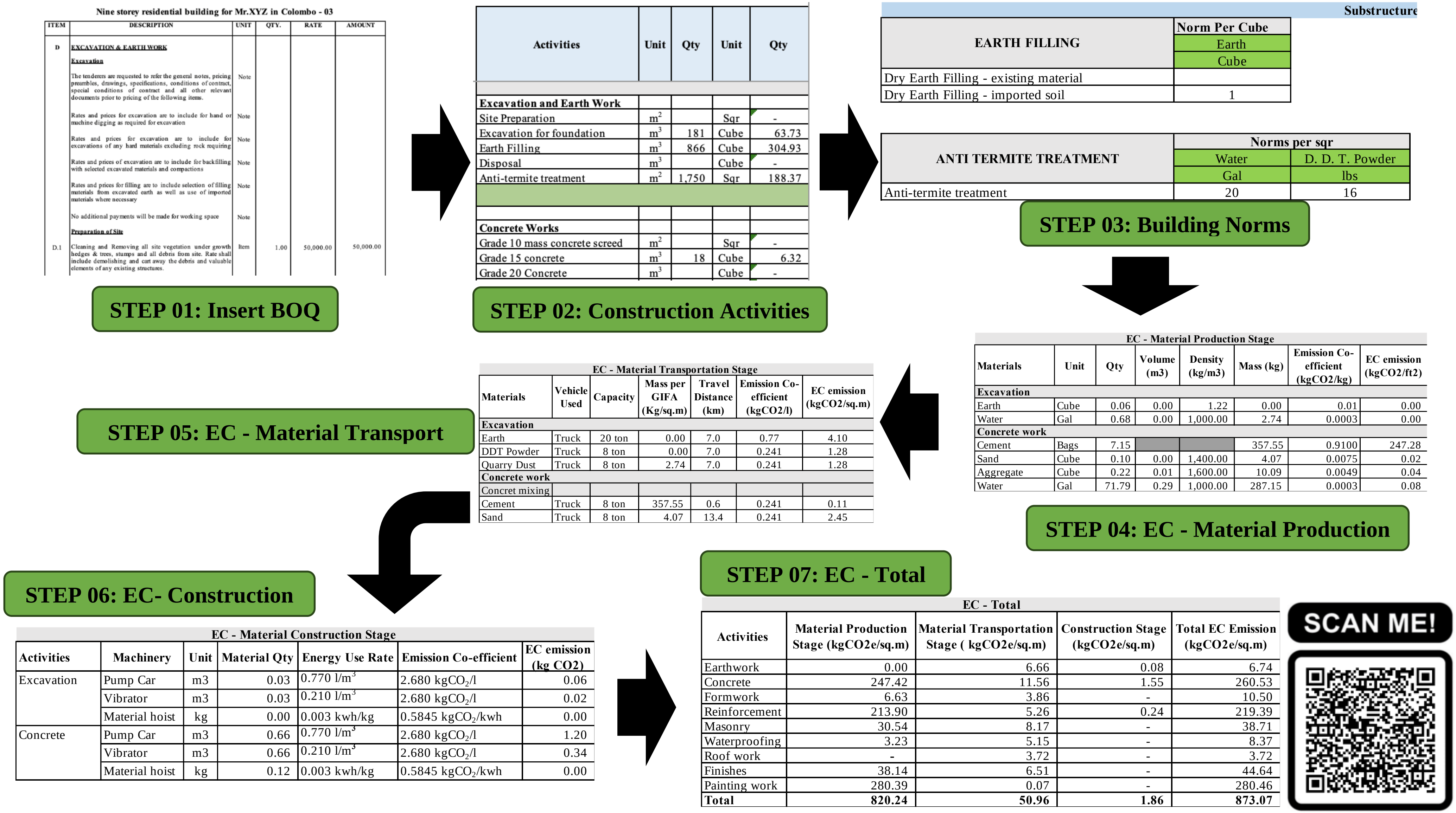


Figure 2: An illustration of the proposed simplified guide for ECA (Scan the QR code to access the digital tool)

4. DISCUSSION AND CONCLUSIONS

The study has assessed the EC emission of a typical high-rise building by a taking a case of a nine-storey residential building. The evaluation concludes that on average, construction of a nine-storey residential building in Sri Lanka results in total EC emission of 873 $kgCO_2$ per m^2 (81.14 $kgCO_2/ft^2$) during cradle to construction stage activities. A similar study was conducted in China for residential building where the EC was 388 $kgCO_2e/ft^2$ (Li et al., 2013). Another study by Kumanayake et al. (2018) identified that the EC of four-storey office building was responsible for 630 $kgCO_2/m^2$ of emission. These significant differences in carbon emissions could be attributed to several factors such as type of construction, materials & machinery used, emission coefficients, methodology used, etc. Accordingly, the current study contributes to knowledge base that the emission varies across geographical contexts and it warrants an assessment specific to a given location. To this end, the study provides a self-directed simplified guide that enables assessment of EC to any kind proposed building in the local as well as global context. Further, the study provides a detailed assessment at each stage of the process. This would enable construction clients and professionals to consider alternatives where possible to mitigate EC emission.

In terms of findings, the current study concludes that the material production stage is significant, responsible for 94% of total EC emission. The activities, such as painting, concrete and reinforcement were responsible for 87% of materials production emission. Materials such as paint, cement and reinforcement are responsible for 99% of the total emission from material production stage. Therefore, material selection should be done with due consideration to their emission subject to cost implications and other factors deciding the feasibility of the materials.

However, these findings are subject to limitations in terms of co-efficient factors, travel distance, machinery used etc. Thus, the developed simplified guide would enable to derive the EC emission of proposed project using the appropriate and available information of a given project in future.

This research has contributed to the field by developing a simplified EC assessment guide designed for Sri Lankan building construction. Although this study focused on Sri Lankan construction industry, the guide can serve as a valuable reference for other countries aiming to assess the EC emission of building construction. By incorporating their own coefficient factors and local materials and vehicles, similar assessments can be conducted globally.

5. REFERENCES

Abeydeera, L. H. U. W., Mesthrige, J. W., & Samarasinghalage, T. I. (2019). Perception of embodied carbon mitigation strategies: The case of Sri Lankan construction industry. *Sustainability*, *11*(11), 3030. https://doi.org/10.3390/SU11113030

Ahmed Ali, K., Ahmad, M. I., & Yusup, Y. (2020). Issues, impacts, and mitigations of carbon dioxide emissions in the building sector. *Sustainability*, *12*(18), 7427. https://doi.org/10.3390/su12187427

Arenas, N. F., & Shafique, M. (2024). Reducing embodied carbon emissions of buildings – a key consideration to meet the net zero target. *Sustainable Futures*, *7*, 100166. https://doi.org/10.1016/j.sftr.2024.100166

Ariyaratne, C. I., & Moncaster, A. M. (2014). Stand-alone calculation tools are not the answer to embodied carbon assessment. *Energy Procedia*, *62*, 150–159. https://doi.org/10.1016/J.EGYPRO.2014.12.376

Bai, X., Zhong, J., & Huang, D. (2024). Economic instruments for natural resource efficiency: The role of carbon taxation and fiscal policy. *Resources Policy*, *89*, 104614. https://doi.org/10.1016/j.resourpol.2023.104614

Bertoldi, P., Rezessy, S., Lees, E., Baudry, P., Jeandel, A., Labanca, N., Bertoldi, P., Rezessy, S., Lees, E., Baudry, P., Jeandel, A., & Labanca, N. (2010). Energy supplier obligations and white certificate schemes: Comparative analysis of experiences in the European Union. *Energy Policy*, *38*(3), 1455–1469. https://EconPapers.repec.org/RePEc:eee:enepol:v:38:y:2010:i:3:p:1455-1469

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy*, *143*(1), 395–413. https://doi.org/10.1016/J.APENERGY.2015.01.023

De Silva, A. (2017). *The Paris agreement on climate change and Sri Lanka*. Colombo: Lakshman Kadirgamar Institute of International Relations and Strategic Studies.

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

Jackson, D. J., & Kaesehage, K. (2020). Addressing the challenges of integrating carbon calculation tools in the construction industry. *Business Strategy and the Environment*, *29*(8), 2973–2983. https://doi.org/10.1002/BSE.2551

Jayathilaka, G., Thurairajah, N., & Rathnasinghe, A. (2023). Digital data management practices for effective embodied carbon estimation: A systematic evaluation of barriers for adoption in the building sector. *Sustainability*, *16*(1), 236. https://doi.org/10.3390/SU16010236

Kumanayake, R., & Luo, H. (2018a). A tool for assessing life cycle CO_2 emissions of buildings in Sri Lanka. *Building and Environment*, *128*, 272–286. https://doi.org/10.1016/J.BUILDENV.2017.11.042

Kumanayake, R., Luo, H., & Paulusz, N. (2018). Assessment of material related embodied carbon of an office building in Sri Lanka. *Energy and Buildings*, *166*, 250–257. https://doi.org/10.1016/J.ENBUILD.2018.01.065

Kumanayake, R. P., & Luo, H. (2018b). Cradle-to-gate life cycle assessment of energy and carbon of a residential building in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, *46*(3), 355–367. https://doi.org/10.4038/JNSFSR.V46I3.8487

Li, D. Z., Chen, H. X., Hui, E. C. M., Zhang, J. B., & Li, Q. M. (2013). A methodology for estimating the life-cycle carbon efficiency of a residential building. *Building and Environment*, *59*, 448–455. https://doi.org/10.1016/J.BUILDENV.2012.09.012

Ministry of Environment. (2021). Sri Lanka updated nationally determined contributions. In *Ministry of Environment Sri Lanka*.

Myint, N. N., & Shafique, M. (2024). Embodied carbon emissions of buildings: Taking a step towards net zero buildings. *Case Studies in Construction Materials*, *20*, e03024. https://doi.org/10.1016/J.CSCM.2024.E03024

Nawarathna, A., Alwan, Z., Gledson, B., & Fernando, N. (2019). A conceptual methodology for estimating embodied carbon emissions of buildings in Sri Lanka. *Sustainability in Energy and Buildings*, *163*, 83–95. https://doi.org/10.1007/978-981-32-9868-2_8

Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management*, *181*, 687–700. https://doi.org/10.1016/J.JENVMAN.2016.08.036

RICS. (2017). Methodology to calculate embodied carbon of materials. 1st edition. RICS Surveyor Court. UK

UNEP. (2021). *Annual Report 2021*. UN Environment Programme. https://www.unep.org/resources/annual-report-2021

UNEP. (2022). *Global status report for buildings and construction*. https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

Victoria, M. F., Perera, S., Zhou, L., & Davies, A. (2015). Estimating embodied carbon: A dual currency approach. *Sustainable Buildings and Structures - Proceedings of the 1st International Conference on Sustainable Buildings and Structures, ICSBS 2015*, 223–230. https://doi.org/10.1201/B19239-38

Jayoda, T.S.H., Natasha, K.A.D.M. and Rathnayake, U., 2024. Adaptation of green building concept to existing government office buildings in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 66-78. DOI: https://doi.org/10.31705/WCS.2024.6. Available from: https://ciobwcs.com/papers/

ADAPTATION OF GREEN BUILDING CONCEPT TO EXISTING GOVERNMENT OFFICE BUILDINGS IN SRI LANKA

T.H.S. Jayoda[1], K.A.D.M. Natasha[2], and U. Rathnayake[3]

ABSTRACT

At present, the cost spent on constructing, operating, maintaining, and even demolishing buildings has reached an all-time high. When considering a building in operation, 40% to 50% of its costs are the result of energy usage within. Moreover, inefficiently and conventionally constructed buildings contribute to resource wastage in numerous ways, impacting both the environment and society adversely. The Green Building (GB) concept, which is a sustainable development initiative can be considered as a solution as it helps minimise environmental impact and effectively employs resources throughout a building's lifecycle. It guarantees numerous benefits socially, economically, and environmentally. In Sri Lanka many buildings that operate in the private sector have taken the initiative in implementing the GB concept, however, buildings operating in the government or public sector are lagging. This delay can be attributed to several factors, including insufficient funding, limited awareness, and reliance on outdated technology. Through a comprehensive literature review and empirical data from expert interviews and case studies, this research identifies key challenges hindering GB adoption in government sector office buildings in Sri Lanka. Recommendations emphasise the development of a robust framework tailored to government buildings, focusing on regulatory enhancements, stakeholder engagement, and capacity-building initiatives. Such strategies aim to overcome barriers and enhance adoption, fostering sustainability and resilience within the public sector.

Keywords: *Green Building; Office Building; Public Sector; Sustainability; Sustainable Development.*

1. INTRODUCTION

Buildings occupied by humans will interact with the surrounding environment by affecting stormwater runoff, energy, water consumption, transportation patterns, and indoor air quality (Adetokunbo & Emeka, 2015). Accumulated or uncontrolled actions by humans may result in unfavourable impacts and many other complications to the natural balance of the ecosystem and may result in unfavourable phenomena such as environmental pollution, global warming, destruction of ecosystems, etc. As a result, governments introduce sustainable development policies and practices to avoid such

[1] Facility Executive, Facilities Management Integrated, Sri Lanka, shtjayoda98@gmail.com
[2] Temporary Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, miyukin@uom.lk
[3] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, uthpalar@uom.lk

impact. GB concept is one such sustainable development initiative that focuses on environmental responsibility and resource efficiency by focusing on energy and water usage, resource utilisation, indoor environmental quality, and many more facets of a building.

However, it is a known fact that Sri Lankan government-owned buildings are comparatively reluctant to adopt the green building concept especially due to their cost investment, corruption involved, lack of maintenance, lack of policy and protocols, etc. Consequently, these buildings often fall short of meeting modern environmental standards and fail to leverage the long-term benefits associated with sustainable practices. This reluctance underscores the urgent need for targeted interventions and policy reforms to overcome these barriers and foster a more sustainable built environment across government office buildings in Sri Lanka. Furthermore, it was observed that there is a shortage of research and study concerning the government sector's involvement in advocating for the concept of green building. Therefore, this study aims to uncover obstacles and difficulties hindering the implementation of GB concepts in Sri Lanka's government office buildings, thus adding valuable insights to existing research.

2. LITERATURE REVIEW

2.1 INTRODUCTION

In many countries, buildings account for 70% of total power usage, highlighting the importance of energy efficiency in the built environment (U.S. Department of Energy, 2008). Research has shown that green buildings can significantly impact employee performance, increase productivity, decrease lifetime costs, and improve staff well-being (Nalewaik & Venters, 2009). Despite extensive research on the financial advantages of GB technologies, there is limited understanding of the other factors that influence their adoption (Darko et al., 2017; Miller et al., 2008). This issue is even more pronounced in government sector office buildings in Sri Lanka.

2.2 ECONOMIC, ENVIRONMENTAL, AND SOCIAL BENEFITS

Numerous studies have demonstrated a link between enhanced worker productivity and green office design elements (Vivian et al., 2003). GB practices can lead to significant cost savings through reduced energy consumption and operational efficiencies (Gan et al., 2020). Further, improved indoor environmental quality in green buildings can enhance employee productivity and well-being, contributing to higher job satisfaction and reduced absenteeism (Elnaklah et al., 2020).

2.3 BARRIERS TO GREEN BUILDING ADOPTION

The higher upfront costs of green buildings present a serious challenge (Geelani et al., 2012). The lengthy pay-back time is another barrier to sustainable building (Millicent et al., 2015). Additionally, there is a widespread misconception that GBs are expensive and challenging for middle and lower-class individuals to access (Azizi et al., 2015). A lack of knowledge and resistance to change are also significant barriers to GB projects (Djokoto et al., 2014; CEC, 2008). The shortage of skills further hampers green construction efforts, leading to potential delays in project completion (Yusof et al., 2012; Millicent et al., 2015).

2.4 GOVERNMENT POLICIES AND PUBLIC SECTOR CHALLENGES

Although Sri Lanka has several regulatory requirements to support local green growth, no specific law or policy focuses on GB construction (National Environmental Act, 1980; Ratnasiri, 2012). Many government-owned buildings in Sri Lanka are in a state of disrepair and lack innovation in multiple aspects (Pirabath, 2019). Government office buildings are commonly recognised as conventional and outdated, lacking sustainable features (Rajanathan, 2015).

2.5 BENEFITS OF GOING GREEN IN PUBLIC SECTOR OFFICE BUILDINGS

Adapting the green concept can help address these challenges. Green office buildings generally lead to better environmental performance than traditional ones (Zuo et al., 2016). Investment in green office buildings ensures long-term cost returns and benefits, as it ultimately offsets the capital invested (Eichholtz et al., 2013). Improved energy efficiency and reduction of Carbon footprint by green office buildings have been identified. Furthermore, green office buildings promote improved occupant health conditions and productivity compared to conventional ones (Singh et al., 2010). Ensuring effective indoor environmental quality is crucial, with features such as greenery, proper lighting, ventilation, and space planning enhancing a safe workplace (Colenberg et al., 2020). Several GB certification systems, including LEED and WELL Building Standard, acknowledge the significance of biophilic design (Degroff, n.d.). Effective implementation of biophilic design can enhance comfort and pleasure, boost productivity, decrease blood pressure, alleviate sick-building syndrome, promote better health, and raise employee motivation (Kellert & Calabrese, 2015; Tharim et al., 2022).

While the potential benefits of green building practices are well-documented, the challenges to their adoption, particularly in the public sector, must be addressed. Overcoming barriers such as high upfront costs, lack of knowledge, and resistance to change is crucial for the successful integration of green building technologies in Sri Lanka's public sector buildings. Continued research and policy development are needed to promote sustainable building practices and realise their full potential benefits.

3. METHODOLOGY

Data collection for this study was conducted in two phases. Phase 1 consisted of a case study analysis which was later followed up by expert interviews. For the case study, six government office buildings in the Colombo district were selected. The main purpose of this data collection was to identify the challenges and barriers to adopting the green concept in government office buildings. To achieve the research objectives, case study interviews were conducted through structured questionnaires to obtain information related to the research. Data collected from these buildings and their responses were analysed through manual content analysis.

Table 1 depicts the information of the case study participants in this research.

Table 1: Information on case studies

Case Name	Case description	Respondent name	Respondent description
B1	A building that has attempted to follow the green building concept, but latterly failed.	R1	Maintenance Officer
B2	An old building	R2	Landscape Architect
B3	A newly constructed building	R3	Facilities Manager (Trainee)
B4	A renovated building which has gained all the provisions for green features but cannot proceed due to some reasons.	R4	. Senior Scientist
B5	An average-level building.	R5	Facilities Manager
B6	A green building.	R6	Maintenance in charge

As depicted in Table 1, 6 government office buildings of various conditions were subjected to study as the green building adaption and adaptability can be varied based on its structure, innovativeness, and condition. Hence the study has adopted the purposive sampling method. The study further included interviews with respondents beyond facilities management, such as a landscape architect and senior scientist. Their involvement enriched the research by providing specialised insights: the landscape architect contributed expertise in sustainable design and outdoor environment integration, while the senior scientist offered perspectives on environmental impact and technological advancements. Importantly, their inclusion did not compromise the quality of information gathered. Instead, it broadened the study's scope, allowing for a comprehensive exploration of green building practices in office settings. Furthermore, these case studies facilitated direct site visits, interactions with occupants (employees), investigations, and observations, all contributing to an understanding through practical experience. Hence, the findings were not solely relied upon by the respondents.

Two expert interviews were later conducted to validate the data generated through the case studies. Table 2 shows the summarised information of the experts involved.

Table 2: Information of experts

Respondent name	Respondent description
E1	Assistant Director – Landscape division
E2	Facilities Manager

The rationale for choosing the two specialists, a landscape architect and a facilities manager, for validation purposes is based on their complementing knowledge and viewpoints. The Assistant Director in the Landscape Division possesses specialised expertise in outdoor environments, site planning, and vegetation, which is essential for assessing the impact of external factors on building performance. Besides, his extensive tenure in government buildings and his overall understanding of the building and its workings helped immensely. On the other hand, the facilities manager is highly knowledgeable in optimising operational efficiencies, implementing effective maintenance procedures, and addressing user requirements in the building environment. By integrating these two viewpoints, the goal is to attain a thorough validation of research findings, guaranteeing a comprehensive evaluation of both external and internal elements that impact building functionality and user experience.

The research process of this study is summarised in Figure 1.

Figure 1: Research process

4. FINDINGS AND DATA ANALYSIS

4.1 FINDINGS OF CASE STUDY

4.1.1 Phase 1-Case Studies

Data collection from case studies was executed based on an interview guideline which mainly covered areas such as current practices followed, awareness of the GB concept, and feasibility of converting and maintaining a government office building. As the first step, it was crucial to establish that the interviewees were aware of the "GB concept". Accordingly, it was evident that the interviewees had a clear idea about the concept and also found it a necessary practice.

Subsequently, it was crucial to understand the current standpoint of government office buildings in the adaptation of the GB concept. According to the results generated, it was evident that three buildings from the six that were considered under the case study had claimed to adopt the green building concept. Table 3 summarises the current practices followed.

Table 3: Current practices of green building concept in government office buildings in Sri Lanka

Case	Practice GB	Green building features within the building premises			
		Water efficiency	Energy efficiency	IEQ	Sustainable resources
B1	Yes	Rainwater harvesting	Utilising LED bulbs Solar power generation	Natural ventilation through vertical greenery	-
B2	No	-	Utilising LED bulbs	-	-
B3	No	-	Daylighting Energy efficient HVAC system, Windows	CO_2 sensors Daylighting	Proper waste management process
B4	Yes	Zoning and metering	Daylighting Energy efficient HVAC system, Windows	Lighting controlling	Proper waste management process 3R concept
B5	No	-	Solar power generation	-	Proper waste management process
B6	Yes	Rainwater harvesting Wastewater treatment plant	Daylighting Energy efficient HVAC system, Windows Solar power generation	Noise control Visual comfort Adequate ventilation	Proper waste management process

According to Table 3, the GB concept was not adopted by an old building, a newly constructed building, or an average-level building. Despite their non-adherence to these practices, they still incorporate some green features introduced under the criteria by LEEDs (Water efficiency, Energy efficiency, IEQ, Sustainable resources) such as utilising solar power generation and energy-efficient characteristics. Among the GB features followed by government office buildings rainwater harvest harvesting, indoor environmental controls, waste management, and energy-efficient measures can be identified.

While all interviewees agreed on the fact that GB concept could bring significant value to government office buildings in Sri Lanka, they however stated that certain barriers and concerns. Table 4 summarises the main barriers faced by government office buildings in adopting the GB concept based on both the literature review and data collection in this study.

Table 4: Barriers to follow the green building concept in government office buildings

Barriers	Respondents						
	R1	R2	R3	R4	R5	R6	Count
Financial Barriers		✓		✓	✓		3/6
Knowledge Barriers	✓	✓	✓	✓		✓	5/6
Management Inefficiency	✓			✓		✓	3/6
Lack of Facilities		✓					1/6
Social Barriers		✓	✓	✓		✓	4/6
Lack of Support	✓	✓					2/6

According to Table 4, it is evident that there are mainly six barriers that affect the implementation of the green building concept such as financial barriers, knowledge barriers, management inefficiencies, lack of facilities, social barriers, and lack of support. Among them knowledge barriers are reportedly the highest. As per the perception of the interviewees, there is no effective knowledge transfer regarding this concept to the occupants and employees and most of the occupants are almost unaware of the GB concept. Interviewees further stated that the experts working on promoting the GB concept had failed in their task as a result. The interviewees further stated that there are issues in the project management aspects due to the building being designed by one party and built by another, employee turnover, and as a result, the current employees in charge are unaware of the building, and its workings. This has led to difficulties in implementing not only the GB concept but also other changes to the building. Another factor highlighted was that even though most buildings make provisions to adopt the GB concept they do not make any provisions afterwards to maintain and continue. Financial barriers which were recorded acted as a significant barrier that reduced the chances of organisations in making green investments.

As detailed earlier, government office buildings encounter numerous obstacles in embracing the green building concept. Nonetheless, several officials expressed the view that enhanced government engagement could significantly impact this situation. The fact that the government should conduct awareness programs and it should be done starting at the school level, institutional level, and national level was also emphasised. In addition, it was mentioned that the government and regulatory bodies should work in accordance to encourage financial convenience in green investments. In addition, the importance of proper documentation and project management practices in green project continuation was emphasised. It was further stated that to get financial relief, GB certification organisations should revise the fee charged to encourage green practitioners.

The main goal of this study is to produce strategies to adapt the GB concept to government office buildings in Sri Lanka. To accomplish this goal inquiries were made regarding the incorporation of GB elements into government office structures. Respondents were surveyed on four key aspects: water efficiency, energy efficiency, indoor environmental quality, and sustainable resource usage. Table 5 explains the applicability of the GB concept to the selected buildings as per the interviewees and literature findings.

Table 5: Applicability of GB concept to the selected buildings

GB Feature	Applicability to the selected buildings						
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**Count**
Water efficiency							
Wastewater treatment plant				✓		✓	2/6
Rainwater harvesting	✓	✓	✓	✓	✓	✓	6/6
Water-efficient fittings and fixtures	✓	✓	✓	✓	✓	✓	6/6
Energy efficiency							
Energy efficient lighting system	✓	✓	✓	✓	✓	✓	6/6
Smart HVAC systems			✓	✓		✓	3/6
Solar roof panels	✓	✓	✓	✓	✓	✓	6/6
Energy efficient windows	✓	✓	✓	✓	✓	✓	6/6
IEQ measures							
Lighting control and daylighting	✓	✓	✓	✓		✓	5/6
Blinders	✓		✓			✓	3/6

GB Feature	**Applicability to the selected buildings**						
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**Count**
Exhaust fans				✓		✓	2/6
CO_2 sensors	✓		✓	✓		✓	4/6
Sustainable materials and resource usage							
3R concept	✓	✓	✓	✓	✓	✓	6/6
Waste management	✓	✓	✓	✓	✓	✓	6/6

Table 5 describes the extent to which crucial GB features can be adapted to the selected government office buildings in the study. Accordingly, only one building had adopted all the green features, while others had only a few. Therefore, opinions were sought on implementing these features in government office buildings. Responses indicated that rainwater harvesting, water-efficient fixtures, energy-efficient lighting, solar panels, energy-efficient windows, the 3R concept, and waste management could be easily adopted in government office buildings. However, wastewater treatment plants and exhaust fans were identified as challenging to implement in these buildings. Furthermore, there was limited feedback on the feasibility of smart HVAC systems and blinders. Reasons for this are mainly that government buildings are not being generous in investing in highly costly projects. Furthermore, newly constructed buildings had a supportive structure to adopt mentioned GB features due to the flexibility in construction.

However, before the introduction of a novel concept or practice in a building, it is crucial to study the level of employee/occupant awareness in successful execution and continuation. Hence the respondents were questioned about the employee's level of awareness and support regarding the GB concept.

Table 6: Employees' awareness of the GB concept

Case Name	**Employees' awareness of the GB concept**
B1	✓
B2	
B3	
B4	
B5	
B6	✓

Table 6 indicates that employees in only two organiSations are fully informed about the GB concept. These organiSations are: B-the organisation that attempted but failed to implement the GB concept, and B6-the certified GB. Hence it is evident that there is a lack of knowledge and support when it comes to GB in government sector office buildings. The participants suggested that informing employees about new features and gaining their support should be a solution. They recommended conducting awareness programs from higher to lower positions within the organisation and involving industry experts and management in these programs.

Finally, the respondents affirmed their preference for adapting green culture to government office buildings and further stated that adaptation would help them yield the below benefits.

Table 7: Benefits of following the GB Concept

Benefits	**Respondents name**						
	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**Count**
Energy saving	✓	✓		✓	✓		4/6
Cost saving	✓	✓	✓	✓	✓	✓	6/6
Reducing resource usage	✓			✓	✓	✓	4/6
Creating a healthy working environment		✓	✓			✓	3/6
Increasing employee productivity and organisation culture		✓	✓				2/6
Character development	✓	✓					2/6

According to Table 7, cost benefits were the most anticipated in the adaptation of the GB concept, other than that the interviewees also expected energy savings and reduced resource usage. Increased employee development and character development were the least expected benefits.

4.1.2 Phase 2- Expert Interviews

Expert interviews were conducted aiming to confirm the accuracy of the information obtained from the case study interviews. The main purpose of this is to indicate that the output of the research is more accurate and transparent. Primarily, two experts were involved in this phase, one specialised in adhering to the urban development authority guidelines mandated for constructing government buildings, as ratified by the government in 2017, while the other was a facility manager employed abroad.

Although the experts noted that the government sector is less likely to adopt the green concept, they emphasised that this is because public institutions embrace the concept first yet less concerned with keeping it up to date. On the other hand, as E2 pointed out, based on reasons such as the unavailability of long-time national policies, absence of innovation and researchers, unawareness of the GB concept in SL government leaders, negative attitude toward building concept, use of outdated technologies, corruption from top to bottom of government leaders and employees, consumption of outdated online technologies, this concept is rarely applied to government institutions. It was further stated that the GB concept is rarely adopted in old and renovated buildings due to structural inefficiencies.

The experts did note that identifying distinct barriers and drivers for GB concept adaptation may aid in GB concept adaptation successfully. Barriers to adaptation that were mentioned in Table 8.

Table 8: Barriers to adopting GB concept to existing government office buildings

Barriers	**Respondent**	
	E1	**E2**
Unavailability of national policies and standards		✓
Budget constraints	✓	✓
Technological barriers		✓
Poor government leadership and poor consultation by the responsible positions	✓	✓
Poor investment in research and development projects		✓
Unawareness and negative attitude	✓	✓
Lack of ongoing performance evaluation and management		✓

Three primary factors hindering the adoption of green practices include financial limitations, inadequate government leadership and consultation, and a lack of awareness coupled with a negative mindset. In addition issues such as the unavailability of national policies and standards, technological barriers, poor investment in research and development projects and unavailability of continuous performance evaluation and management affected the implementation of the GB concept in government office buildings.

Nevertheless, factors such as regulatory incentives and stakeholder support were noted to influence the adoption of green practices. Guidelines established by professional organisations such as the Green Building Council of Sri Lanka (GBCSL), the Urban Development Authority Sri Lanka (UDA), and the Sustainable Development Council of Sri Lanka (SDCSL) can serve as valuable references. It was said that everyone in the government, including specialists, the general public, and workers, should support the implementation of GB. It was underlined that this idea provides advantages for individuals, institutions, the nation, and society at large. In addition, it was recommended that awareness campaigns should be launched to spread the word about this idea. However, the fact that the government should initiative in this matter was emphasised.

5. DISCUSSION

Literature reviews depict a green building as one that maximises resource efficiency, including water, energy, and materials, aiming to reduce negative environmental and health impacts. It revealed obstacles such as financial, regulatory, social, knowledge, and industrial barriers-that impede the implementation of GB concepts in Sri Lanka government-owned buildings including office buildings. Furthermore, several key factors that influence the construction of GB such as regulatory incentives, stakeholder support, ecological considerations, and social responsibility were revealed. Additionally, essential elements such as water efficiency, energy efficiency, indoor environmental quality, staff training, and effective material and resource usage were identified as crucial components of the implementation process.

Just as there has been limited research conducted on the adoption of GB practices in government sector buildings, there are relatively few buildings that have obtained green building certification. As per the findings, only one building had the GB certification while the rest claimed to adopt few GB features. As factors that hindered the adaptation of old structures and condition of buildings, financial barriers, poor project management practices, knowledge barriers, and lack of managerial involvement and support were identified and this fact was later affirmed not only by the literature findings yet by the case studies and experts. Other than that the existence of corruption and fraud in the government sector too was highlighted by the experts. However, drivers that motivated the adaptation availability of various rules and regulations by leading professional bodies such as GBCSL, UDASL, and SDCSL were mentioned. Other than that drivers such as government and non-government encouragement, client's demand, contractor’s support, environmental sustainability, and social responsibility were identified. Regardless of these drivers, Government office buildings have failed to adopt the GB concept and are intensively lagging especially due to the lack of finances, poor research and development in this area, and poor project management and handling practices. The interviewees and experts further affirmed that lack of action in continuous development and improvement, maintenance, and lack of authority were other key factors that hindered GB's adaptability.

Respondents largely proposed government support as the primary solution to overcoming obstacles in implementing green practices in government office buildings. Suggestions included government-led awareness programs spanning from schools to national levels, a collaboration between government bodies and regulatory agencies to facilitate financial assistance, and the presence of designated representatives involved from building construction to usage. Additionally, it was suggested that GB certification organisations should reconsider their fees to provide financial relief.

However, it is more than evident that actions to implement the GB concept should be taken at each level; individually, institutionally, and at the national level.

Figure 2 presents a summary of the findings of this research.

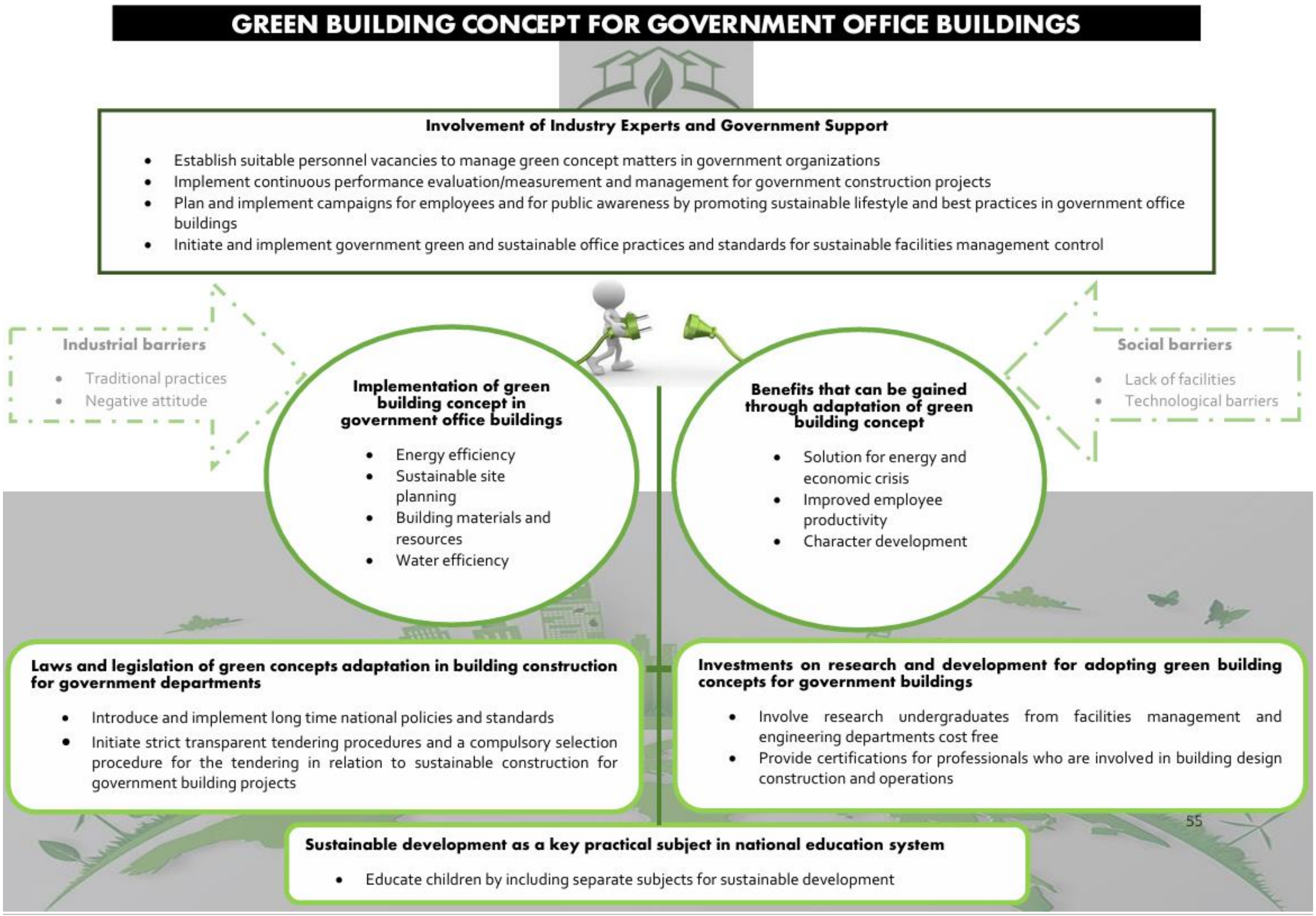


Figure 2: Framework for green building concept for office buildings in Sri Lanka

This framework guides government office buildings in adopting GB concepts to achieve benefits at national, organisational, and individual levels. It emphasises energy efficiency, sustainable site planning, sustainable materials, quality interior environments, and water efficiency, supported by guidelines from certification bodies such as Blue Green Sri Lanka and the GREENSL® Rating System. These practices can address energy and economic crises, conserve natural resources, and enhance work environments, boosting productivity and organisational culture. Implementation challenges include social barriers (traditional practices, negative attitudes, unawareness) and industrial barriers (lack of facilities, technological challenges, risk, and uncertainty). Overcoming these requires government support, industry expert involvement, establishing roles such as Facilities Manager and Green Officer, and public awareness campaigns. Supporting measures include laws and legislation for GB, transparent tendering for sustainable projects, investments in research and development, and integrating sustainable development into education with practical, innovation-focused curricula.

6. CONCLUSIONS AND RECOMMENDATIONS

The background investigation revealed a lower inclination of Sri Lankan government buildings towards adopting the green concept. Hence this study aims to assess the effectiveness of implementing the GB concept in existing government office buildings, taking these findings into account. Initially, literature findings guided the identification of the implementation process for the green concept, highlighting a focus on energy-efficient lighting, daylighting, and waste management, with limited attention to water efficiency and Indoor Environmental Quality (IEQ) measures. Case study findings underscored barriers to implementing the concept in such buildings, including financial constraints, knowledge gaps, management inefficiencies, inadequate facilities, societal hindrances, and lack of support. Ultimately, the synthesis of literature review findings and analysis outcomes paved the way for the adaptation of the GB concept in existing government office buildings by identifying various barriers, drivers, and difficulties faced.

7. REFERENCES

Abdul Tharim, A. H., Ahmad, A. C., Saarani, P. S. N., Haossain, N. Q. R., Purwanto, E., Tafridj, I. S. I., Purisari, R., & Prasetio, T. (2022). The determinant factors of biophilic design strategies and occupants' psychological performance in office building. Malaysian Journal of Sustainable Environment, Special Issue, June, 87-106. doi: 10.24191/myse.v9i3.18292.

Adetokunbo, I., & Emeka, M. (2015). Urbanization, housing, homelessness and climate change.Journal of Design and Built Environment, 15(2), 12. https://doi.org/10.22452/jdbe.vol15no2.3

Azizi, N. Z. M., Abidin, N. Z., & Raofuddin, A. (2015). Identification of soft cost elements in green projects: Exploring experts' experience. *Procedia - Social and Behavioral Sciences, 170(1)*, 18-26. https://doi.org/10.1016/j.sbspro.2015.01.009

Council of the Commission for Environmental Cooperation. (2008, May 30). Green Building in North America. Retrieved from Opportunities and Challenges: http://www3.cec.org/islandora/en/item/2335-green-building-in-north-america-opportunities-and-challenges-en.pdf

Colenberg, S., Jylhä, T., & Arkesteijn, M. (2020). The relationship between interior office space and employee health and well-being – a literature review. Building Research & Information, 49(3), 352–366. https://doi.org/10.1080/09613218.2019.1710098

Darko, A., Chan, A. P. C., Ameyaw, E. E., He, B.-J., & Olanipekun, A. O. (2017). Examining issues influencing green building technologies adoption: The United States green building experts' perspectives. *Energy and Buildings, 144*, 320-332. https://doi.org/10.1016/j.enbuild.2017.03.060

Elnaklah, R., Fosas, D., & Natarajan, S. (2020). Indoor environment quality and work performance in "green" office buildings in the Middle East. *Building Simulation, 13*(5), 1043-1062. https://doi.org/10.1007/s12273-020-0695-1

Eichholtz, P., Kok, N., & Quigley, J. M. (2013). The economics of green building. Review of Economics and Statistics, 95 (1), 50–63. Retrieved from https://EconPapers.repec.org/RePEc:gam:jsusta:v:13:y:2021:i:24:p:13863-:d:703081

Gan, V. J. L., Lo, I. M. C., Ma, J., Tse, K. T., Cheng, J. C. P., & Chan, C. M. (2020). Simulation optimization towards energy-efficient green buildings: Current status and future trends. *Journal of Cleaner Production, 254*, 120012. https://doi.org/10.1016/j.jclepro.2020.120012

Geelani, S., Geelani, S., Bhat, S., Haq, S., Mir, N., Junaid, S., & Zafar, B. (2012). Green building development for a sustainable environment with special reference to India. *International Journal of Environment and Bioenergy, 4*(2), 86-100. https://api.semanticscholar.org/CorpusID:116287779

Miller, N., Spivey, J., & Florance, A. (2008). Does green pay off? *Journal of Real Estate Portfolio Management, 14*(4), 385-400. https://doi.org/10.1080/10835547.2008.12089822

Millicent, A.-K., William, G.-A., & Simon, A. O. (2015). Sustainable construction implementation in Ghana: Focusing on awareness and challenges. *Civil and Environmental Research*, *7*(6), 1-12. Retrieved from https://core.ac.uk/reader/234677960.

Nalewaik, A., & Venters, V. (2009). Cost Benefits of Building Green. *Cost Engineering*. pp. 28–34.

National Environmental Act. (1980). *No 47 of 1980.* Colombo: Government Publication Bureau.

Pirabath, M.D.C., Rajini, D., Mahendrarajah, G., & Premanathan, T. (2019, December). *Space planning and management practices in government office buildings: Case studies in Sri Lanka*. Paper presented at the 10th International Conference on Sustainable Built Environment (ICSBE), Sri Lanka.

Ratnasiri, J. (2012). Sustainable Development - Is Sri Lanka on the Right Path? *Professor A.W.Mailvaganam Memorial Oration*, (pp. 1-11). Colombo.

Singh, A., Syal, M., Grady, S., & Korkmaz, S. (2010). Effects of green buildings on employee health and productivity. *American Journal of Public Health, 100*(9), 1665-1668. https://doi.org/10.2105/AJPH.2009.180192

Vivian , L., Volker , H., & Beran , G. (2003). Linking Energy to Health and Productivity in the Built Environment Evaluating the Cost-Benefits of High Performance Building and Community Design for Sustainability, Health and Productivity. Center for Building Performance and Diagnostics, Carnegie Mellon University.

Wanniarachchi, D. (2022, September 1). The reasons for the failure of public projects in Sri Lanka as a developing country and the state of the country after the failure, with a main focus on the Mattala airport project. Retrieved from https://www.researchgate.net/publication/363174919_The_reasons_for_the_failure_of_public_projects_in_sri_lanka_as_a_developing_country_and_the_state_of_the_country_after_the_failure_With_a_mainly_focus_on_the_mattala_airport_project

U.S. Energy. (2008, October). *Energy efficiency trends in residential*. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/bt_stateindustry.pdf

Yusof, N., Awang, H., & Abidin, N. (2012). A foresight into green housing industry in Malaysia. *World Academy of Science, Engineering and Technology: International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 6*(2), 55-63. doi.org/10.5281/zenodo.1081413

Naganarasimhulu, T. and Tawalare, A.G., 2024. Addressing the skilled professional shortage in Indian sustainable construction: A focus on awareness, education, training, and policy interventions. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 79-91. DOI: https://doi.org/10.31705/WCS.2024.7. Available from: https://ciobwcs.com/papers/

ADDRESSING THE SKILLED PROFESSIONAL SHORTAGE IN INDIAN SUSTAINABLE CONSTRUCTION: A FOCUS ON AWARENESS, EDUCATION, TRAINING, AND POLICY INTERVENTIONS

Talari Naganarasimhulu[1] and Abhay Tawalare[2]

ABSTRACT

The sustainable construction industry is experiencing rapid growth, propelled by the urgent global need to reduce environmental impact and enhance resilience in the built environment. Nevertheless, this expansion is met with a significant deficit of skilled professionals equipped with the necessary knowledge and expertise in sustainable construction practices. This research explores the multifaceted approach required to rectify this shortage, with a primary focus on enhancing awareness and education, addressing training needs, and implementing effective policy interventions. This study begins with the examination of existing literature related to sustainable construction education, training, and current strategies to identify gaps and challenges. The research methodology entails a literature review to identify factors causing skilled professional shortages in construction. Semi-structured interviews with construction professionals follow this to confirm and explore underlying reasons. Transcripts are then analysed using content analysis to extract main themes and sub-themes. Gaining insight into the root causes of skilled shortages and the challenges within sustainable construction guides the development of targeted strategies aimed at attracting more professionals to the field. Proposed strategies for addressing shortages are validated with construction professionals, and conclusions are drawn. This approach not only helps alleviate professional shortages but also fosters sustainable growth within the sector. The findings of the study offer valuable insights for stakeholders, educational institutions, and policymakers, enabling them to enhance their approaches to sustainability in the construction industry.

Keywords: *Construction Industry; Shortage; Skilled Professional; Sustainable Built Environment; Sustainable Construction*

1. INTRODUCTION

Sustainable development ensures meeting present needs without jeopardising future generations' ability to meet their own, based on the principle that society should

[1] PhD Scholar, Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India, naga.narasimha654@outlook.com

[2]Assistant Professor, Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India, abhaytawalare@civ.vnit.ac.in

responsibly use available resources in line with future needs (Mohd-Rahim et al., 2016). The Indian construction industry is a key economic sector contributing significantly to social and economic development (Knight Frank & RICS, 2023). However, the shortage of skilled professionals is a factor impacting project success within the industry (Alshahrani et al., 2023). Skilled construction professionals are essential for designing, building, and maintaining infrastructure, utilising their expertise to incorporate technological advancements, meet project needs, and support the rehabilitation of existing structures (Fathima & Umarani, 2023). Despite people's inclination towards jobs in glamorous industries, the construction industry in many regions still suffers from a negative reputation due to concerns including quality issues, work-related accidents leading to fatalities, perceived lack of professionalism among workers, low productivity levels, and detrimental environmental impacts (Ling et al., 2016).

In 2018, the National Skill Development Corporation (NSDC) projected significant workforce growth, with an expected increase from 45 million in 2013 to 75 million by 2022. The sector was anticipated to generate a demand for 31 million jobs over nine years, divided into 13.98 million jobs required from 2013 to 2017 and 17.15 million jobs needed from 2017 to 2022 (KPMG Adisory Services Pvt. Ltd., 2013). Despite these projections, the real estate and construction sector in India saw a 25% decline in employment from 2017 to 2021, as reported by Statista (2023). However, a critical shortage of skilled professionals poses a formidable threat to sustained expansion.

The scarcity of project managers significantly impacts sustainable construction, leading to cost escalation, delays, diminished quality, increased accidents, and heightened rework (Oke et al., 2018). The shortage of skilled labour significantly impacts construction projects, leading to cost overruns and schedule delays due to lower productivity within the allotted time (Kim et al., 2020). Further to Elbashbishy and El-Adaway (2024), given that labour costs typically constitute 30% to 50% of total project expenses, effective management of labour issues and productivity improvement are critical for ensuring the financial success of projects. These effects directly influence the economic, social, and environmental aspects of sustainable development.

The prior research focused on labour issues such as shortages and employment stability; it mainly documented factors and expected impacts on construction projects. Most of the studies analyse skilled labour flow in construction, aiming to understand shortage complexities and clarify their causes and effects on projects (Alshahrani et al., 2023; Elbashbishy & El-Adaway, 2024; Kim et al., 2020; Mohd-Rahim et al., 2016; Oke et al., 2018). Despite the growing importance of sustainable construction for environmental and economic challenges, India faces a significant shortage of skilled professionals in this sector (Alshahrani et al., 2023; Mohd-Rahim et al., 2016; Oke et al., 2018). Existing literature primarily addresses the general shortage in construction, with limited focus on sustainable construction's specific needs and challenges. Moreover, comprehensive strategies integrating awareness, education, training, and policy interventions are lacking. This research aims to fill this gap by analysing the factors influencing the skilled professional shortage in sustainable construction and proposing targeted strategies to improve professional skills and availability in this critical field. The objective of this research is to investigate and identify the factors contributing to the shortage of skilled professionals in the Indian sustainable construction sector. It aims to analyse these factors comprehensively, assess their impact on the industry, and propose targeted strategies to enhance awareness, education, training, and policy interventions. The study seeks to provide insights and recommendations that can effectively address the skilled professional shortage, thereby promoting sustainable practices and development in the construction industry in India.

2. FACTORS RESPONSIBLE FOR SKILL PROFESSIONAL SHORTAGE IN SUSTAINABLE CONSTRUCTION

2.1 EDUCATIONAL GAPS

The shortage of educational programs specifically tailored to sustainable construction practices, coupled with the predominant focus of construction programs on traditional methods, leaves a significant gap in training for new techniques (Welfare et al., 2021). To maintain and sustain the construction workers, it was essential to offer prompt evaluations, feedback, and professional training (Karakhan et al., 2023).

2.2 ECONOMIC FACTORS

Adequate pay is a primary reason for entering the industry (Welfare et al., 2021). A larger investment in labour wages will increase the supply of skilled workers, resulting in higher productivity, which will have a positive impact on the supply of skilled workers by either lowering the attrition rate or attracting more people into the construction industry (Aiyetan & Dillip, 2018). Because the current income level is insufficient to justify the physically demanding work required by the construction industry, the majority of young workers do not prioritise this industry as a high priority in their career choice. Therefore, the industry will not be able to draw in young workers until workers' earnings and benefits can be enhanced to a suitably alluring level (Ho, 2016). Moreover, Zhou and Lowe (2003) notes that there is a lack of financial incentives, such as subsidies or tax breaks, to encourage the adoption of sustainable practices, making it economically unattractive for professionals to specialise in this field. Industry culture and workplace dynamics

Undesirable working conditions are associated with working outdoors, such as extreme weather conditions, heat, and cold (Welfare et al., 2021). There may be a decrease in labour attrition due to job dissatisfaction if the working environment is improved through a policy of health and safety and investment in improving working conditions, supported by government policy, which will subsequently enable the reduction of shortages of skilled laborers in the industry (Aiyetan & Dillip, 2018). High physical demands and harsh working conditions in construction sites are key barriers to joining the industry (Sing et al., 2017). It is difficult to draw new participants to the sector due to the perplexing challenges of uncomfortable, unsafe, and dirty working conditions (Ho, 2016). The degree to which employees of a firm or organisation believe they are treated equally and evaluated fairly without experiencing any form of prejudice (Karakhan et al., 2023). Equity is considered to be the most critical component for achieving a high degree of workforce sustainability by frontline workers and supervisors (Karakhan et al., 2023). The pressures of labour and skill shortages would be relieved if new immigrants, women, and ethnic minorities had access to the right training and employment possibilities (Ho, 2016).

Because one significant accident can result in a sharp decline in the number of new hires in the business, the problem of hazards needs to be treated seriously (Ho, 2016). Employers are urged to have written, open policies in place that support professional development, leadership, and communication training and establish clear guidelines for promotions to all levels (Karakhan et al., 2023).

2.3 PROFESSIONAL DEVELOPMENT AND NETWORKS

Limited professional networks and associations focused on sustainable construction restrict opportunities for knowledge sharing and professional growth. Chan et al. (2018) suggest that the absence of robust professional communities dedicated to sustainability in construction prevents the dissemination of best practices and collaboration among professionals. Female role models do seem to have a practical substantial factor that is more strongly influencing female students' decisions to enrol in the CM degree program (Bigelow et al., 2018).

2.4 TECHNOLOGICAL BARRIERS

Technological barriers also contribute to the shortage of skilled professionals in sustainable construction. Limited access to the latest sustainable construction technologies and materials presents a significant hurdle (Giesekam et al., 2014). Moreover, insufficient investment in research and development (R&D) within this sector hampers innovation and the creation of new sustainable practices and materials (Matar et al., 2008).

2.5 AWARENESS AND DEMAND

Low awareness and demand for sustainable construction practices among stakeholders also significantly contribute to the skills shortage. Many developers and clients are unaware of the long-term benefits of sustainable construction, leading to a preference for conventional methods, which reduces market demand for sustainable projects and diminishes the incentive for professionals to specialise in this field (Zuo & Zhao, 2014).

The shortage of skilled professionals in sustainable construction in India is a multifaceted issue rooted in educational gaps, low awareness and demand, economic factors, regulatory inconsistencies, professional development barriers, technological constraints, industry culture, and workplace dynamics. Addressing these challenges requires comprehensive strategies that encompass educational reforms, increased awareness, supportive policies, economic incentives, and a shift in industry practices toward sustainability.

3. RESEARCH METHODOLOGY

Our research employs a qualitative approach to explore professionals' perspectives and experiences in the sustainable construction sector, suited for understanding the complex nature of skilled professional shortages. The research methodology comprises a literature review to identify factors contributing to skilled professional shortages in construction, followed by semi-structured interviews with 17 construction professionals, including 3 HR personnel, 5 project managers, and 9 project engineers. The professionals interviewed in our study were selected from the Maharashtra region within India, and their insights may not necessarily generalise to the entire country's construction industry. The specific region was chosen because of the combination of supportive policies, economic development, corporate responsibility, awareness, and availability of resources. These interviews aim to confirm and identify factors responsible for skilled professional shortages and explore underlying reasons not covered in the literature. Purposive sampling was employed to capture a diverse range of professionals in sustainable construction. Participants were selected based on their expertise and relevance to the research objectives, thus enriching the breadth of perspectives examined. One-on-one interviews were conducted to gather rich, detailed insights, allowing flexibility to delve deeply into topics and adapt to new information. While focus group interviews were not conducted, participants were encouraged to share and discuss their experiences, capturing a range of perspectives and fostering a deeper understanding of the issues. The interviews underwent transcription and analysis via NVivo10, a qualitative data analysis software, to facilitate content analysis (Gaur & Tawalare, 2022). Factors contributing to skilled professional shortage were initially coded as nodes through open coding, then grouped under constructs based on discussions and discretion of senior respondents. Additional analysis was undertaken to assess respondents' consensus regarding the viability of strategies to address the skilled shortage for the sustainable construction industry. The interviews underwent Micro-Interlocutor Analysis (MIA), a method by which assesses verbal and non-verbal responses in focus groups (Gaur & Tawalare, 2022 Leech & Onwuegbuzie, 2008), representing agreement via a matrix format while tracking respondents' interactions, response nature, familiarity with questions, and nonverbal cues, as detailed by (Gaur & Tawalare, 2022; Patil & Laishram, 2016).

Table 1: Characteristics of respondents

Characteristics	Gender		Experience (Years)			Education	
	Male	**Female**	**5-10**	**10-20**	**>20**	**Graduation**	**Post-Graduation**
Frequency	12	5	9	5	3	13	4
(%)	70.6	29.4	52.9	30	18	76.5	23.5

4. RESULT AND DISCUSSION

The findings from the content analysis of the semi-structured interviews regarding the factors responsible for the skilled workforce shortage in the construction industry provided a wide perspective and valuable insights into the various aspects influencing the shortage (Table 2). The factors contributing to the Skilled Professional Shortage (SPS) are presented in Table 2 following the analysis.

Table 2: Results of content analysis: Factors responsible for skilled professional shortage sustainable construction

Theme	Subtheme	Description	Author	No of occurrences
Economic	Lack of Financial Incentives	There are limited financial incentives, subsidies, or tax breaks for companies and professionals to adopt sustainable construction practices.	(Zhou & Lowe, 2003)	23
	Limited research and development	Insufficient research and development efforts focused on sustainable construction practices and materials.	(Matar et al., 2008)	8

Theme	Subtheme	Description	Author	No of occurrences
Workplace dynamics	Remuneration and Benefits	Unavailability of basic needs on the construction site, e.g., clean water, toilet, etc	(Welfare et al., 2021)	26
	Working condition	Physically challenging Health and safety issues on construction sites	(Welfare et al., 2021), (Ho, 2016)	15
	Lack of Supportive Leadership and Recognition	Effective leadership that promotes and supports sustainable practices is crucial for fostering a culture of sustainability	(Karakhan et al., 2023)	17
Education and Training Gaps	Training & internships	Lack of / improper training for students in college	(Karakhan et al., 2023)	25
	Course Curriculum	Teaching at the college level is not according to what the industry wants	(Welfare et al., 2021)	13
Industry culture	Working hours	working hours are not flexible, long working hours	(Aiyetan & Dillip, 2018)	18
	Work-life balance	Unable to spend time in non-professional life	(Koc et al., 2022)	20
	Perception of Sustainability	Perceiving sustainable construction is prohibitively expensive, deterring investment in training and hiring skilled professionals.	(Macherla, 2023)	20
	Job security	Lack of job security	(Escamilla et al., 2016)	23
	Gender Bias	Female participation is much less as compared to male professionals	(Escamilla et al., 2016)	14
	Resistance to change	A culture that is resistant to adopting new sustainable practices and technologies, preferring traditional methods	(Gehlot & Shrivastava, 2022)	25
Awareness and Adoption	Limited Awareness	Many construction companies and professionals are not fully aware of the benefits and techniques of sustainable construction.	(Zuo & Zhao, 2014)	19
	Limited access to advanced technologies	Limited access to advanced technologies and materials required for sustainable construction.	(Giesekam et al., 2014)	25

Column 5 in the above table displays the frequency of mentions for each specific factor in the interviews. The sub-factors, represented in Column 2, correspond to the child nodes, while the constructs in Column 1 represent the parent nodes established through discussions with respondents and existing literature. Through analysis, the following 15 sub-factors are categorised into 5 main constructs: economic, educational, workplace dynamics, industry culture, awareness, and adoption. From the content analysis, the most responsible factors for the skilled professional shortage for sustainable construction are remuneration and benefits, training and internships, Resistance to change, and Limited access to advanced technologies.

The respondents identified remuneration and benefits compared to other professional jobs as a significant factor contributing to the shortage of skilled workers. The perception of delayed salary payments also emerged as a concern. Some respondents mentioned that economic downturns, layoffs, and lack of investment further contribute to the shortage.

Respondent 3 stated,

> *Firstly, if somebody is going to adopt any skill, he or she thinks about the outcome, that is, pay or scope. If other sectors are giving better salaries compared to civil, then obviously they will choose these sectors. So, give them good packages and opportunities.*

Respondents highlighted the unavailability of basic needs, such as clean water and toilets, at construction sites, which can impact the attractiveness of the industry. The physically challenging nature of the work and health and safety issues on construction sites were mentioned as factors that discourage individuals from pursuing a career in construction and which lead to further skilled professional shortages.

Respondents expressed concerns about the lack of or improper training provided to students in college, indicating a mismatch between the skills taught in institutions and industry requirements related to sustainable construction. Due to insufficient field experience, new entrants are not liable to work directly in the industry; the organisation has to train them initially from the basics.

Respondents felt that the teaching at the college level is not aligned with industry expectations, which affects the development of practical skills required in the construction sector. Respondents 2, 4, and 6 stated that;

> *As per their experience, the knowledge gained during graduation and the required knowledge in practical fields are totally different. Students need to struggle after pursuing a degree separately to skill themselves; the 4 years of engineering are not worth it. Private colleges do offer such courses but fail in teaching and developing skills. Also, our education system is all about memorising things rather than the actual execution.*

The inflexibility and long working hours were identified as a challenge affecting work-life balance and overall job satisfaction by Aiyetan and Dillip (2018) as well. Respondents mentioned the inability to take casual leaves and the mental stress associated with heavy workloads.

The construction industry's physically and mentally demanding nature was seen as a hindrance to maintaining a balance between professional and personal life. Respondent 6 stated,

> *We cannot take even casual leaves according to our personal needs; authorities issue leaves according to job site needs.*

The perception of the industry as physically demanding, less glamorous, and male-dominated affected the attractiveness of the sector, particularly among the younger generation. Concerns about job security within the construction industry were also raised. Respondent 8 stated,

> *Many new entrants consider industry only as a blue-collar job and physically demanding job less glamorous than other sectors, and they do not want to work in such challenging conditions. The nature of the industry is not like an attractive office job like the IT sector; financial growth is very slow, and the work culture, especially on-site work not suitable for females.*

Respondents also highlighted the low participation of females in the construction industry, both at the professional and educational levels, indicating the presence of gender bias. Female respondents 10 and 15 stated,

> *Speaking as a female professional, in our industry, female participation is very less as compared to male professionals. At the education level also. We cannot deny if we look present scenario that our construction sector is male-dominated. So, this is one of the factors responsible.*

Many professionals believe that resistance to change within traditional practices hinders the adoption of innovative, sustainable techniques. Additionally, limited access to advanced technologies restricts the industry's ability to attract and retain skilled professionals capable of implementing sustainable construction practices effectively. Respondents 10, 15 and 17 states that,

> *These perceptions underscore the need for policy support, industry collaboration, and educational initiatives to overcome resistance to change and enhance access to advanced technologies in the Indian construction sector, thereby promoting sustainable practices more effectively.*

Categorising these factors into economic, educational, workplace dynamics, and industry culture constructs facilitates the analysis and comprehension of the diverse elements impacting individuals within their employment and industry contexts. This structured classification enables a comprehensive examination of the factors influencing various aspects of the workforce shortage in the Indian construction industry, aiding in the identification of areas for improvement or intervention.

4.1 Effective Ways to Address the Skilled Workforce Shortage in Sustainable Construction

Similarly, the results of the Micro-Interlocutor Analysis (MIA) are outlined in Table 3.

Table 3: Results of micro-interlocutor analysis: Ways to address the workforce shortage

Strategy	Description	Mean
Education, Training, and Awareness		
Occupational Awareness Campaigns	Increasing awareness among students, parents, and career counsellors about the diverse opportunities and potential of careers in the construction industry	++
Cooperative Industry-Academia Engagement	Fostering stronger partnerships between construction companies and educational institutions to align educational programs with industry requirements.	++

Strategy	Description	Mean
Social Networking and Digital Spaces	Use social media, websites, and blogs to display construction industry successes, trends, and daily operations, targeting younger audiences with visual and interactive content.	+−
Sustainability and Innovation	Emphasise the importance of sustainability and technology in making the industry appealing to environmentally conscious and tech-savvy individuals.	+−
Industry-Relevant Training	Providing opportunities for upskilling and continuous professional development to both students and existing professionals in the construction industry	++
Improving the industry's image and perception		
Incentives and Recognition	Offering competitive salaries, benefits, and growth prospects can position the construction industry as an appealing and financially rewarding career choice.	++
Strengthening Employment Stability	Prioritising job security and professional development can entice individuals to explore its stable and promising career opportunities.	++
Enhancing Work-Life Balance	Recognise the importance of work-life balance in the construction industry and implement measures to improve it.	++
Diversity Empowerment Programs	Embrace diversity and inclusion within the construction sector by creating a supportive and inclusive work environment.	+−
Addressing Safety Concerns	Emphasise the industry's dedication to worker safety and the measures taken to maintain a secure working environment.	++

Note: ++ = strongly agree; + = agree; +− = neutral; − = disagree; and −− = strongly disagree

The last column depicts the average effectiveness of strategies utilised to address skilled professional shortages, organised into constructs derived from common themes identified through discussions with respondents and existing literature. Analysis indicated that respondents generally agreed (+/++) with most strategies, yet they maintained a neutral stance (+−) on three specific strategies: S3, S4, and S9.

4.1.1 Education, Training, and Awareness

Increasing awareness among graduates about the construction industry and its potential career opportunities was suggested by respondents to change perceptions and attract more individuals to the field in order to tackle the skilled professional shortage problem.

> *Many young people are not aware of the opportunities available in the construction trades. One way to address this is to increase awareness and interest in the trades by providing information and resources to schools, community centres, and youth organisations.*

Design specialised educational programs and training courses tailored to sustainable construction practices, encompassing areas such as green building materials, energy-efficient design, renewable energy systems, and sustainable construction techniques.

> *Collaborating with academic institutions, industry associations, and government agencies to develop and promote educational programs can significantly impact our industry and pave the way for a more sustainable built environment.*

Implementing internship programs throughout the academic years to bridge the gap between industry expectations and college course curricula by establishing collaborations between industry and educational institutions. Respondents emphasised the need for a revised course curriculum that focuses on practical learning and industry requirements.

> *Reforms should be made in the syllabus of engineering colleges, especially private low-grade colleges. In such a college, teachers should be well-trained and experienced enough to deliver the required knowledge and skills to students, which is a demand of the industry. Regular site visits and exposure to unique structures were suggested to develop interest and provide real-world experiences to students.*

4.1.2 Improving the Industry's Image and Perception

Many respondents expressed the need to improve salaries in the construction industry to attract and retain skilled professionals. Higher salaries were seen to motivate individuals to choose careers in construction.

> *Providing incentives, perks, promotions, and flexible working hours were mentioned as ways to enhance employee welfare and satisfaction, along with ensuring basic facilities at construction sites, including proper safety measures.*

Providing a good work-life balance was mentioned to attract and retain skilled workers in the construction industry. One of the respondents stated,

> *Provide proper salary, incentives, perks, increments, safety, and basic needs according to the site and location and give a good work-life balance so we can spend a good time with our family and friends; this will help to sort out the shortage of workforce.*

Ensuring job security and stability can alleviate concerns and improve employee satisfaction. Respondents highlighted the importance of adopting new technologies and increasing automation in the construction industry.

Implementing policies related to recruitment, training, retention, working hours, and salary fixation was suggested to improve the overall working environment and employee satisfaction. One of the respondents stated,

> *Policies about working hours should be fixed by authorities, either by the government or by the company. Salary should be given as per work done. There must be certain regulations about salary fixation and increments. Aware and motivated students to enter the industry by giving exposure to the industry through industry and institution collaboration. Motivate them to work in such challenging conditions by knowing the role of civil engineers in society.*

Increasing awareness among graduates about the construction industry and its potential career opportunities was suggested by respondents to change perceptions and attract more individuals to the field in order to tackle the skilled professional shortage problem. One of the respondents stated,

> *Many young people are not aware of the opportunities available in the construction trades. One way to address this is to increase awareness and interest in the trades by providing information and resources to schools, community centres, and youth organisations.*

Enhancing female participation in the construction industry through various initiatives, such as providing extra perks, stipends, or compensation and nurturing female students during their degree programs, was mentioned as an important aspect of addressing the skilled professional workforce shortage.

5. CONCLUSIONS

In summary, this research emphasises the urgent need to address the skilled professional shortage in India's sustainable construction sector, highlighting the significance of prioritising awareness, education, training, and policy interventions. Through an in-depth exploration of this multifaceted issue, critical gaps and challenges within the industry have been brought to light. Employing a comprehensive approach that encompasses a thorough review of existing literature. Expert interviews and validation of proposed strategies with industry stakeholders, this study lays the foundation for fostering sustainable growth and development in the sector. The insights derived from this research offer invaluable guidance for policymakers, educational institutions, and industry practitioners, offering a clear pathway to effectively navigate and alleviate the skilled professional shortage while advancing sustainability goals within Indian construction practices. In this research, conclusions are drawn based on qualitative data and analysis methods. Therefore, future studies must be conducted using quantitative data analysis with effective sample sizes across different countries and industries. While the research may focus on awareness, education, training, and policy interventions, there may be insufficient analysis of how factors such as gender, caste, geographic location, and socio-economic status intersect with access to educational opportunities, training programs, and employment prospects in the construction sector.

6. REFERENCES

Aiyetan, O. A., & Dillip, D. (2018). System dynamics approach to mitigating skilled labour shortages in the construction industry : A South African context. *Construction Economics and Building*, *18*(4), 45-63, Retrieved from http://dx.doi.org/10.5130/AJCEB.v18i4.6041

Alshahrani, A., Alaboud, N., Leje, M. I., Karban, A., & Altowerqi, Z. (2023). Rating the significance of the factors influencing shortage of skilled laborers for sustainable construction: a perception of Makkah construction practitioner. *Journal of Umm Al-Qura University for Engineering and Architecture*, *14*(1), 13–25. Retrieved from https://doi.org/10.1007/s43995-023-00013-5

Bigelow, B. F., Saseendran, A., & Elliott, J. W. (2018). Attracting Students to construction education programs: An exploration of perceptions by gender. *International Journal of Construction Education and Research*, *14*(3), 179–197. Retrieved from https://doi.org/10.1080/15578771.2017.1280101

Chan, A. P. C., Darko, A., Olanipekun, A. O., & Ameyaw, E. E. (2018). Critical barriers to green building technologies adoption in developing countries: The case of Ghana. *Journal of Cleaner Production*, *172*, 1067–1079. Retrieved from https://doi.org/10.1016/j.jclepro.2017.10.235

Elbashbishy, T., & El-adaway, I. H. (2024). Skilled worker shortage across key labor-intensive construction trades in union versus nonunion environments. *Journal of Management in Engineering*, *40*(1), 1–18. Retrieved from https://doi.org/10.1061/jmenea.meeng-5649

Escamilla, E., Ostadalimakhmalbaf, M., & Bigelow, B. F. (2016). Factors impacting hispanic high school students and how best to reach them for the careers in the construction industry. *International Journal of Construction Education and Research*, *12*(2), 82–98. Retrieved from https://doi.org/10.1080/15578771.2015.1077296

Fathima, M. H., & Umarani, C. (2023). Fairness in human resource management practices and engineers' intention to stay in Indian construction firms. *Employee Relations*, *45*(1), 156–171. Retrieved from https://doi.org/10.1108/ER-07-2021-0308

Gaur, S., & Tawalare, A. (2022). Investigating the role of BIM in stakeholder management: Evidence from a metro-rail project. *Journal of Management in Engineering*, *38*(1). Retrieved from https://doi.org/10.1061/(ASCE)me.1943-5479.0000979

Gehlot, M., & Shrivastava, S. (2022). Sustainable construction Practices: A perspective view of Indian construction industry professionals. *Materials Today: Proceedings*, *61*, 315–319. Retrieved from https://doi.org/10.1016/j.matpr.2021.09.493

Giesekam, J., Barrett, J., Taylor, P., & Owen, A. (2014). The greenhouse gas emissions and mitigation options for materials used in UK construction. *Energy and Buildings*, *78*, 202–214. Retrieved from https://doi.org/10.1016/j.enbuild.2014.04.035

Ho, P. H. K. (2016). "Analysis of competitive environments, business strategies, and performance in hong kong's construction industry." *Jornal of Management Engineering*, 32 (2): 4015044. Retrieved from https://doi.org/10.1061/(ASCE)ME.1943-5479.0000399.

Karakhan, A. A., Nnaji, C. A., Gambatese, J. A., & Simmons, D. R. (2023). Best practice strategies for workforce development and sustainability in construction. *Practice Periodical on Structural Design and Construction*, *28* (1), 4022058. Retrieved from https://doi.org/10.1061/(ASCE)SC.1943-5576.0000746.

Kim, S., Chang, S., & Castro-Lacouture, D. (2020). Dynamic modeling for analyzing impacts of skilled labor shortage on construction project management. *Journal of Management in Engineering*, *36*(1), 1–13. Retrieved from https://doi.org/10.1061/(ASCE)me.1943-5479.0000720

Knight Frank & RICS. (2023). *Skilled employment in construction sector in India*. https://www.knightfrank.co.in/research

Koc, K., Gurgun, A. P., Ozbek, M. E., Kalan, D., Clevenger, C., & Omur-Ozbek, P. (2022). Comparative analysis of work-life balance perceptions of civil engineering students. *Journal of Civil Engineering Education*, *148*(2). Retrieved from https://doi.org/10.1061/(ASCE)ei.2643-9115.0000057

KPMG Advisory Services Pvt Ltd. (2013). *Human resource and skill requirements in the building, construction, and real-estate sector*. https://skillsip.nsdcindia.org/knowledge-products/human-resource-and-skill-requirements-building-construction-and-real-estate

Leech, N. L., & Onwuegbuzie, A. J. (2008). Qualitative data analysis: A compendium of techniques and a framework for selection for school psychology research and beyond. *School Psychology Quarterly*, *23*(4), 587–604. Retrieved from https://doi.org/10.1037/1045-3830.23.4.587

Ling, F. Y. Y., Leow, X. X., & Lee, K. C. (2016). Strategies for Attracting more construction-trained graduates to take professional jobs in the construction industry. *Journal of Professional Issues in Engineering Education and Practice*, *142*(1), 1–11. Retrieved from https://doi.org/10.1061/(ASCE)EI.1943-5541.0000256

Macherla, U. R. T. (2023). A survey study on challenges and factors affecting adopting sustainable construction methods in indian construction industry. *MATEC Web of Conferences*, *384*, 01004. https://doi.org/10.1051/matecconf/202338401004

Matar, M. M., Georgy, M. E., & Ibrahim, M. E. (2008). Sustainable construction management: Introduction of the operational context space (OCS). *Construction Management and Economics*, *26*(3), 261–275. Retrieved from https://doi.org/10.1080/01446190701842972

Mohd-Rahim, F. A., Mohd-Yusoff, N. S., Chen, W., Zainon, N., Yusoff, S., & Deraman, R. (2016). The challenge of labor shortage for sustainable construction. *Planning Malaysia Journal*, (5), 77–88. Retrieved from https://doi.org/10.21837/pmjournal.v14.i5.194

National Skill Development Corporation (2018), *Board's report and audited financial statement for the financial year 2018-19*. https://nsdcindia.org/annual-reports

Oke, A., Aigbavboa, C., & Khangale, T. (2018). Effect of skills shortage on sustainable construction. In *Advances in Human Factors, Sustainable Urban Planning and Infrastructure: Proceedings of the AHFE 2017 International Conference on Human Factors, Sustainable Urban Planning and Infrastructure, The Westin Bonaventure Hotel, Los Angeles, California, USA*, 17−21 July 2017. (pp. 303-309). Springer International Publishing. https://doi.org/10.1007/978-3-319-60450-3_29

Oke, A., Aigbavboa, C., & Khangale, T., (2018). Effect of skills shortage on sustainable construction. In J. Charytonowicz (Eds.), *Advances in Human Factors, Sustainable Urban Planning and*

Infrastructure, (303–309). Springer International Publishing. https://doi.org/10.1007/978-3-319-60450-3_29

Patil, N. A., & Laishram, B. S. (2016). Sustainability of Indian PPP procurement process. *Built Environment Project and Asset Management*, *6*(5), 491–507. Retrieved from https://doi.org/10.1108/BEPAM-09-2015-0043

Sing, M. C. P., Tam, V. W. Y. ; Fung, I. W. H., & Liu, H. J. (2017). Critical analysis of construction workforce sustainability in a developed economy case study in Hong Kong. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, *171* (7), 342–350. Retrieved from https://doi.org/https://doi.org/10.1680/jensu.17.00007.

Statista. (2023, May). *Number of employees in the real estate and construction sector in India from the financial year 2017 to the financial year 2023*. Statista. https://www.statista.com/statistics/1213080/india-employees-in-real-estate-and-construction-sector/

Welfare, K., Sherratt, F., & Hallowell, M. (2021). Perceptions of construction work: Views to consider to improve employee recruitment and retention. *Journal of Construction Engineering and Management, 147*(7), 1–11. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002057

Zhou, L., & Lowe, D. (2003). Economic challenge of sustainable construction. In D. Proverbs (Ed.), Proceedings of the RICS construction and building research conference, school of engineering and the built environment, Wolverhampton, 1-2 September 2003. (pp. 113-126). RICS Foundation.

Zuo, J., & Zhao, Z. Y. (2014). Green building research-current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, *30*, 271–281. Retrieved from https://doi.org/10.1016/j.rser.2013.10.021

Jayasinghe, J.D.S.S., Hadiwattege, C. and Ilangakoon, I.W.M.A.D., 2024. Addressing traditional HRM challenges in the construction industry: Insights from modern HRM Literature. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 92-104. DOI: https://doi.org/10.31705/WCS.2024.8. Available from: https://ciobwcs.com/papers/

ADDRESSING TRADITIONAL HRM CHALLENGES IN THE CONSTRUCTION INDUSTRY: INSIGHTS FROM MODERN HRM LITERATURE

J.D.S.S. Jayasinghe[1], C. Hadiwattege[2], and I.W.M.A.D. Ilangakoon[3]

ABSTRACT

The construction industry plays a pivotal role in the socio-economic development of any country. However, traditional Human Resource Management (HRM) practices within this sector face numerous challenges, including high labour turnover, skill shortages, and safety concerns, which adversely affect productivity and employee well-being. This study provides an extensive review of modern HRM literature designed to address these challenges towards enhancing organisational performance of the construction industry. The research methodology involved a comprehensive literature review spanning publications from 1990 to 2024, utilising search engines such as Scopus, Google Scholar, Emerald Insight, and Science Direct. The findings reveal that traditional HRM practices, characterised by their administrative focus and reactive approach, have led to significant issues in the construction sector. In contrast, modern HRM practices, which emphasise strategic alignment, employee engagement, continuous learning, and leveraging technology, offer viable solutions. Specifically, practices such as Strategic HRM (SHRM), agile HRM, and data-driven HRM are particularly effective in managing the industry's unique challenges, including workforce mobility, economic fluctuations, and the integration of new technologies. This study contributes to the existing body of knowledge by highlighting the potential of modern HRM practices to transform HRM in the construction industry. Future research should focus on empirically validating the impact of these practices on project performance and exploring innovative HRM strategies tailored to the sector's specific needs.

Keywords: *Construction Industry; Human Resources Management; Modern HRM Concepts; Overcoming HRM Challenges; Traditional HRM.*

1. INTRODUCTION

The construction industry is a major contributor of driving social and economic development in any country (Oke et al., 2019). Marked by its dynamic, project-based, and complex nature, (Srour et al., 2017), the sector also employs a spectrum of labour, including migrant, casual, and transient workers, alongside professional staff (Wilkinson

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, samadhijayasinghe123@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, chandanieh@uom.lk
[3] Junior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, ashinsanai@uom.lk

et al., 2012). Notably, Human Resource (HR) costs constitute a significant portion of total construction expenditure (Al-Hosani & Rashid, 2022).

Meanwhile, the industry's project-oriented complexity and tight schedules along with lengthy working hours, significantly impact employee well-being, both mentally and physically, alongside their job satisfaction, skill development, and work-life balance (Khan et al., 2022). Additionally, the construction industry continues to fall behind in HRM practices, technology adoption, and productivity growth (Kokkaew et al., 2022). However, efficient HRM is crucial for sustainable project outcomes (Othman et al., 2012).

The construction sector's dynamic, project-based structure poses challenges to traditional HRM practices, including poor productivity, skilled labour shortages, and occupational health risks (Fortune et al., 2022; Marambage & Maduwansha, 2021; Yankov & Kleiner, 2001). Moreover, aligning organisational objectives with existing HRM capabilities remains a critical challenge, necessitating innovative strategies to address evolving industry demands (Uzoamaka et al., 2021; Yankov & Kleiner, 2001). Despite these challenges, the construction industry's adaptability facilitates the integration of innovative HRM concepts, emphasising an employee-centric approach to mitigate existing challenges (Lyngnes, 2024). In recent years, there has been a growing recognition that enhancing HRM performance is essential for improving efficiency, productivity, and cost-effectiveness in the construction industry (Fortune et al., 2022).

Modern HRM in construction emphasises strategic workforce management to enhance project performance, focusing on employee welfare and organisational goals (Wilkinson et al., 2012), with research yet to fully elucidate the precise impact of modern HRM practices on project performance (Chapano et al., 2018). Moreover, HRM aligns with most of the key success factors in construction, including efficiency enhancement, professionalism elevation, and procurement strategy improvement (Al-Hosani & Rashid, 2022). Hence, an effective HRM framework would elevate employee involvement and dedication towards an intended output, by addressing their concerns such as work-life balance, while focusing on the organisational reputation and resource utilisation (Al-Hosani & Rashid, 2022).

Despite the critical role of HRM in the construction industry, there is limited understanding of how modern HRM practices can effectively address the challenges posed by traditional HRM approaches. This gap in knowledge highlights the need for a deeper exploration of contemporary HRM strategies to enhance their application in this sector. In this context, this paper aims to explore the application of modern HRM practices in overcoming the challenges associated with traditional HRM practices in the construction industry. By conducting a comprehensive literature review and synthesising existing research and insights, this study seeks to offer valuable recommendations for practitioners, researchers, and policymakers to improve HRM practices within the construction sector.

2. RESEARCH METHODOLOGY

An extensive body of literature delves into the historical development of a subject and studies the key themes to deepen the significance of the study (Saunders et al., 2023). Snyder (2019) further elaborates on this, stating that a comprehensive literature synthesis aids in establishing the theoretical roots of a study. Hence, to obtain a thorough grasp of the challenges of traditional HRM in the construction industry and the modern HRM strategies to address them, the findings of a literature analysis served as the foundation for this paper.

A comprehensive literature review was conducted by referring to books, reports, theses, journals, and conference proceedings to identify the concept of traditional HRM, the issues of traditional HRM in the construction industry, and the applicable modern HRM strategies to overcome them. The literature review included publications from 1990 to 2023 to ensure a broad and historical perspective on HRM practices in the construction industry. To compile a comprehensive literature synthesis, search terms such as 'Traditional Human Resources Management Practices in Construction Industry', and 'Challenges of Traditional Human Resources Management in Construction', 'Modern Human Resource Management Practices', 'Trends of Human Resource Management in Construction Industry' were filtered using the available search engines including 'Scopus', 'Google Scholar', 'Emerald Insight', and 'Science Direct'.

3. FINDINGS AND DISCUSSION

3.1 TRADITIONAL HRM IN THE CONSTRUCTION INDUSTRY

Traditional HRM, often referred to as personnel management, has been the foundation of HR operations for decades (Torrington et al., 2017). Traditional HRM practices are typically characterised by, (i) their administrative focus dealing with day-to-day operations rather than long-term strategic goals (Torrington et al., 2017), (ii) reactive approach to managing people (Kramar, 2014), (iii) hierarchical organisational structure with a strong emphasis on adherence to policies and procedures (Storey, 2006), and (iv) limited employee development focusing on job-specific skills and mandator safety training rather than broader professional development hindering long-term career growth and employee satisfaction (Tharenou et al., 2007).

Similarly in the construction industry, these practices often emphasise administrative functions, focusing on compliance and labour relations, with minimal strategic alignment (Bukhari et al., 2021). These practices typically involve 'hard' HRM models that prioritise control, cost efficiency, and task-oriented management, particularly for manual workers (Druker et al., 1996). Traditional approaches are characterised by reactive and opportunistic pragmatism, showing little strategic integration with corporate objectives (Duberley & Walley, 1995).

However, traditional HRM challenges exert both beneficial and detrimental effects on the global construction industry (Akomah et al., 2020). Renowned for its complexity (Fortune et al., 2022) and project-based structure, the construction sector demands workforce flexibility and extensive subcontracting, posing numerous challenges for HRM and employment relations (Wilkinson et al., 2012). Thus, HRM activities encounter significant obstacles, including high labour costs, lack of permanent staff, skill shortages, reliance on ad hoc labourers, funding inconsistencies, and inadequate management policy frameworks (Fortune et al., 2022). Table 2 further demonstrates the literature findings on challenges and issues of traditional HRM in the construction industry.

3.2 MODERN HRM CONCEPTS

The construction industry has traditionally relied on conventional HRM practices; however, there is increasing recognition of the need to adopt modern HRM approaches to address contemporary challenges (Stone et al., 2015). The transition involves a cultural shift towards recognising the strategic value of HR, investing in employee development, and leveraging technology to enhance HRM functions (Wright & Nishii, 2007).

Modern HRM practices integrate strategic elements to enhance organisational performance and employee development (Boselie et al., 2005). These practices are often derived from 'soft' HRM models that emphasise employee motivation, development, and well-being (Druker et al., 1996). This paradigm shift reflects the growing recognition of employees as key assets and a source of competitive advantage (Guest, 2011). Thus, modern HRM is characterised by; (i) the strategic alignment of HRM with organisational objectives (Boselie et al., 2005), (ii) proactive and transformational approach that fosters innovation and adaptability (Guest, 2011), (iii) recognition of employee engagement and empowerment (Alfes et al., 2013), (iv) commitment to continuous learning and development including leadership development, cross-functional training, and personal development opportunities (Noe, 2010), and (v) leveraging technology and analytics to optimise HRM processes and improve decision-making (Marler & Fisher, 2013). Table 1 sets forth a summary of literature findings on several modern HRM concepts identified.

Table 1: Modern HRM concepts

No.	Modern HRM Concept	Reference
01.	Strategic HRM (SHRM)	[1], [2], [3]
02.	Employee engagement and well-being	[4], [5], [6], [7], [8]
03.	Talent management	[9], [10], [11]
04.	Diversity and inclusion	[12], [13]
05.	Agile HRM	[14], [15]
06.	Performance management	[16], [17], [18]
07.	Learning and development (L&D)	[19], [20], [21]
08.	HR analytics and data-driven HRM	[22], [23], [24], [25], [26]
09.	Employer branding	[27], [28], [29]
10.	Change management	[30], [31]
11.	Corporate social responsibility (CSR)	[32], [33]
12.	Technology and HRM (HR tech)	[34], [35], [36], [37], [38]
13.	Workforce planning and succession planning	[24], [25], [39]
14.	Employee empowerment and participation	[40], [41], [42],
15.	Smart HRM	[23], [43]
16.	Sustainable HRM	[44], [45], [46], [47]
17.	Psychological safety	[5], [48]

[1] (Wright & McMahan, 1992), [2] (Boxall & Purcell, 2003), [3] (Delery & Doty, 1996), [4] (Schaufeli & Bakker, 2004), [5] (Kahn, 1990), [6] (Harter et al., 2002), [7] (Morgan, 2017), [8] (Leblebici, 2012), [9] (Collings & Mellahi, 2009), [10] (Lewis & Heckman, 2006), [11] (Cappelli, 2009), [12] (Cox, 1993), [13] (Roberson, 2006), [14] (Dikert et al., 2016), [15] (Denning, 2016), [16] (Aguinis, 2019), [17] (Denisi & Pritchard, 2006), [18] (Armstrong, 2014), [19] (Noe, 2010), [20] (Aguinis & Kraiger, 2009), [21] (Swanson & Holton, 2009), [22] (Bassi, 2011), [23] (Marler & Boudreau, 2017), [24] (Kavanagh et al., 2012), [25] (Hendrickson, 2003), [26] (Bondarouk & Ruël, 2013), [27] (Backhaus & Tikoo, 2004),

[28] (Berthon et al., 2005), [29] (Ambler & Barrow, 1996), [30] (Kotter, 2009), [31] (Burnes, 2004), [32] (Carroll, 1999), [33] (McWilliams & Siegel, 2001), [34] (Parry & Tyson, 2011), [35] (Bondarouk & Ruël, 2009), [36] (Strohmeier, 2009), [37] (Stone et al., 2015), [38] (Marler & Fisher, 2013), [39] (Rothwell, 2010), [40] (Huselid, 1995), [41] (Spreitzer, 1995), [42] (Becker & Huselid, 2006), [43] (Tambe et al., 2019), [44] (Ehnert & Harry, 2012), [45] (Jabbour & Santos, 2008), [46] (Renwick et al., 2013), [47] (Jackson et al., 2011), [48] (Edmondson, 1999)

Correspondingly, modern HRM in construction aims to address the industry's specific challenges, such as project-based work environments and the need for flexibility in managing multiple forms of employment (Raja et al., 2013). Recent studies indicate that modern HRM practices focus on comprehensive frameworks that include leadership development, employee engagement, and strategic alignment of HR policies with business goals (Bukhari et al., 2021). These practices improve employee satisfaction and enhance organisational competitiveness and project performance (Ling et al., 2018). They help construction firms attract and retain high-potential talent, ensuring balanced growth and long-term success (Rajhans & Bhavsar, 2023).

3.3 CHALLENGES OF TRADITIONAL HRM IN THE CONSTRUCTION INDUSTRY

In response to the myriad challenges faced by the construction industry concerning traditional HRM practices, Duke II and Udono (2012) argue that effective HRM now requires new attitudes, perspectives, and competencies geared towards fostering creativity and innovation within organisations. Table 2 presents a summary of literature findings on the challenges encountered by traditional HRM practices in the construction industry and the strategies provided by modern HRM practices to address them.

Table 2: Modern HRM strategies to address traditional HRM challenges in the construction industry

No.	Challenge of Traditional HRM Practices		Modern HRM Solution	
01.	High labour turnover and workforce mobility	[1], [2]	SHRM	[1], [2]
02.	Skill shortages and workforce ageing	[3]	L & D	[3], [7]
			HR analytics and data-driven HRM	[21], [22]
03.	Safety and health concerns	[4]	Agile HRM	[4]
			Psychological safety	[23]
04.	Seasonal and economic fluctuations	[5]	SHRM	[5], [6]
05.	A diverse and transient workforce	[2]	Diversity and inclusion	[2], [24]
06.	Lack of training and development	[6]	L&D	[6], [25], [26]
07.	Inadequate workforce planning	[7]	HR analytics and data-driven HRM	[7], [21]
08.	Resistance to change	[8]	Change management	[8], [27], [28]
09.	Compliance with labour laws and regulations	[9]	SHRM	[1], [9]
10.	Communication barriers	[10]	Employee engagement and well-being	[10], [29]
11.	Project-based nature of work	[11]	Agile HRM	[3], [11]

No.	Challenge of Traditional HRM Practices		Modern HRM Solution	
12.	Financial constraints	[12]	CSR	[12], [30]
13.	Integration of new technologies	[13]	HR tech	[13], [31], [32]
14.	Reliance on subcontractors and temporary labour	[14]	Employee empowerment and participation	[14], [33]
15.	Talent retention	[15], [16], [17], [18], [19], [20]	Talent management	[15], [34], [35]

[1] (Raja et al., 2013), [2] (Bukhari et al., 2021), [3] (Raiden et al., 2004), [4] (Harvey et al., 2019), [5] (Srivastava & Agarwal, 2012), [6] (Pató et al., 2022), [7] (Abanda et al., 2017), [8] (Demirkesen & Tezel, 2021), [9] (Olawumi et al., 2018), [10] (Porwal & Hewage, 2013), [11] (Söderlund & Bredin, 2006), [12] (Shah & Sankar, 2013), [13] (Evans & Farrell, 2020), [14] (Vass & Gustavsson, 2017), [15] (Rajhans & Bhavsar, 2023), [16] (Phua, 2012), [17] (Kokkaew et al., 2022), [18] (Srour et al., 2017), [19] (Hongmin & Yanbing, 2011), [20] (Thompson, 2011), [21] (Kavanagh et al., 2012), [22] (Bassi, 2011), [23] (Edmondson, 1999), [24] (Cox, 1993), [25] (Noe, 2010), [26] (Aguinis & Kraiger, 2009), [27] (Kotter, 2009), [28] (Burnes, 2004), [29] (Schaufeli & Bakker, 2004), [30] (Carroll, 1999), [31] (Parry & Tyson, 2011), [32] (Bondarouk & Ruël, 2009), [33] (Huselid, 1995),[34] (Collings & Mellahi, 2009), [35] (Lewis & Heckman, 2006)

As illustrated by Table 2, the construction industry faces numerous challenges stemming from traditional HRM practices, which often lead to high labour turnover, workforce mobility, and skill shortages. High labour turnover and workforce mobility cause instability and increased recruitment costs (Bukhari et al., 2021; Raja et al., 2013). SHRM can address these challenges by aligning HRM practices with organisational goals, thereby enhancing employee retention and stability (Bukhari et al., 2021; Raja et al., 2013). Simultaneously, skill shortages and an ageing workforce complicate the landscape, causing delays and increased costs (Raiden et al., 2004). Implementing L&D programmes can mitigate these issues by continuously upgrading the skills of the workforce, while HR analytics can provide data-driven insights to identify and fill skill gaps (Abanda et al., 2017; Bassi, 2011; Kavanagh et al., 2012; Raiden et al., 2004). Additionally, compliance with labour laws and regulations requires significant administrative effort and can lead to legal challenges if not managed properly (Olawumi et al., 2018). SHRM can streamline compliance by integrating legal requirements into strategic HR planning, thereby reducing the risk of non-compliance (Olawumi et al., 2018; Raja et al., 2013).

Safety and health concerns due to the hazardous nature of construction work result in project delays and legal liabilities (Harvey et al., 2019). Agile HRM and fostering a culture of psychological safety can improve workplace safety by promoting adaptive, responsive HR practices and ensuring that employees feel safe to report hazards (Edmondson, 1999; Harvey et al., 2019). In addition, the project-based nature of construction work necessitates the rapid formation and disbanding of teams, which can disrupt team cohesion and knowledge transfer (Söderlund & Bredin, 2006). Agile HRM practices can address this by promoting flexibility and adaptability in team management (Raiden et al., 2004; Söderlund & Bredin, 2006). Furthermore, seasonal and economic fluctuations present another challenge, leading to unstable employment and workforce planning difficulties (Srivastava & Agarwal, 2012). SHRM can help organisations better navigate these fluctuations by integrating long-term strategic planning with HRM practices (Pató et al., 2022; Srivastava & Agarwal, 2012). Moreover, financial constraints often limit investment in employee development and retention strategies (Shah & Sankar, 2013). CSR initiatives can provide a framework for investing in employee well-being and sustainable practices, thereby enhancing organisational reputation and employee loyalty (Carroll, 1999; Shah & Sankar, 2013).

Managing a diverse and transient workforce requires effective communication and coordination (Bukhari et al., 2021). Emphasising diversity and inclusion can create a more cohesive and collaborative work environment, improving team dynamics and productivity (Bukhari et al., 2021; Cox, 1993). Moreover, communication barriers among various stakeholders can lead to misunderstandings, errors, and project delays (Porwal & Hewage, 2013). Fostering employee engagement and well-being can enhance communication and collaboration, ensuring that all team members are aligned with project goals (Porwal & Hewage, 2013; Schaufeli & Bakker, 2004). Alongside this, lack of training and development affects productivity and innovation (Pató et al., 2022). Implementing robust L&D programmes can ensure continuous skill development and career growth opportunities for employees, leading to higher engagement and retention (Aguinis & Kraiger, 2009; Noe, 2010; Pató et al., 2022). Moreover, resistance to change is a pervasive issue in the construction industry, hindering the adoption of modern HRM practices and technologies (Demirkesen & Tezel, 2021). However, effective change management strategies, such as those proposed by Kotter (2009) and Burnes (2004), can facilitate smoother transitions by involving all stakeholders in the change process and addressing resistance proactively.

The integration of new technologies such as BIM and lean construction is another challenge due to the traditional practices prevalent in the industry (Evans & Farrell, 2020). Embracing Technology and HRM can facilitate the adoption of these technologies, improving efficiency and project outcomes (Bondarouk & Ruël, 2009; Evans & Farrell, 2020; Parry & Tyson, 2011). In addition, reliance on subcontractors and temporary labour forces complicates the enforcement of consistent HRM practices (Vass & Gustavsson, 2017). Empowering employees and promoting participation can enhance commitment and consistency across the workforce (Huselid, 1995; Vass & Gustavsson, 2017). Lastly, talent retention is a significant challenge due to the competitive and transient nature of the construction industry (Rajhans & Bhavsar, 2023). Effective talent management strategies can help attract, develop, and retain skilled workers, ensuring that the organisation remains competitive and capable of meeting its project demands (Collings & Mellahi, 2009; Lewis & Heckman, 2006; Rajhans & Bhavsar, 2023).

4. CONCLUSIONS AND WAY FORWARD

This comprehensive literature review has explored the challenges associated with traditional HRM practices in the construction industry and the potential solutions offered by modern HRM strategies. The findings indicate that traditional HRM practices, characterised by administrative focus, reactive approaches, and limited employee development, have resulted in significant issues such as high labour turnover, skill shortages, safety concerns, lack of training and development, and talent retention. These challenges have hindered productivity and employee well-being in the construction sector. Modern HRM practices, which emphasise strategic alignment, employee engagement, continuous learning, and leveraging technology, offer viable solutions to these challenges. SHRM, agile HRM, and data-driven HRM are particularly effective in addressing the industry's specific needs, such as managing a transient workforce, ensuring safety, and navigating economic fluctuations. By integrating such modern HRM practices, construction firms can enhance organisational performance, improve employee satisfaction, and achieve better project outcomes.

Thus, this study has provided a comprehensive overview of the application of modern HRM practices within the construction industry to address the challenges of traditional HRM. Future research should focus on empirically validating the impact of these practices on construction project performance and exploring innovative HRM strategies tailored to the industry's unique challenges, which would further benefit the sector.

5. REFERENCES

Abanda, F. H., Tah, J. H. M., & Cheung, F. K. T. (2017). BIM in off-site manufacturing for buildings. *Journal of Building Engineering*, *14*, 89–102. doi:10.1016/j.jobe.2017.10.002

Aguinis, H. (2019). *Performance management* (3rd ed.). John Wiley & Sons, Inc. Rretrieved from https://vulms.vu.edu.pk/Courses/HRM713/Downloads/Performance%20Management%203rd%20Edition%20by%20Aguinis.pdf.

Aguinis, H., & Kraiger, K. (2009). Benefits of training and development for individuals and teams, organizations, and society. *Annual Review of Psychology*, *60*(1), 451–474. doi:10.1146/annurev.psych.60.110707.163505

Akomah, B. B., Ahinaquah, L. K., & Mustapha, Z. (2020). Skilled labour shortage in the building construction industry within the central region. *Baltic Journal of Real Estate Economics and Construction Management*, *8*(1), 83–92. doi:10.2478/bjreecm-2020-0006

Alfes, K., Truss, C., Soane, E. C., Rees, C., & Gatenby, M. (2013). The relationship between line manager behavior, perceived HRM practices, and individual performance: Examining the mediating role of engagement. *Human Resource Management*, *52*(6), 839–859. doi:10.1002/hrm.21512

Al-Hosani, A. E. Y., & Rashid, N. B. A. (2022). Conceptual framework of sustainable green human resource management (SGHRM) and its effect on sustainability in green building. *Journal of Tianjin University Science and Technology, 55*(4), 562-575. doi:10.17605/OSF.IO/5DRXF

Ambler, T., & Barrow, S. (1996). The employer brand. *Journal of Brand Management*, *4*(3), 185–206. doi:10.1057/bm.1996.42

Armstrong, M. (2014). *Armstrong's handbook of performance management: An evidence-based guide to delivering high performance* (13th ed.). Ashford Colour Press Ltd. Retrieved from https://nibmehub.com/opac-service/pdf/read/Armstrong's%20Handbook%20of%20Human%20Resource%20Management%20Practice.pdf

Backhaus, K., & Tikoo, S. (2004). Conceptualizing and researching employer branding. *Career Development International*, *9*(5), 501–517. doi:10.1108/13620430410550754

Bassi, L. (2011). Raging debates in HR analytics. *People and Strategy*, *34*(2), 14–18. Retrieved from https://mcbassi.com/wp/wp-content/uploads/2018/06/RagingDebatesInHRAnalytics.pdf

Becker, B. E., & Huselid, M. A. (2006). Strategic human resources management: Where do we go from here? *Journal of Management*, *32*(6), 898–925. doi:10.1177/0149206306293668

Berthon, P., Ewing, M., & Hah, L. L. (2005). Captivating company: Dimensions of attractiveness in employer branding. *International Journal of Advertising*, *24*(2), 151–172. doi:10.1080/02650487.2005.11072912

Bondarouk, T., & Brewster, C. (2016). Conceptualising the future of HRM and technology research. *The International Journal of Human Resource Management*, *27*(21), 2652–2671. doi:10.1080/09585192.2016.1232296

Bondarouk, T., & Ruël, H. (2013). The strategic value of e-HRM: Results from an exploratory study in a governmental organization. *The International Journal of Human Resource Management*, *24*(2), 391–414. doi:10.1080/09585192.2012.675142

Bondarouk, T. V., & Ruël, H. J. M. (2009). Electronic human resource management: Challenges in the digital era. *The International Journal of Human Resource Management*, *20*(3), 505–514. doi:10.1080/09585190802707235

Boselie, P., Dietz, G., & Boon, C. (2005). Commonalities and contradictions in research on human resource management and performance. *Human Resource Management Journal*, *15*(3), 67–94. doi:10.1111/j.1748-8583.2005.tb00154.x

Boxall, P., & Purcell, J. (2003). Strategy and human resource management. *Management Decision*, *57*(1), 523–524. doi:10.1108/00251740310479368

Bukhari, H., Musarat, M. A., Alaloul, W., & Altaf, M. (2021). Human resource management (HRM) practices in construction organizations: A review. *International Review of Civil Engineering (IRECE)*, *12*(4), 255–263. doi:10.15866/irece.v12i4.18848

Burnes, B. (2004). Kurt Lewin and the planned approach to change: A re-appraisal. *Journal of Management Studies*, *41*(6), 977–1002. doi:10.1111/j.1467-6486.2004.00463.x

Cappelli, P. (2009). Talent on demand – Managing talent in an age of uncertainty. *Strategic Direction*, *25*(3). doi:10.1108/sd.2009.05625cae.001

Carroll, A. B. (1999). Corporate social responsibility: Evolution of a definitional construct. *Business & Society*, *38*(3), 268–295. doi:10.1177/000765039903800303

Chapano, M., Iwu, C. G., & Twum-Darko, M. (2018). The impact of high performance work practices on project performance. A case study of construction companies in South Africa. *Œconomica, 14*(1), 45-59. Retrieved from http://digitalknowledge.cput.ac.za/handle/11189/6526

Collings, D. G., & Mellahi, K. (2009). Strategic talent management: A review and research agenda. *Human Resource Management Review*, *19*(4), 304–313. doi:10.1016/j.hrmr.2009.04.001

Cox, T. (1993). *Cultural diversity in organizations: Theory, research & practice*. Berrett-Koehler publ.

Delery, J. E., & Doty, D. H. (1996). Modes of theorizing in strategic human resource management: Tests of universalistic, contingency, and configurations performance predictions. *Academy of Management Journal*, *39*(4), 802–835. Retrieved from https://arwana007.wordpress.com/wp-content/uploads/2012/02/modes-of-theorizing-in-shrm.pdf

Demirkesen, S., & Tezel, A. (2021). Investigating major challenges for industry 4.0 adoption among construction companies. *Engineering, Construction and Architectural Management*, *29*(3), 1470-1503. doi:10.1108/ECAM-12-2020-1059

Denisi, A. S., & Pritchard, R. D. (2006). Performance appraisal, performance management and improving individual performance: A motivational framework. *Management and Organization Review*, *2*(2), 253–277. doi:10.1111/j.1740-8784.2006.00042.x

Denning, S. (2016). Agile's ten implementation challenges. *Strategy & Leadership*, *44*(5), 15–20. doi:10.1108/SL-08-2016-0065

Dikert, K., Paasivaara, M., & Lassenius, C. (2016). Challenges and success factors for large-scale agile transformations: A systematic literature review. *Journal of Systems and Software*, *119*, 87–108. doi:10.1016/j.jss.2016.06.013

Druker, J., White, G., Hegewisch, A., & Mayne, L. (1996). Between hard and soft HRM: Human resource management in the construction industry. *Construction Management and Economics*, *14*(5), 405–416. doi:10.1080/014461996373278

Duberley, J. P., & Walley, P. (1995). Assessing the adoption of HRM by small and medium-sized manufacturing organizations. *The International Journal of Human Resource Management*, *6*(4), 891–909. doi:10.1080/09585199500000052

Duke II, J. E., & Udono, E. N. (2012). A new paradigm in traditional human resource management practices. *Journal of Management and Sustainability*, *2*(2), 158-162. doi:10.5539/jms.v2n2p158

Edmondson, A. (1999). Psychological safety and learning behavior in work teams. *Administrative Science Quarterly*, *44*(2), 350–383. doi:10.2307/2666999

Ehnert, I., & Harry, W. (2012). Recent developments and future prospects on sustainable human resource management: Introduction to the special issue. *Management Revue*, *23*(3), 221–238. doi:10.5771/0935-9915-2012-3-221

Evans, M., & Farrell, P. (2020). Barriers to integrating building information modelling (BIM) and lean construction practices on construction mega-projects: A Delphi study. *Benchmarking: An International Journal*, *28*(2), 652–669. doi:10.1108/BIJ-04-2020-0169

Fortune, N. C., Udobi, D. A. N., & Chisom, N. C. (2022). Evaluation of the challenges of human resource management practices in construction companies in Awka South, Anambra State. *IRE Journals*, *5*(8), 209-220. Retrieved from https://www.irejournals.com/formatedpaper/1703210.pdf

Guest, D. E. (2011). Human resource management and performance: Still searching for some answers: Human resource management and performance. *Human Resource Management Journal*, *21*(1), 3–13. doi:10.1111/j.1748-8583.2010.00164.x

Harter, J. K., Schmidt, F. L., & Hayes, T. L. (2002). Business-unit-level relationship between employee satisfaction, employee engagement, and business outcomes: A meta-analysis. *Journal of Applied Psychology*, *87*(2), 268–279. doi:10.1037/0021-9010.87.2.268

Harvey, E. J., Waterson, P., & Dainty, A. R. J. (2019). Applying HRO and resilience engineering to construction: Barriers and opportunities. *Safety Science*, *117*, 523–533. doi:10.1016/j.ssci.2016.08.019

Hendrickson, A. R. (2003). Human resource information systems: Backbone technology of contemporary human resources. *Journal of Labor Research*, *24*(3), 381–394. doi:10.1007/s12122-003-1002-5

Hongmin, L. & Yanbing, D. (2011). Research in HRM of small and medium-sized construction enterprises. In *International conference on business management and electronic information (BMEI)*, *The United* States, 13-15 May 2011. (pp.190–193). doi:10.1109/ICBMEI.2011.5920426

Huselid, M. A. (1995). The impact of human resource management practices on turnover, productivity, and corporate financial performance. *Academy of Management Journal*, *38*(3), 635–672. doi:10.2307/256741

Jabbour, C. J. C., & Santos, F. C. A. (2008). Relationships between human resource dimensions and environmental management in companies: Proposal of a model. *Journal of Cleaner Production*, *16*(1), 51–58. doi:10.1016/j.jclepro.2006.07.025

Jackson, S. E., Renwick, D. W. S., Jabbour, C. J. C., & Muller-Camen, M. (2011). State-of-the-art and future directions for green human resource management: Introduction to the special issue. *German Journal of Human Resource Management*, *25*(2), 99–116. doi:10.1177/239700221102500203

Kahn, W. A. (1990). Psychological conditions of personal engagement and disengagement at work. *Academy of Management Journal*, *33*(4), 692–724. doi:10.2307/256287

Kavanagh, M. J., Thite, M., & Johnson, R. D. (Eds.). (2012). *Human resource information systems: Basics, applications, and future directions* (2^{nd} ed.). Sage. Retrieved from https://www.researchgate.net/publication/277249737_Thite_M_Kavanagh_MJ_Johnson_R_D_2012_Evolution_of_human_resource_management_human_resource_information_systems_The_role_of_information_technology_In_Kavanagh_MJ_Thite_M_Johnson_R_D_Eds_Human_Resource_

Khan, A. N., Khan, N. A., & Soomro, M. A. (2022). The impact of moral leadership on construction employees' psychological behaviors. *IEEE Transactions on Engineering Management*, *69*(6), 2817–2825. doi:10.1109/TEM.2020.3020371

Kokkaew, N., Peansupap, V., & Jokkaw, N. (2022). An empirical examination of knowledge management and organizational learning as mediating variables between HRM and sustainable organizational performance. *Sustainability*, *14*(20), 13351. doi:10.3390/su142013351

Kotter, J. P. (2009, September). Leading change: Why transformation efforts fail. *IEEE Engineering Management Review*, *37*(3), pp. 42-48. Retrieved from https://typeset.io/papers/leading-change-why-transformation-efforts-fail-53ve8fhtey

Kramar, R. (2014). Beyond strategic human resource management: Is sustainable human resource management the next approach? *The International Journal of Human Resource Management*, *25*(8), 1069–1089. doi:10.1080/09585192.2013.816863

Leblebici, D. (2012). Impact of workplace quality on employee's productivity: Case study of a bank in Turkey. *Journal of Business, Economics, & Finance*, *1*(1), 38-49. Retrieved from https://dergipark.org.tr/tr/download/article-file/374627

Lewis, R. E., & Heckman, R. J. (2006). Talent management: A critical review. *Human Resource Management Review*, *16*(2), 139–154. doi:10.1016/j.hrmr.2006.03.001

Ling, F. Y. Y., Ning, Y., Chang, Y. H., & Zhang, Z. (2018). Human resource management practices to improve project managers' job satisfaction. *Engineering, Construction and Architectural Management*, *25*(5), 654–669. doi:10.1108/ECAM-02-2017-0030

Lyngnes, A. M. (2024). *Building and Construction: Understanding the Employee-centric Organization*. Retrieved from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://landfcg.com/wp-content/uploads/Building-and-Construction.pdf

Marambage, H. M. B. P., & Maduwansha, N. A. N. J. (2021). Factors affecting work-life balance of construction industries' site workers in Colombo District, Sri Lanka (with special reference to Acces Engineering plc.) *International Journal of Arts and Commerce*, *10*(6), 29–40. Retrieved from https://www.academia.edu/66194344/Factors_Affecting_Work_Life_Balance_of_Construction_Industries_Site_workers_in_Colombo_District_Sri_Lanka_With_Special_Reference_to_Acces_Engineering_plc_

Marler, J. H., & Boudreau, J. W. (2017). An evidence-based review of HR analytics. *The International Journal of Human Resource Management*, *28*(1), 3–26. doi:10.1080/09585192.2016.1244699

Marler, J. H., & Fisher, S. L. (2013). An evidence-based review of e-HRM and strategic human resource management. *Human Resource Management Review*, *23*(1), 18–36. doi:10.1016/j.hrmr.2012.06.002

McWilliams, A., & Siegel, D. (2001). Corporate social responsibility: A theory of the firm perspective. *The Academy of Management Review*, *26*(1), 117. doi:10.2307/259398

Morgan, J. (2017). *The employee experience advantage: How to win the war for talent by giving employees the workspaces they want, the tools they need, and a culture they can celebrate*. Wiley. Retrieved from https://www.perlego.com/book/992031/the-employee-experience-advantage-how-to-win-the-war-for-talent-by-giving-employees-the-workspaces-they-want-the-tools-they-need-and-a-culture-they-can-celebrate

Noe, R. A. (2010). *Employee training and development* (5th ed.). McGraw-Hill Education. Retrieved from https://dedi1968blog.wordpress.com/wp-content/uploads/2018/04/employee-training-and-development.pdf

Oke, A., Aghimien, D., Aigbavboa, C., & Musenga, C. (2019). Drivers of sustainable construction practices in the Zambian construction industry. *Energy Procedia*, *158*, 3246-3252. doi:10.1016/j.egypro.2019.01.995

Olawumi, T. O., Chan, D. W. M., Wong, J. K. W., & Chan, A. P. C. (2018). Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts. *Journal of Building Engineering*, *20*, 60–71. doi:10.1016/j.jobe.2018.06.017

Othman, I., Idrus, A., & Napiah, M. (2012). Human resource management in the construction of a sustainable development project: Towards successful completion. *Environmental Impact*, *162*, 169-180. doi:10.2495/EID120161

Parry, E., & Tyson, S. (2011). Desired goals and actual outcomes of e-HRM: E-HRM goals and outcomes. *Human Resource Management Journal*, *21*(3), 335–354. doi:10.1111/j.1748-8583.2010.00149.x

Pató, B. Sz. G., Kovács, K., & Abonyi, J. (2022). Challenges of the fourth industrial revolution in HRM: *International Journal of Human Capital and Information Technology Professionals*, *13*(1), 1–14. doi:10.4018/IJHCITP.300308

Phua, F. T. T. (2012). Do national cultural differences affect the nature and characteristics of HRM practices? Evidence from Australian and Hong Kong construction firms on remuneration and job autonomy. *Construction Management and Economics*, *30*(7), 545–556. doi:10.1080/01446193.2012.682074

Porwal, A., & Hewage, K. N. (2013). Building information modeling (BIM) partnering framework for public construction projects. *Automation in Construction*, *31*, 204–214. doi:10.1016/j.autcon.2012.12.004

Raiden, A. B., Dainty, A. R. J., & Neale, R. H. (2004). Current barriers and possible solutions to effective project team formation and deployment within a large construction organisation. *International Journal of Project Management*, *22*(4), 309–316. doi:10.1016/j.ijproman.2003.08.002

Raja, J. Z., Green, S. D., Leiringer, R., Dainty, A., & Johnstone, S. (2013). Managing multiple forms of employment in the construction sector: Implications for HRM. *Human Resource Management Journal*, *23*(3), 313–328. doi:10.1111/j.1748-8583.2012.00202.x

Rajhans, K., & Bhavsar, V. (2023). Impending need of sustainable human resource management practices in construction industry: Evidence from India. *International Journal of Construction Management*, *23*(13), 2249–2259. doi:10.1080/15623599.2022.2050569

Renwick, D. W. S., Redman, T., & Maguire, S. (2013). Green human resource management: A review and research agenda. *International Journal of Management Reviews*, *15*(1), 1–14. doi:10.1111/j.1468-2370.2011.00328.x

Roberson, Q. M. (2006). Disentangling the meanings of diversity and inclusion in organizations. *Group & Organization Management*, *31*(2), 212–236. doi:10.1177/1059601104273064

Rothwell, W. J. (2010). *Effective succession planning: Ensuring leadership continuity and building talent from within* (4th ed.). Amacom: American Management Association. Retrieved from https://hcmindonesia.wordpress.com/wp-content/uploads/2012/12/9b-successionplanhandbook.pdf

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2023). *Research methods for business students* (9th Edition). Pearson. Retrieved from https://www.pearson.com/en-au/media/gnqjwj0v/9781292402727_sample.pdf

Schaufeli, W. B., & Bakker, A. B. (2004). Job demands, job resources, and their relationship with burnout and engagement: A multi-sample study. *Journal of Organizational Behavior*, *25*(3), 293–315. doi:10.1002/job.248

Shah, S., & Sankar, R. N. A. (2013). Human resource management in the changing business environment of the Indian construction industry: A case study. *Emerald Emerging Markets Case Studies*, *3*(6), 1–17. doi:10.1108/EEMCS-05-2012-0095

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. doi:10.1016/j.jbusres.2019.07.039

Söderlund, J., & Bredin, K. (2006). HRM in project-intensive firms: Changes and challenges. *Human Resource Management*, *45*(2), 249–265. doi:10.1002/hrm.20107

Spreitzer, G. M. (1995). Psychological, empowerment in the workplace: Dimensions, measurement and validation. *Academy of Management Journal*, *38*(5), 1442–1465. doi:10.2307/256865

Srivastava, E., & Agarwal, N. (2012). The emerging challenges in HRM. *International Journal of Scientific & Technology Research* *1*(6), 46–48. Retrieved from https://www.slideshare.net/slideshow/theemergingchallengesinhrm/52981750

Srour, F. J., Srour, I., & Lattouf, M. G. (2017). A survey of absenteeism on construction sites. *International Journal of Manpower*, *38*(4), 533–547. doi:10.1108/IJM-08-2015-0135

Stone, D. L., Deadrick, D. L., Lukaszewski, K. M., & Johnson, R. (2015). The influence of technology on the future of human resource management. *Human Resource Management Review*, *25*(2), 216–231. doi:10.1016/j.hrmr.2015.01.002

Storey, J. (Ed.). (2006). *Human resource management: A critical text* (2nd ed.). Thomson Learning.

Strohmeier, S. (2009). Concepts of e-HRM consequences: A categorisation, review and suggestion. *The International Journal of Human Resource Management*, *20*(3), 528–543. doi:10.1080/09585190802707292

Swanson, R. A., & Holton, E. F. (2009). *Foundations of human resource development*. Berrett-Kohler Publishers. Retrieved from https://lsms.ac/wp-content/uploads/2023/02/18.pdf

Tambe, P., Cappelli, P., & Yakubovich, V. (2019). Artificial intelligence in human resources management: Challenges and a path forward. *California Management Review*, *61*(4), 15–42. doi:10.1177/0008125619867910

Tharenou, P., Saks, A. M., & Moore, C. (2007). A review and critique of research on training and organizational-level outcomes. *Human Resource Management Review*, *17*(3), 251–273. doi:10.1016/j.hrmr.2007.07.004

Thompson, P. (2011). The trouble with HRM. *Human Resource Management Journal*, *21*(4), 355–367. doi:10.1111/j.1748-8583.2011.00180.x

Torrington, D., Hall, L., & Taylor, S. (2017). *Human resource management* (10th ed). Financial Times Prentice Hall. Retrieved from https://dokumen.pub/human-resource-management-9781292129099-9781292129112-9781292191522-5005025235-2662672692-1292129093.html

Uzoamaka, O. E., Chisom, N. C., & Chinemenma, O. A. (2021). Analysis of human resources management practices and challenges in construction companies in Nigeria. *European Modern Studies Journal, 5*(3), 209–218. Retrieved from https://www.researchgate.net/publication/352296752

Vass, S., & Gustavsson, T. K. (2017). Challenges when implementing BIM for industry change. *Construction Management and Economics*, *35*(10), 597–610. doi:10.1080/01446193.2017.1314519

Wilkinson, A., Johnstone, S., & Townsend, K. (2012). Changing patterns of human resource management in construction. *Construction Management and Economics*, *30*(7), 507–512. doi:10.1080/01446193.2012.711562

Wright, P.M. & Nishii, L.H. (2007, August). *Strategic HRM and organizational behavior: Integrating multiple levels of analysis.* (CAHRS Working Paper No. 07 - 03). Retrieved from https://ecommons.cornell.edu/server/api/core/bitstreams/8318d2bf-0b5a-4685-9e2d-bc3cf9703964/content

Wright, P. M., & McMahan, G. C. (1992). Theoretical Perspectives for Strategic Human Resource Management. *Journal of Management*, *18*(2), 295–320. doi:10.1177/014920639201800205

Yankov, L., & Kleiner, B. H. (2001). Human resources issues in the construction industry. *Management Research News*, *24*(3/4), 101–105. doi:10.1108/01409170110782711

Bimsara, K.D.M., Abenayake, D.N., Lingasabesan, V. and Shanika, V.G., 2024. Adopting circular economy practices in major building materials and elements to minimise waste in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 105-118. DOI: https://doi.org/10.31705/WCS.2024.9. Available from: https://ciobwcs.com/papers/

ADOPTING CIRCULAR ECONOMY PRACTICES IN MAJOR BUILDING MATERIALS AND ELEMENTS TO MINIMISE WASTE IN SRI LANKA

K.D.M. Bimsara[1], D.N. Abenayake[2], Vithusha Lingasabesan[3], and V.G. Shanika[4]

ABSTRACT

Construction waste causes soil and water pollution, resulting in severe social and environmental concerns. Construction waste management systems in Sri Lanka are reactive and felt only when waste is generated. Hence, a proactive approach such as Circular Economy (CE) to minimising waste generation is required. The individual disposal of construction materials and elements contributes highly to construction waste in Sri Lanka, e.g., timber, bricks, doors, and windows. Therefore, applying CE practices concerning major building materials and elements is essential to minimise waste proactively. Thus, this study aims to guide the adoption of CE practices in major building materials and elements to minimise waste in the Sri Lankan context. A comprehensive literature review was conducted on the CE concept and its application to main building materials and elements. Using snowball sampling, ten experts fulfilling predefined criteria were selected and interviewed to collect qualitative data. The collected data were analysed using content analysis. Results show that current, material selection in Sri Lankan construction projects does not consider CE aspects. Current disposal practices include demolition and combusting while reusing and recycling are rarely used. The study recommended recycling, downcycling, cradle-to-cradle approach, material banks, and reduction to dispose of building materials and elements towards adopting the CE concept. CE can be implemented from the design stage to the whole life cycle, preferably initial stages, as an applicable practice to the Sri Lankan construction industry leading to minimising building materials and elements.

Keywords: *Building Elements; Circular Economy; Construction Materials; End of Life; Waste Management.*

1. INTRODUCTION

Construction and Demolition (C&D) waste consists of numerous materials including metals, plastic, timber, concrete, insulation materials, gypsum-based materials (Ghosh et al., 2016), PVC, and rubble (Elgizawy et al., 2016). Construction waste disposal causes

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, mahimabimsara@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dilanina@uom.lk
[3]Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, vithushal@uom.lk
[4] PhD scholar, Department of Construction Management, University of South Australia, Australia, vidsy006@mymail.unisa.edu.au

soil and water pollution (Patil et al., 2021) and negatively affects a country's environment, costs, productivity, and society (Nagapan et al., 2011). Concerning the high amount of waste, an approach to re-use, remanufacture, and regenerate materials can be a prominent solution, which is why circularity concepts must be implemented (Liu et al., 2017).

CE concept reverses “make, use, dispose of,” which generates a massive pile of waste in the current linear economy by creating a loop/circle as in nature (Ellen MacArthur Foundation [EMF], 2015). Hence, a Circular Economy (CE) model would be an excellent solution to maintain the generation of construction waste (Mangialardo & Micelli, 2018), which is to be implemented at the earlier stages of construction projects (Benachio et al., 2020). CE concept could be used in the planning and design stages for decision-making (Sanchez & Haas, 2018), which determines the requirement of re-using materials in higher percentages when the building is demolished at the end of its lifetime (Benachio et al., 2020).

The selection of building materials must be in line with the CE concept. Therefore, the designers must select the most appropriate materials (Antonini et al., 2020; Campbell, 2019). Those decisions are to be made at the planning stage, supporting the implementation of CE in the construction industry.

In the Sri Lankan context, construction material wastage is high during construction and demolition (Liyanage et al., 2019). As per the survey by Arsath et al. (2023), construction waste is generated due to activities such as discarded building materials, debris from renovations, and demolitions. Furthermore, Arsath et al. (2023) suggest incorporating the principles of Reduce, Reuse, and Recycle (3R) and innovative methods to mitigate this Construction and Demolition (C&D) waste. Although many research studies have been conducted worldwide to investigate how to adopt CE principles in building materials and elements (e.g. Mohammadiziazi & Bilec, 2023; Bertino et al., 2021), there is a dearth of studies in the Sri Lankan context. Accordingly, this research is mounting the research problem: “How CE practices can be adopted in building materials and elements to minimise C&D waste in the Sri Lankan Construction industry?” Thus, this study aims to guide the adoption of CE practices in major building materials and elements to minimise C&D waste in Sri Lanka.

2. LITERATURE REVIEW

2.1 MATERIAL WASTE IN THE CONSTRUCTION INDUSTRY

The construction sector generates almost one-third of all waste in developing countries (Eckelman et al., 2018). C&D waste varies depending on the type of construction activity (Gulghane & Khandve, 2015). It includes materials such as concrete, wood, bricks, tiles, glass, steel, metal, and roofing (Arsath et al., 2023). Berge (2007) stated that the contribution of construction materials to waste generation starts at primary levels, from raw material extraction to transformation, construction, and demolition. Building materials are disposed of in landfills after construction projects and the end of service life (Nasi et al., 2017).

Therefore, minimising material waste is the most appropriate way to reduce C&D waste generation. Arsath et al. (2023) suggest that selecting sustainable materials at the design and planning stage can significantly reduce waste. According to Eberhardt et al. (2022), such material selection is a prevalent method for implementing CE in buildings.

The Sri Lankan construction industry must focus on enhancing the transition towards a more resource-efficient and sustainable future with CE implementation (Weerakoon et al., 2023). However, the current waste management practices in Sri Lanka are primarily linear (Victar & Waidyasekara, 2023) due to construction professionals' lack of awareness of CE (Weerakoon et al., 2023). Therefore, Wijewansha et al. (2021) emphasised the requirement for more studies on CE implementation strategies in the Sri Lankan construction industry.

2.2 APPLYING CIRCULAR ECONOMY PRACTICES TO BUILDING MATERIALS AND ELEMENTS

"A CE is an economic system designed with the intention that maximum use is extracted from resources and minimum waste is generated for disposal" (Deutz, 2020. p.193). The CE concept is focused on changing the traditional pattern of "take-make-dispose" by keeping resources in use for more extended periods where waste is considered valuable input (EMF, 2015). Thus, the CE concept is focused on the circularity of resources while reducing waste (Stahel, 2019), minimising the extraction, and reducing the need for inefficient material extraction (Benachio et al., 2020). Schroeder et al. (2018) manifested that applying CE practices can accomplish many Sustainable Development Goals (SDGs). Hence, applying CE to the construction industry helps achieve sustainable construction and enhance performance (Núñez-Cacho et al., 2018).

The construction industry is the major buyer of resources (Stahel, 2019) and uses significant resources for which the CE concept can be adopted (Adams et al., 2017). However, construction materials end up as waste at the end of building life cycles (Adams et al., 2017). Therefore, CE implementation in the construction sector is necessary to reduce waste generation and disposal (Hossain & Ng, 2018). It focuses on the material supply chain and recovery of materials for direct reuse (Akinade & Oyedele, 2019). Hence, adopting CE can reduce the amount of extraction from resources, promoting reuse, reduction, recycling, upcycling, remanufacturing, and repair (Stahel, 2016), material banks (Manelius et al., 2019) and material passports (Copeland & Bilec, 2020). EMF (n.d) provided three major principles of CE i.e. (i) eliminate, (ii) circulate, and (iii) regenerate, where circulate refers to circulating the products and materials at their highest value.

Among many CE practices, reuse, reduce, repair, recycle, and recover have an immense potential to minimise material waste in the construction industry (Mancini et al., 2021). Table 1 gives the CE practices and their brief explanations per the literature.

Table 1: Circular economy practices

CE Practice	Explanation	Sources
Reuse	Using materials without any transformation	Vefago and Avellaneda (2013); EMF (2015).
Reduce	Minimise waste of product within its production and use phases	Kirchherr et al. (2017); Akenji et al. (2016).
Recycle	The process of reusing waste to create new products with equal qualities to their previous stage and fit for the same purpose again	Gao et al. (2001); Chini (2007)
Repair	Fixing or restructuring a product to its previous state	Kirchherr et al. (2017);
Recover	Recover material from waste	Akanbi et al. (2019)

C&D waste of building materials and components largely contributes to waste generation in the Sri Lankan context (Liyanage et al., 2019). However, effective C&D waste management, including construction materials and elements, is still lacking in developing countries including Sri Lanka (Arsath et al., 2023). CE principles allow more building products, elements, and materials to re-enter the supply chain by recovering them from waste (Bertino et al., 2021). Therefore, adopting CE principles in building materials and elements requires research study in the Sri Lankan construction industry.

3. RESEARCH METHODOLOGY

A literature review was conducted to identify the CE concept, CE principles, and its applicability to C&D waste management. The Sri Lankan construction industry is in the initial stages of implementing the CE concept (Weerakoon et al., 2023). Therefore, a quantitative approach cannot be used to collect the data due to many construction industry practitioners' lack of awareness of the concept, where selecting a reliable large sample was difficult. The primary goal of qualitative research is to investigate and understand the circumstances and experiences of individuals (Kumar & Shukla, 2022) while allowing researchers to participate actively in data collection (Creswell & Creswell, 2017). Therefore, a qualitative research approach was chosen for this study to collect qualitative data using semi-structured interviews with experts having both CE and C&D waste management knowledge and experience. This allowed the researcher to obtain precise data on CE principles and C&D waste management, focusing on building materials and elements while acquiring any additional data that emerged during interviews. Accordingly, 15 experts with CE and waste management experience were selected for the interviews. Due to the saturation of data, only Ten expert interviews were conducted to collect data. Finding professionals who are aware of CE was challenging; therefore, the snowball sampling technique was used to select building construction experts for interviews, fulfilling the criteria shown in Table 2.

Table 2: Selection criteria of interviewed experts

Code	R1	R 2	R 3	R 4	R 5	R 6	R 7	R 8	R 9	R10
Designation	**Project Manager**	**Quantity Surveyor**	**Quantity Surveyor**	**Architect**	**Quantity Surveyor**	**Civil Engineer**	**Architect**	**Quantity Surveyor**	**Quantity Surveyor**	**Project manager**
Having more than 5 years of experience	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Construction-related reputed professionals	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Graduated in a construction-related degree	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Working at reputed organisations	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Verbal interview data were audio-recorded with the interviewees' consent and transcribed to textual data. The qualitative data gathered in this study were analysed using the 'Content Analysis' method, which makes systematic, credible, valid, and replicable inferences from text (Drisko & Maschi, 2016).

4. RESEARCH FINDINGS AND DISCUSSION

Due to time constraints, this study was limited to a few building materials, elements, and CE principles for collecting data. Accordingly, concrete, wood, and steel were identified as three major materials that are commonly used in building structures in the Sri Lankan context. Altogether, four building elements were identified i.e., (i) columns and beams, (ii) roofs, (iii) walls, and (iv) floors, considering them as main elements related to building envelopes. Moreover, six CE practices were selected i.e. (i) recovered, (ii) reused, (iii) designed for disassembly, (iv) recycled, (v) repaired, and (vi) reduced to conduct the interview.

4.1 Aspects Considered in the Current Construction Material Selection Process: Concrete, Steel and Wood

The current considerations in selecting construction materials, specifically concrete, steel, and wood, for a construction project are demonstrated in Table 3.

Table 3: Current material selection aspects

Material Selection Aspects	Concrete	Steel	Wood
Cost/ Price	R1, R2, R3, R4, R6, R7, R8, R9	R1, R2, R5, R7, R8	R1, R2, R6, R7, R10
Suitability to environment/ Green credentials	RI, R4		R5
Design lifetime	R1, R5	R1	
Strength (Grade)	R2, R3, R4, R5, R7, R8, R10	R2, R3, R4, R5, R6, R7, R9	R3, R4
Workability	R2, R3, R6		
Brand/Quality	R2	R2	R6
Fire resistance	R3		
Approval requirements	R4		
Durability	R8, R9		R2, R10
Familiarity	R8, R10	R3	R9
Exposed conditions		R1	
Flexibility/ Versatility		R3, R10	R3
Availability of workmanship		R4, R5, R6	
Fast construction		R5	
Functionality		R8	
Aesthetical view			R1, R4, R5, R8, R9
Blending to location			R1, R8
Use/Purpose			R6
Natural Experience			R5
Availability			R1, R2, R3, R7, R9

As per Table 3, interviewees mentioned several aspects they currently consider when selecting concrete, steel, and wood for construction. Accordingly, most experts consider cost and strength when selecting concrete and steel since these materials are mostly used for structural purposes. On the other hand, cost, aesthetic view, and availability are the most concerning factors when selecting wood. However, experts rarely consider CE-related aspects, such as reusability and recyclability, in the current material selection process.

4.2 CONSIDERATION OF THE END-OF-LIFE (EOL) OF A BUILDING WHEN SELECTING MATERIALS AT THE DESIGN AND CONSTRUCTION STAGE

As per all the interviewees, in the Sri Lankan context, mild attention is given to the building's EOL at its design and construction stage. The interviewed experts explored the reasons behind this, as shown in Figure 1.

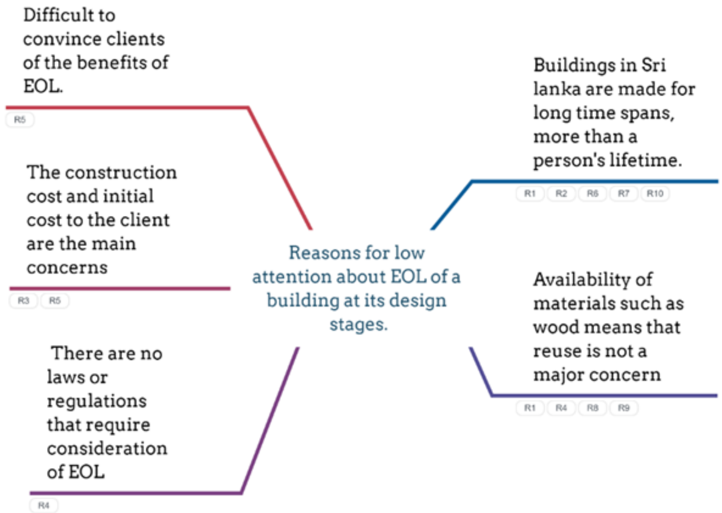


Figure 1: Reasons for low attention on EOL of a building at its design stages

As per findings, although steel and wood are sometimes reused at the EOL of buildings, their reusability is not considered at the design stage. Further, R1 mentioned, "*concrete structures are made for long periods; in Sri Lanka, we cannot have such long-term plans and predictions*". In line with that, R8 stated that due to the long-life span of buildings, EOL is less considered by builders and clients. R5, R6, R7 and R10 supported the argument that the EOL of a building may not come within the Client's lifetime. Thus, it is not considered at the designing stage. R5 explained that even though professionals consider EOL, it is difficult to convince its benefits to clients. On the other hand, R3 said, *"We still give little regard for EOL; we are mainly concerned with the initial cost"*. R4 stated that though materials from buildings can be reused and recycled to some extent, it is not a significant concern at the design stage. R8 added, "*Now, builders give a certain consideration to the EOL of a building due to some policies, but still, they are not self-motivated to do so"*.

4.3 DISPOSAL OPTIONS OF ELEMENTS IN PRACTICE

According to current practice, the interviewees were asked about the disposal techniques used in the construction industry to dispose of selected building elements made of selected materials.

Table 4 gives experts' responses on the disposal methods of major building elements based on the material used to construct the respective building element.

Table 4: Disposal of major building elements

	Disposal Options in Current Practice

Building Element	Building Material	Demolish	Combustion	Reuse	Recycle	Recover
Columns & Beams	Concrete	All		R3		
	Steel			R3, R5, R7, R8	R3, R5, R10	
	Wood		R4, R5	R5, R9		R5
Roof	Concrete	All				
	Steel			R3	R3	
	Wood		R5, R6	R1, R2, R5		R5
Walls	Concrete	R1, R2, R4, R5, R6				
	Wood		R5, R6	R3, R5, R10	R9	R5
	Brick/Block	R1, R2, R5, R9	R5	R3		
Floors	Concrete	R1, R3, R5, R7, R9				
	Steel			R5	R5	
	Wood		R6, R10	R5, R9		R5

As per Table 4, all the respondents stated that concrete columns and beams are landfilled after demolition because the reusability of concrete is questionable. However, R3 noted, *"Sometimes precast decorated concrete columns are disassembled and fixed in structures only for aesthetical appearance*". Similarly, the reuse of steel columns and beams in Sri Lanka is mostly limited to steel fixtures due to the lack of design for disassembly practices [R8].

All the respondents opined that concrete flat roofs are demolished and landfilled (refer to Table 4). As per R1, most wooden rafters and purlins are reused. R2 and R5 mentioned that roof tiles and asbestos are reused, and gypsum boards are sometimes recycled.

As shown in Table 4, many interviewees stated that concrete-made, cement block-made walls are demolished and landfilled in the current practice. R2 said, *"Practically, reusing cement blocks is very difficult because we do not have the technology to separate them"*. In addition, R3 highlighted, *"Bricks can be reused more than blocks. However, the plaster cannot be reused."* On the other hand, R9 said, *"Sometimes internal walls can be made of timber partitions, which can be reused or recycled"*.

The fourth major building element considered for the study is floors. R6 said, *"After a long use, wooden floor finishes cannot be easily used for any purpose; therefore, combustion is the option"*. However, R9 argued, *"Most of the timber planks used in floors can be reused because usually very quality wood is used for flooring". R4 said, "Wood combustion is a good option if we use the energy it generates"*.

4.4 APPLY CIRCULAR ECONOMY PRACTICES FOR BUILDING MATERIALS AND ELEMENTS

Table 5 illustrates the suggestions given by respondents regarding disposal options of certain materials and elements instead of current practice. In addition, the table consists of the areas to improve, considering CE practice to minimise waste.

Table 5: Disposal options found empirically

Suggested Option related to CE practice	Experts highlighted	Example(s) mentioned
Use of reusable and flexible building elements	R1, R5, R6	Internal walls and partitions
Have short-life span buildings with flexible design	R2, R4, R6, R7	Reuse columns, beams and wall panels
Design buildings based on reused and recycled materials and elements	R1, R3, R8	Reuse columns, beams, roof tiles, wall bricks, doors, and windows. Design buildings to give an antique look
Use building elements or materials to get at least a lower value from them	R2, R4, R7	Use concrete and wood waste for landscaping, roads, walking paths
Demolish with minimum waste and maximise reusability	R3, R6, R8, R9, R10	Demolish brick walls carefully to reuse bricks, roofs to reuse roof tiles and timber members. Steel members.
After-sale service from suppliers/ manufacturers and suppliers. Return to manufacturers after use for recycling or reproduction.	R3	Wall panels, roofing sheets, steel

Interviewees described that Sri Lankans are used to constructing buildings that last longer than they need to; however, their needs change as the generations change. Therefore, R2 stated that buildings with 20-25 years of life span are enough. "*The design should have the flexibility to be easily redesigned. The use of heavy-duty materials is not necessary*". [R2]. Therefore, the waste generated through the lifetime of a building will be less in short-life-span buildings with flexible designs where assembly and disassembly are easy.

R3 suggested obtaining after-sales services from suppliers who provide technical support and awareness on maintaining and recycling, sometimes buying old stock. Moreover, R3 emphasised encouraging builders and clients to finalise their designs using reused/ recycled materials without using virgin materials. This concept can be incorporated among contractors of government projects to use materials recovered from other projects.

R6 stated that current disposal options need less waste generative, *"the most preferred option for concrete is demolishing because it is hard to reuse, but if we can demolish with minimum waste and landfill, it is still a better option*". R4 believes that concrete structures could be crushed and used as the aggregate for road fillings. The remaining crushed concrete particles could be used to fill walking paths. Further, R4 stated*, "If the wood is not treated, then wood can be used as compost, and sometimes wood can be downcycled to particles and used as a landscaping material, for example, in children's parks"*.

R3 accused, *"The problem is that the current buildings are not designed to be deconstructed and are constructed to demolish. If disassembly is available, you can take out the parts to reuse. However, in Sri Lanka, even the rebars are not reused"*. R8 said that in other countries, satisfying with minimum resources is practice. However, we still do not have that ideology in Sri Lanka. R9 stated, *"There are material surveyors in other* *countries to estimate exact material requirements avoiding overconsumption and waste. Therefore, Sri Lanka also needs material surveyors as a profession".*

4.5 IMPLEMENTING CE PRACTICES IN THE SRI LANKAN CONSTRUCTION INDUSTRY

All respondents emphasised the need know the concept for its proper application. As per the findings, the practical use of CE is problematic since the clients and society are unaware of the CE concept. Therefore, the CE concept must be taught at schools, and the syllabuses must be updated to acknowledge society. R3 said, *"Whether we like it or not, we have to do it since the world is moving towards CE"*. Furthermore, to apply this CE concept in Sri Lanka, "*firstly we have to do it by heart and have the mindset to do it, and secondly, government regulations and mandatory curriculum must be implemented, thirdly particular incentives to be given for practising, formal accreditors, certificates like LEEDS certificates must be given and finally tax concession for practising resource-saving concepts*" [R3].

R4. R6 and R7 also responded positively to CE in Sri Lanka. R4 said, "*CE can be applied at any stage of a project lifecycle and get benefits*". R4 further explained that the applicability of CE does not depend on the geographical area, and it considers the availability of certain alternative materials. As per R7, the availability of technology for enhanced recycling is questionable in Sri Lanka. R8 said, "*CE should be implemented in every country; even though there are technology-related limitations, we can start from the material selection process*". On the other hand, R5 said, "*We have not been using many material-saving concepts, which require necessary rules and regulations*". Due to the economic crisis, Sri Lanka has restricted the importation of building materials including steel, cement, and tiles. Therefore, the findings highlighted that the Sri Lankan construction industry could have benefited if CE practices of reusing, reducing, and recycling had been considered for building materials and elements during that period. In conclusion, all the respondents were positive about implementing CE in the Sri Lankan context, especially in selecting building materials and designing building elements.

4.6 INITIATION OF IMPLEMENTING CE PRACTICE FOR BUILDING MATERIALS AND ELEMENTS IN SRI LANKA

Interviewees were further asked their opinion on the initiation steps that should be taken to implement CE practices relating to building materials and elements in the Sri Lankan context. R1, R2 and R5 suggested applying the CE concept to building materials and elements in public sector projects. R1 mentioned, *"Government can commence applying CE concept in public projects, where they can promote using recycled materials and elements"*. R5 added, *"Government projects can be advised to use reusable materials and elements from other demolished buildings, thereby reducing the cost"*. R10 proposed that this can be enhanced by having a policy framework in the government and enforcing regulations. R8 urged, "*government has to enforce strict regulations for demolition of buildings restricting demolishing buildings as a whole"*. R8 added, *"This will allow demolitions to be done carefully, saving materials and elements as much as possible for reuse*". R6 proposed developing a separate specialisation for contractors named 'demolition contractors.

R2, R4, and R7 emphasised the need for public awareness programmes regarding reusable and recycled materials and elements and their use. R7 highlighted, *"We can promote the* *use of reusable and recycled materials and elements among the public by using marketable terms like 'antiques"*. R4 suggested promoting the establishment of material banks in the Sri Lankan construction industry, where regulatory authorities like the Construction Industry Development Authority (CIDA) can be involved.

5. DISCUSSION

The study findings disclosed that the current building material selection process and element design in the Sri Lankan construction industry do not concern CE practices including reducing, reusing, recycling, and designing for disassembly. Experts argued that attention to the EOL of buildings is required at these stages to minimise C&D waste of building materials and elements. However, there is low attention paid to the EOL of buildings in the material selection process due to the long building life span in Sri Lanka, clients' preference for initial cost, and the absence of related laws and regulations. Research studies by Akinade et al. (2019), Hart et al. (2019), Hossain et al. (2020), Kanters (2020), and Rakhshan et al. (2020) identified a lack of consideration of EOL issues in materials selection as a barrier for CE implementation in building materials and elements which is affected by an unwillingness by the client, and lack of regulations.

The study's findings suggest that building design and material selection are required to minimise C&D waste. Considering this, Rahla et al. (2021) identified *"recycled and recovered content from the buildings which reaches the EOL"* as the first significant CE criteria for material selection. Moreover, Zoghi et al. (2022) emphasised the need to choose construction materials that make the reusability and recyclability of building components. Similarly, Schiller et al. (2019) identified design for disassembly as a branch of reuse that can be applied to building elements including walls, columns, and beams. In line with that, Cooper et al. (2021) also identified the design requirement to emphasise reducing waste.

The literature emphasises the importance of reusing building materials and elements and reducing the use of virgin materials in construction to minimise C&D waste and protect the environment (Stahel et al., 2019; Vefago & Avellaneda, 2013). This study suggests designing based on reused materials as much as possible to apply CE principles to building elements and materials.

Findings mentioned the method of downcycling for applying CE to building materials and elements, a concern in literature for decades (e.g., by Gao et al., 2001). The cradle-to-cradle approach and closed-loop supply chain management are introduced in literature (e.g., Braungart & McDonough, 2002), which reclaims products by nature or returns them as another product when they are no longer used. Experts also proposed this approach when disposing of building materials and elements.

Accordingly, the literature review identifies disposal options for building materials and elements related to CE practices, which need to be applied in the Sri Lankan construction industry to reduce C&D waste of building materials and elements.

6. CONCLUSIONS

Circular Economy (CE) is a widely accepted concept focused on circulating materials in loops, maximising their use, and generating minimum waste. The CE practices were identified as reuse, reduce, recycle, repair, recover, design for disassembly, material bank concept and material passports. The study was limited to building materials concrete, steel, wood, and building elements: columns and beams, roofs, walls, and floors to adapt the CE concept. The selection aspects of major building materials identified are unrelated to Sri Lankan CE practices. The disposal practices used in the current practice were identified for the building elements columns and beams, roof, wall, and floor. All the concrete elements are demolished in the current practice, and wood is combusted. Landfills with materials are highly used, while reuse and recycling are rarely used in the Sri Lankan context.

CE is identified as an ideal concept to be implemented for building materials and elements to reduce C&D waste in the Sri Lankan construction industry. The research found that since CE supports the circularity of materials within the country, it reduces the need for imports, which is very beneficial during situations such as economic crises where imports are restricted. It is identified that the main steps should be taken at the material selection and element design stages to enable most of the CE practices including reuse and recycling at the EOL. The study identified reusing, recycling, downcycling, and cradle-to-cradle approaches to be implemented in the Sri Lankan construction industry with building elements and materials to reduce C&D waste. Further, to minimise waste in the Sri Lankan construction industry, flexible design enabling disassembly, a short span of buildings, after-sales services from suppliers, encouragement from contractors and clients, and the use of materials recovered from other projects were proposed.

Accordingly, this study investigated from a qualitative, in-depth perspective how CE practices can be adopted in building materials and elements to minimise C&D waste in the Sri Lankan construction industry.

This study contributes to the body of knowledge by outlining certain CE practices that could be implemented at a building's EOL as disposal options for building materials and elements. Further, the study offers a guide to initiate the implementation of CE for building materials and elements in Sri Lanka. Establishing material banks, enforcing strict regulations for demolition works, raising public awareness, and developing separate specialisations for demolition contractors are strategies to initiate the implementation of the CE concept for building materials and elements in the Sri Lankan construction industry. Further, this study would contribute to developing a sustainable nation in this wide society by proposing ways to minimise the waste generated from construction and demolition.

The study addressed CE practices for specific materials and elements in building construction. It focused on CE implementation in the Sri Lankan construction industry. However, the research findings can also be extended to other contexts matching similar settings.

Further studies can be carried out to investigate the adoption of CE practices for other building materials and elements to make the globe sustainable for future generations.

7. REFERENCES

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges, and enablers. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Davila Delgado, J. M., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production*, *223*, 386–396. https://doi.org/10.1016/J.JCLEPRO.2019.03.172

Akenji, L., Bengtsson, M., Bleishwitz, R., Tukker, A., & Schandl. H (2016). Ossified materialism: Introduction to special volume on absolute reductions in material throughput and emissions. *Journal of Cleaner Production, 132*, 1- 12. https://doi.org/10.1016/j.jclepro.2016.03.071

Akinade, O. O., & Oyedele, L. O. (2019). Integrating construction supply chains within a circular economy: An ANFIS-based waste analytics system (A-WAS). *Journal of Cleaner Production*, *229*, 863–873. https://doi.org/10.1016/J.JCLEPRO.2019.04.232

Akinade, O. O., Oyedele, L., Oyedele, A., Delgado, M. D., Bilal, M., Akanbi, L., Ajayi, A., & Owolabi, H.A. (2019). Design for deconstruction using a circular economy approach: Barriers and strategies for improvement. *Production Planning and Control*, 31(10), 829- 840. http://dx.doi.org/10.1080/09537287.2019.1695006

Antonini, E., Boeri, A., Lauria, M., & Giglio, F. (2020). Reversibility and durability as potential indicators for circular building technologies. *Sustainability 2020, 12*(18). https://doi.org/10.3390/SU12187659

Arsath, A. H., Haleeth, H. M., Nifal, M.N.M., Pithurjan, I., Saeenthan, S. (2023). Construction and demolition waste in Sri Lanka. *Department of civil engineering*, university of Jaffna.

Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *260*(1). https://doi.org/10.1016/J.JCLEPRO.2020.121046

Berge, B. (2007). Ecology of building materials. Routledge.

Bertino, G., Kisser, J., Zeilinger, J., Langergraber, G., Fischer, T., & Österreicher, D. (2021). Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials. *Applied Science, 11*(3), 939. https://doi.org/10.3390/app11030939

Braungart, M., & McDonough, W. (2002). *Cradle to cradle: Remaking the way we make things.* North Point Press, United States.

Campbell, A. (2019). Mass timber in the circular economy: Paradigm in practice? *Proceedings of the institution of civil engineers: Engineering sustainability*, *172*(3), 141–152. https://doi.org/10.1680/JENSU.17.00069

Chini, A. R. (2007). General issues of construction material recycling in USA. In *Proceedings of sustainable construction*, (pp. 848- 855).

Cooper, T., Kaner, J., Furmston, K., & Cutts, A. (2021). Furniture lifrtimes in a circular economy: A state-of-the-art review. *4th plate 2021 virtual conference, Limerick, Ireland*, 26- 28 May 2021. (pp. 1-8).

Copeland, S., & Bilec, M. (2020). Buildings as material banks using RFID and building information modeling in a circular economy. *Procedia CIRP*, *90*, 143–147. https://doi.org/10.1016/J.PROCIR.2020.02.122

Creswell, J. W., & Creswell, J. D. (2017). Research design: Qualitative, quantitative, and mixed methods approach. Sage Publications

Deutz, P. (2020). Circular economy. *International Encyclopedia of Human Geography (Second Edition), 193-201.* https://doi.org/10.1016/B978-0-08-102295-5.10630-4

Drisko, J.W. & Maschi, T. (2016). *Content Analysis*. Oxford University Press, New York: USA

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2022). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management 18*(2), 1-21. http://dx.doi.org/10.1080/17452007.2020.1781588

Eckelman, M. J., Brown, C., Troup, L. N., Wang, L., Webster, M. D., & Hajjar, J. F. (2018). Life cycle energy and environmental benefits of novel design- for- deconstruction structural systems in steel buildings. *Building and Environment, 143*, 421- 430. https://doi.org/10.1016/j.buildenv.2018.07.017

Elgizawy, S. M., El-Haggar, S. M., & Nassar, K. (2016). Slum development using zero waste concepts: Construction waste case study. *Procedia Engineering, 145*, 1306–1313. https://doi.org/10.1016/J.PROENG.2016.04.168

Ellen MacArthur Foundation. (2015). *Towards a circular economy vol.1: An economic and business rationale for an accelerated transition*. Ellen MacArthur Foundation. Retrieved January 23, 2024, from https://www.ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition

Ellen MacArthur Foundation. (n.d). *Circular economy introduction*. Ellen MacArthur Foundation. Retrieved July 14, 2024, from https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Gao, W., Ariyama, T., Ojima, T., & Meier, A. (2001). Energy impacts of recycling disassembly material in residential buildings. *Energy and Buildings*, *33*(6), 553–562. https://doi.org/10.1016/S0378-7788(00)00096-7

Ghosh, S. K., Haldar, H. S., Chatterjee, S., & Ghosh, P. (2016). An optimization model on construction and demolition waste quantification from building. *Procedia Environmental Sciences*, *35*, 279–288. https://doi.org/10.1016/j.proenv.2016.07.008

Gulghane, A. A., & Khandve, P. V. (2015). Management for construction materials and control of construction waste in construction industry: A review. *Journal of Engineering Research and Applications, 5*(4), 59- 64. https://www.ijera.com/papers/Vol5_issue4/Part%20-%201/K504015964.pdf

Hart, J., Adams, K., Giesekam, J., Tingley, D. D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: The case of the built environment. *Procedia CIRP*, *80*, 619–624. https://doi.org/10.1016/j.procir.2018.12.015

Hossain, M. U., & Ng, S. T. (2018). Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *Journal of Cleaner Production*, *205*, 763- 780. https://doi.org/10.1016/j.jclepro.2018.09.120

Hossain, M. U., Ng, S. T., Antwi- Afari, P., & Aamor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews*, 130, 109948. https://doi.org/10.1016/j.rser.2020.109948

Kanters, J. (2020). Circular building design: An analysis of barriers and drivers for a circular building sector. *Buildings*, *10*(4), 77. https://doi.org/10.3390/buildings10040077

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/J.RESCONREC.2017.09.005

Kumar, R., & Shukla, S. (2022). Creativity, proactive personality and entrepreneurial intentions: Examining the mediating role of entrepreneurial self-efficacy. *Global Business Review*, *23*(1), 101–118. https://doi.org/10.1177/0972150919844395

Liu, L., Liang, Y., Song, Q., & Li, J. (2017). A review of waste prevention through 3R under the concept of circular economy in China. *Journal of Material Cycles and Waste Management*, *19*(4), 1314–1323. http://dx.doi.org/10.1007/s10163-017-0606-4

Liyanage, K. L. A. K. T., Waidyasekara, K. G. A. S., Mallawarachchi, B. H., & Pandithawatta, T. P. W. S. I. (2019). Origins of construction and demolition waste generation in the Sri Lankan construction industry. *Proceedings of the world conference on waste management, 1*, (pp. 1- 8). https://doi.org/10.17501/26510251.2019.1101

Mancini, S.D., de Medeiros, G.A., Paes, M.X., de Oliveira, B. O. S., Antunes, M. L. P., de Souza, R. G., Ferraz, J. L., Bortoleto, A. P., & de Oliveira, J. A. P. (2021).Circular economy and solid waste management: Challenges and opportunities in Brazil. *Circular Economy and Sustainability*, *1*, 261- 282. https://doi.org/10.1007/s43615-021-00031-2

Manelius, A. M., Nielsen, S., & Kauschen, J. S. (2019). City as material bank – Constructing with reuse in Musicon, Roskilde. *IOP Conference Series: Earth and environmental science*, *225*(1), 5- 7 February 2019. Brussels, Belgium. https://doi.org/10.1088/1755-1315/225/1/012020

Mangialardo, A., & Micelli, E. (2018). Rethinking the construction industry under the circular economy: Principles and case studies. In A. Bisello, D. Vettorato, P. Laconte, & S. Costa (Eds.), *Smart and sustainable planning for cities and regions: SSPCR 2017*, *green energy and technology* (pp. 333-344). Springer, Cham. https://doi.org/10.1007/978-3-319-75774-2_23

Mohammadiziazi, R., & Bilec, M.M. (2023). Quantifying and spatializing building material stock and renovation flow for circular economy. *Journal of Cleaner Production, 389*, 135765. https://doi.org/10.1016/j.jclepro.2022.135765

Nagapan, S., Rahman, I. A., & Asmi, A. (2011). A review of construction waste cause factors. *Asian conference of real estate: Sustainable growth managing challenges (ACRE 2011),* Thistle Hotel, Johor Bahru, Malaysia. https://core.ac.uk/download/pdf/12007609.pdf

Nasi, M. H. A., Genovese, A., Acquaye, A. A., Koh, S. C. L., & Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics, 183*(Part B), 443- 457. https://doi.org/10.1016/j.ijpe.2016.06.008

Núñez-Cacho, P., Górecki, J., Molina, V., & Corpas-Iglesias, F. A. (2018). New measures of circular economy thinking in construction companies. *Journal of EU Research in Business, 2018.* https://doi.org/10.5171/2018.909360

Patil, R. A., Ghisellini, P., & Ramakrishna, S. (2021). Towards sustainable business strategies for a circular economy: Environmental, social and governance (ESG) performance and evaluation., *An introduction to circular economy* (pp.527-554). http://dx.doi.org/10.1007/978-981-15-8510-4_26

Rakhshan, K., Morel, J. C., Alaka, H., & Charef, R. (2020). Components reuse in the building sector – A systematic review. *Waste Management and Research: The Journal for a Sustainable Circular Economy, 38*(4), 347–370. https://doi.org/10.1177/0734242X20910463

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Selection criteria for building materials and components in line with the circular economy principles in the built environment—A review of current trends. *Infrastructures, 6*(4), 49. https://doi.org/10.3390/infrastructures6040049

Sanchez, B., & Haas, C. (2018). A novel selective disassembly sequence planning method for adaptive reuse of buildings. *Journal of Cleaner Production*, *183*, 998–1010. https://doi.org/10.1016/J.JCLEPRO.2018.02.201

Schiller, G., Lützkendorf, T., Gruhler, K., Lehmann, I., Mörmann, K., Knappe, F., & Muchow, N. (2019). Material flows in buildings' life cycle and regions-material inventories to support planning towards circular economy. *IOP Conference series: Earth and environmental science*, *290*(1), 2- 4 July 2019. Prague, Czech Republic. https://doi.org/10.1088/1755-1315/290/1/012031

Schroeder, P., Anggraeni, K., & Weber, U. (2018). The relevance of circular economy practices to the sustainable development goals. *Journal of Industrial Ecology, 23*(1), 77- 95. https://doi.org/10.1111/jiec.12732

Stahel, W. R. (2016). The circular economy. *Nature*, *531*, 435–438. https://doi.org/10.1038/531435a

Stahel, W. R. (2019). *The circular economy : A user's guide* (1st ed.).Routlede.

Vefago, L. H. M., & Avellaneda, J. (2013). Recycling concepts and the index of recyclability for building materials. *Resources, Conservation and Recycling, 72*, 127- 135. https://doi.org/10.1016/j.resconrec.2012.12.015

Victar, H. C., & Waidyasekara, K. G. A. S. (2023). Circular economy strategies for waste management in Sri Lanka: A focus on demolitions and repurpose and material recovery and production stages. *Waste Management & Research: The Journal for a Sustainable Circular Economy.* https://doi.org/10.1177/0734242X231206988

Weerakoon, T.G., Wimalasena, S., & Zvirgdins, J. (2023). Assessment of implementation of circular economy framework in the Sri Lankan construction sector. *Baltic Journal of Real Estate Economics and Construction Management, 11*(1), 133-152. https://doi.org/10.2478/bjreecm-2023-0009

Wijewansha, A.S., Tennakoon, G. A., Waidyasekara, K. G. A. S., Ekanayake, B.J. (2021). Implementation of circular economy principles during pre- construction stage: The case of Sri Lanka. *Built Environment Project and Asset Management, 11*(4), 750-766. https://doi.org/10.1108/BEPAM-04-2020-0072

Zoghi, M., Rostami, G., Khoshand, A., & Motalleb, F. (2022). Material selection in design for deconstruction using Kano model, fuzzy-AHP and TOPSIS methodology. *Waste Management & Research: The Journal for a Sustainable Circular Economy, 40*(4), 4. https://doi.org/10.1177/0734242X211013904

Bandara, D.M.U.S., Jayasinghe, J.A.S.K. and Coomasaru, P., 2024. Advancing digital technology adaptation in Sri Lankan construction firms. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 120-131. DOI: https://doi.org/10.31705/WCS.2024.10. Available from: https://ciobwcs.com/papers/

ADVANCING DIGITAL TECHNOLOGY ADAPTATION IN SRI LANKAN CONSTRUCTION FIRMS

D.M.U.S. Bandara[1], J.A.S.K. Jayasinghe[2] and P. Coomasaru[3]

ABSTRACT

The persisting reliance of the construction industry on traditional technologies has perpetuated inefficiencies, particularly in coordination and collaboration. Addressing the slow adoption of contemporary digital innovations, this study aims to both investigate the technical advancements and barriers impeding their integration into the Sri Lankan construction industry and find out how to facilitate their adoption. Drawing from a convenience sample of 72 professionals with diverse experiences and an expert group with over a quarter-century in the field, a mixed-methods analysis entailing NVivo for qualitative data and SPSS for quantitative insights was employed. The study spotlights Building Information Modelling (BIM), 3D printing, and augmented and virtual reality as acclaimed technological strides, with unmanned aerial vehicles being less recognised. Identified obstacles include high maintenance costs, skill deficits, and industry-specific challenges, with proposed strategies such as professional training, awareness campaigns, increased investments, and governmental support. Ultimately, the research underscores the importance of digital technology for productivity, accuracy, safety, and innovation in construction, aiming to guide AEC firms in overcoming digital integration barriers and facilitating the adoption of these technologies.

Keywords: *Adopting; Advantages; Construction Industry; Digital Technology; Failure.*

1. INTRODUCTION

The construction sector is fundamental to the economic proliferation of nations, contributing significantly to the annual revenue generation across the globe. However, in Sri Lanka its progression is impeded by resistance to technological evolution, resulting in productivity that trails behind that of sectors where technology is rapidly advanced (Barbosa et al., 2017). As urban landscapes expand, the demand for efficient housing and infrastructure emerges as a double-edged sword; while posing challenges, it simultaneously beckons the industry towards a technological metamorphosis (Chen et al., 2022). This study focuses on the Architecture, Engineering, and Construction (AEC) industry in Sri Lanka, examining the digital technology adoption among various types of

[1] Student, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, ushansankalpa1999@gmail.com
[2] Academic Instructor, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, sathya.jayasinghe7@gmail.com
[3] Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, pramuditha.c@sliit.lk

construction firms, including engineering firms, quantity surveying firms, architectural firms, and project management firms.

In this era, scientific innovations are not merely adjuncts but pivotal forces capable of catalysing industry-wide revolutions. These advancements promise to decomplexify construction processes by providing enhanced methodologies for project planning, design, and maintenance, underpinned by the strategic interpretation of visual data (Day & Schoemaker, 2000). The crux of the issue, however, lies in the sluggish pace at which the construction sector adopts these innovations, a pace which stifles productivity and dampens the industry's efficiency (Sabol, 2008).

The impetus for this research stems from the critical necessity to elevate the performance and efficiency of the construction industry through the assimilation of emergent technologies. It is imperative to address the imperative goals of augmenting efficiency, productivity, safety, and sustainability, thereby propelling the sector toward the adoption of avant-garde technological advances in its operational processes (Loosemore, 2014). The spectrum of digital technology, encompassing data generation, storage, and processing, ushers in an era of unprecedented interaction among humans, machines, and inter-systemic digital platforms (Ibem & Laryea, 2014).

Despite the acknowledged need for such technologies, their adoption is stymied by obstacles that are deeply rooted within the industry's framework, often leading to an escalation in project failures and abandonments. Motivated by this pressing issue, this research aims to investigate the technical advancements and challenges hindering technology adoption in the Sri Lankan construction industry, with the dual goal of understanding these barriers and devising effective methods to facilitate the adoption and integration of digital technologies. This study seeks to enhance the uptake of digital innovations and streamline construction processes, ultimately improving productivity, safety, and efficiency in the sector. The digitalisation of the AEC sector promotes innovation and requires an integrated, data-driven approach among stakeholders (Ikediashi & Ogwueleka, 2016). Addressing the current state of digital collaboration and tool utilization in construction is paramount; enhancements in this domain are essential to boost the adoption of technology and streamline construction processes effectively (Oesterreich & Teuteberg, 2016).

2. LITERATURE REVIEW

2.1 CURRENT STATE OF THE CONSTRUCTION INDUSTRY

The contemporary construction industry stands at a crossroads, where the adoption of sustainable practices is essential for growth across social, economic, cultural, and transit domains. This shift towards sustainability is driven by escalating resource scarcity, economic growth and demographic expansion, compelling the sector to embrace green construction methodologies (Jayalath & Gunawardhana, 2017). The transition demands a departure from traditional artisanal techniques towards enhancing the workforce's technical prowess to integrate and operationalise advanced technology seamlessly. A smarter construction industry promises significant improvement in accuracy, productivity and efficiency.

The pace of the construction process is closely tied to field performance, which hinges on optimising costs and timelines, meticulous on-site material management, effective equipment utilisation, and innovative visualisation techniques (Srivastava et al., 2022). These elements are crucial in steering the industry towards a technologically adept future, emphasising the importance of digital fluency in reshaping construction landscapes.

2.2 CONSTRUCTION INDUSTRY 4.0 (CI4)

The advent of Industry 4.0 (I4) heralds a transformative era where emerging trends and technologies redefine manufacturing processes, extending their impact on the construction sector by promising substantial social and economic advantages. This evolution introduces a holistic approach to managing product lifecycles, with profound implications for health, energy, and urban development (Baur & Wee, 2015). Central to this shift is the principle of technology transfer, which facilitates the relocation of technological capabilities across units, enriching the industry's innovation landscape (Bozeman et al., 2015).

Technological advancements under the I4 umbrella are categorised into five domains i.e. (i) communication, (ii)data collection, (iii) analytics, (iv) automation in construction, and (v) visualisation and planning. Each plays a pivotal role in enhancing operational outcomes such as safety, efficiency, quality, productivity, and sustainability (Chen et al., 2022; Frank et al., 2019). Despite the benefits, the sector faces significant hurdles, notably the shortage of skilled personnel and the prohibitive costs associated with deploying these new tools (Sacks et al., 2018).

At the core of the construction technology framework are the cloud-based common data environment and Building Information Modelling (BIM), which safeguard project data throughout its lifecycle and provide sophisticated modelling and simulation capabilities crucial for the industry's advancement (Oesterreich & Teuteberg, 2016). This strategic integration of I4 principles promises unparalleled efficiency and innovation, contingent upon overcoming barriers to technology adoption and skill enhancement.

2.3 EMERGING DIGITAL TECHNOLOGIES IN THE CONSTRUCTION INDUSTRY

The construction sector has increasingly harnessed digital technology, marking a pivotal shift towards enhancing its processes and outcomes. Bilal et al. (2016) detailed the integration and impact of big data analytics in construction, demonstrating its potential to refine the construction process when combined with other digital innovations. Further exploration by Cai et al. (2019) examined the current landscape of automation and robotics within the industry, providing insights into their applicability and the pathways for successful implementation.

Visualisation technologies, specifically Augmented Reality (AR) and Virtual Reality (VR), have been thoroughly investigated by Guo et al. (2017) who underscored their significance in advancing construction health and safety management while acknowledging the challenges of broader adoption. Similarly, Tay et al. (2017) scrutinised the advancements and hurdles in adopting 3D printing and additive manufacturing, offering a comprehensive overview of the sector's evolving technological needs and future directions.

Key technological innovations shaping the future of construction include BIM, AR, VR, Artificial Intelligence (AI), cybersecurity, Unmanned Aerial Vehicles (UAV), cloud-based project management, blockchain, and laser scanners. BIM emerges as a cornerstone technology, facilitating intricate model creation that encapsulates digital representations of physical and functional characteristics of places (Sacks et al., 2018). This is complemented by CAD's role in generating and visualising both 2D and 3D models, with BIM's capability extending to generating up to 6D models, thereby promoting an integrated project information-sharing ecosystem across the construction lifecycle (Begić & Galić, 2021; Takim et al., 2013).

UAVs are highlighted for their capacity to gather diverse image data, including high-definition visuals and thermal imaging, through varied sensing methods, enhancing the precision of 3D building models and facilitating regular inspections throughout a building's service life (Guo et al., 2017; Mader et al., 2016). The distinction between AR and VR is articulated through their respective applications, with AR augmenting real-world environments and VR creating entirely simulated settings (Balali et al., 2018; Milgram & Kishino, 1994).

Blockchain technology, recognised for its transformative potential across various sectors, promises to secure transactions within a decentralised network, ensuring the integrity of digital records (Hamida et al., 2017; Zheng et al., 2017). Meanwhile, terrestrial 3D laser scanning offers a comprehensive suite for geospatial surveys, construction monitoring, and heritage conservation, embodying the diversity of laser scanning technologies available (Holgado-Barco et al., 2014; Jaselskis et al., 2005).

2.4 OBSTACLES IN ADOPTING DIGITAL TECHNOLOGIES IN CONSTRUCTION

Navigating the digital transformation within the AEC sector reveals significant interoperability challenges among associations and professions. These complications arise from attempts to trade, offer, or incorporate data and business models through existing data frameworks or authorised practices, often leading to a failure in effectively connecting different systems (Sacks et al., 2018). This difficulty can be attributed to various factors such as the fragmented nature of the industry, the diversity in data requirements, the flexibility of data methodologies, the necessity for innovation skills, and the trade-offs involved in achieving broad business objectives through the development of interoperable programs and frameworks.

Training, or rather the lack thereof, emerges as another significant hurdle. The absence of specialised digital training modules within educational institutions places additional pressure on the industry to equip its workforce with the necessary skills, further complicating the adoption of digital technologies (Holt et al., 2015). The scarcity of technically proficient staff represents a substantial barrier to embracing technological innovations within construction practices (Hamida et al., 2017).

Moreover, the importance of ensuring secure and appropriate access to information within cooperative IT environments cannot be overstated. Ongoing challenges related to privacy, security, and evolving standards necessitate continuous revisions to support a nuanced exchange of information and mitigate obstacles to the widespread adoption of digital technologies (Lapierre & Cote, 2007). Additional studies by Zhang et al. (2019) and Arif et al. (2020) highlight the critical need for robust training programs and secure IT environments to overcome these barriers, emphasising the global relevance of these challenges.

3. METHODOLOGY

This study employed a mixed-method approach to investigate the barriers and facilitators of digital technology adoption in the Sri Lankan construction industry. Initially, a comprehensive literature review was conducted, and NVivo software was utilised to perform thematic analysis, identifying key themes such as high maintenance costs, skill deficits, and the importance of BIM. These themes guided the formulation of research questions. A pilot survey was then administered to a small sample of industry practitioners to refine these questions, ensuring clarity and relevance. The main survey, conducted using convenience sampling, targeted a larger group of construction professionals, including engineers, quantity surveyors, architects, and project managers. The survey data were analysed using basic statistical methods to identify trends and insights.

To validate the survey findings, structured interviews were conducted with experienced professionals, also selected through convenience sampling. These interviews provided deeper insights into the barriers and facilitators of digital technology adoption. The interview data were analysed using NVivo to identify recurring themes and validate the survey results. This mixed-method approach allowed for a comprehensive exploration of the digital adoption landscape in the Sri Lankan construction sector, combining quantitative data with qualitative expert validation. The methodology ensured that the study was grounded in both theoretical insights and practical experiences, providing a robust foundation for the analysis and recommendations.

4. DATA COLLECTION AND ANALYSIS

4.1 DEMOGRAPHIC PROFILE OF RESEARCH PARTICIPANTS

Table 1 presents the educational background and work experience of the 72 research participants, ranging from Diploma to master’s degree holders. A significant share, especially engineers, reports five to ten years of industry experience, suggesting a mid-career level expertise prevalent in the study sample. Other roles such as Quantity Surveyors (QSs) and Architects are represented, with some professionals bringing over 20 years of experience to the mix. This demographic diversity reflects varied levels of familiarity with digital technologies within the construction sector.

Table 1: Demographic profile

Academic Qualification	Diploma		Higher Diploma				Bachelor's Degree			Master's Degree		Other
Years of experience	0-5	5-10	0-5	5-10	10-20	>20	0 -5	5-10	10-20	10-20	> 20	5-10
Engineer	-	2	-	-	5	2	2	10	5	2	1	-
QS	3	-	7	3	3	-	6	8	3	2	-	1
Architect	-	-	-	-	-	-	2	2	-	-	1	-
PM	-	-	-	-	-	-	-	-	-	-	2	-

4.2 FAMILIARITY AND APPLICATION OF DIGITAL TECHNOLOGIES IN THE CONSTRUCTION INDUSTRY

The survey data, visualised in Figure 1 reveals the current state of digital technology awareness among industry professionals. Notably, BIM is widely recognised in Sri Lanka, with 96% of respondents indicating familiarity. In contrast, knowledge of UAVs is considerably low, with only 8% awareness. The awareness levels for other digital technologies including AR/VR, Blockchain, Laser Scanning, and 3D Printing fall between these extremes, suggesting an intermediate understanding within the sector. The survey further suggests cloud systems and data collection apps are recognised yet not detailed in Figure 1.

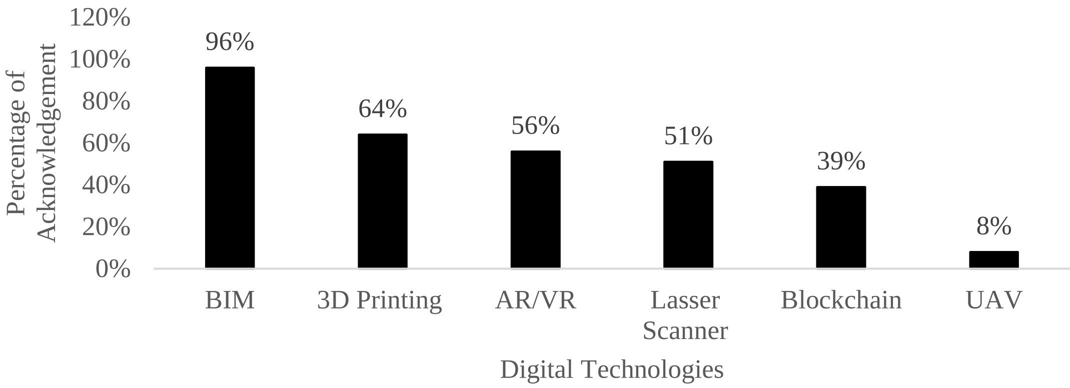


Figure 1: Knowledge of the digital technologies

4.3 PERSISTENCE OF CONVENTIONAL METHODS IN THE CONSTRUCTION INDUSTRY

The Sri Lankan construction industry's enduring reliance on traditional technologies is primarily due to several significant obstacles. Foremost among these is the high expense associated with the adoption of new digital technologies, which includes both upfront and hidden costs. This financial burden deters many firms from undertaking such initiatives. An inherent resistance to change further amplifies this reluctance, compelling organisations to adhere to familiar systems and procedures to guarantee successful integration. Additionally, the insufficient provision of training within the industry stifles both awareness and application of novel technologies in project execution.

The scarcity of professionals proficient in digital technologies further accentuates this challenge. Financial limitations also constitute a major obstacle, as organisations grapple with allocating sufficient resources toward technological investments that promise to enhance project management and efficiency.

In addition, restrictive government policies, which may involve imposing additional taxes or raising the costs of digital equipment, hinder technological progress by limiting accessibility for key industry players such as Project Managers (PM). Collectively, these challenges emphasise the construction industry's continued preference for traditional methods despite the clear advantages that digital innovations can offer.

4.4 IMPEDIMENTS TO TECHNOLOGY ADOPTION IN CONSTRUCTION

The research reveals, through a graphical analysis, in Figure 2, that the most prominent barriers obstructing the implementation of new technologies in Sri Lanka are due to high costs of technological upkeep, inadequate relevant skills within the industry, and a long-standing history of poor technology adoption rates. With 83% of experts identifying the prohibitive maintenance expenses, 58% recognising the lack of a skilled workforce, and 57% noting the industry's resistance to new technology integration, these issues are at the forefront of concerns hindering modernisation in the construction sector.

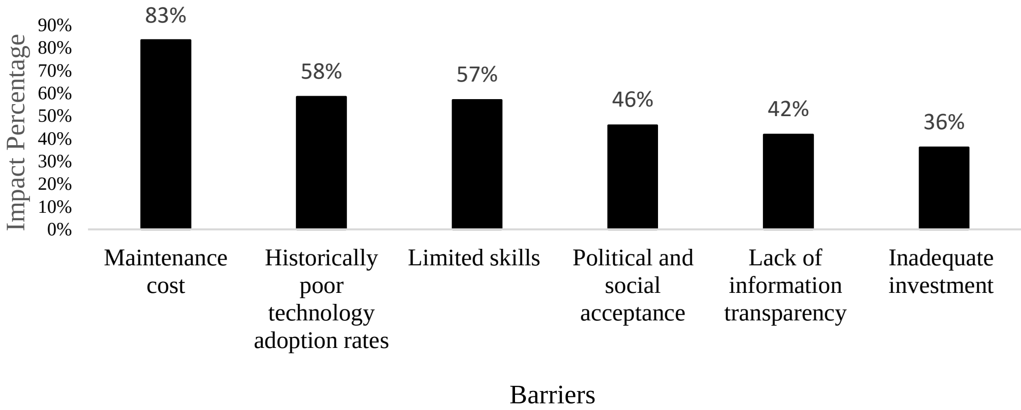


Figure 2: Barriers to implementing new technologies

Table 2 reveals respondents' perceptions of barriers to digital technology implementation, categorised by profession. Engineers, constituting 83% of surveyed and engineers, increasingly cite high maintenance costs as a hindrance. QSs, 81% of their total, similarly highlighted this concern.

The high cost of digital technology has challenged the implementation of digital technology in the AEC industry in Sri Lanka, the lack of trained staff in digital tools for construction participants, and the lack of skilled labour. The findings of this current study are that the cost of purchasing and maintaining digital tools and the lack of training among staff are the main reasons for not implementing digital technology within the construction industry.

Table 2: Barriers to the implementation of new technologies according to the profession

Barriers	Engineer	QS	Architect	PM	Value
High Maintenance cost	25	30	4	1	25%
Historically poor technology adoption rates in the industry	22	19	1	-	18%
Limited relevant skills base in the construction industry	17	20	3	1	18%
Political and social acceptance	17	13	1	2	14%
Existing weak Information transparency and transmission	7	20	3	-	13%
Inadequate mechanisms and investment in research and development	5	16	4	1	11%

4.5 IMPLICATIONS OF NOT ADOPTING DIGITAL TECHNOLOGY

Survey findings from the Sri Lankan construction sector highlight the significant implications of not adopting digital technologies. Notably, 75% of respondents indicate that implementing digital technologies could result in substantial cost savings. Similarly, 68% believe that digital technologies could lead to higher productivity levels. Furthermore, 64% suggest that efficiency levels could be improved, while 58% indicate that labour and workforce-related issues could be mitigated. Additionally, 44% of respondents believe that digital technologies could enhance safety levels. These findings are visually summarised in Figure 3**.**

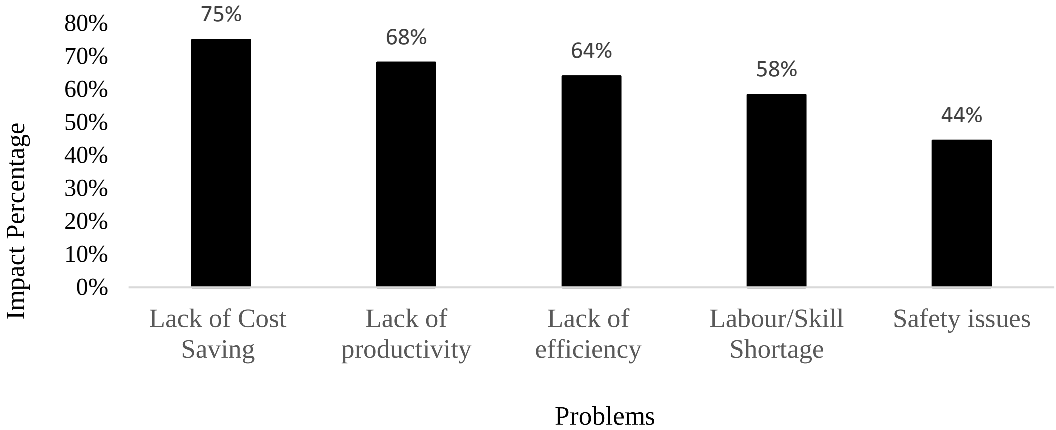


Figure 3: Problems due to non-implementation of digital technology

In Table 3, the consensus among engineers and QS emphasises the lack of high costs as a primary concern, with 71% of engineers and 76% of QS agreeing. These figures underscore financial barriers and skill gaps as significant impediments to digital adoption in the industry.

Table 3: Problems due to the non-implementation of digital technology

Problems	Engineer	QS	Architect	PM	Value
Lack of cost-saving	20	27	5	2	25%
Lack of productivity	21	24	2	2	22%
Lack of efficiency	19	22	3	2	21%
Skill labour shortages	16	19	5	2	19%
Safety issues	15	12	5	-	14%

4.6 ADVANTAGES OF IMPLEMENTING DIGITAL TECHNOLOGY

A survey among construction professionals has highlighted the significant advantages of digital technology, with the greatest impact seen in improved productivity, acknowledged by 90% of respondents. This is closely followed by better safety and more accurate customer communication. These results, depicted in Figure 4, reflect a strong industry recognition of the multiple benefits offered by digital advancements.

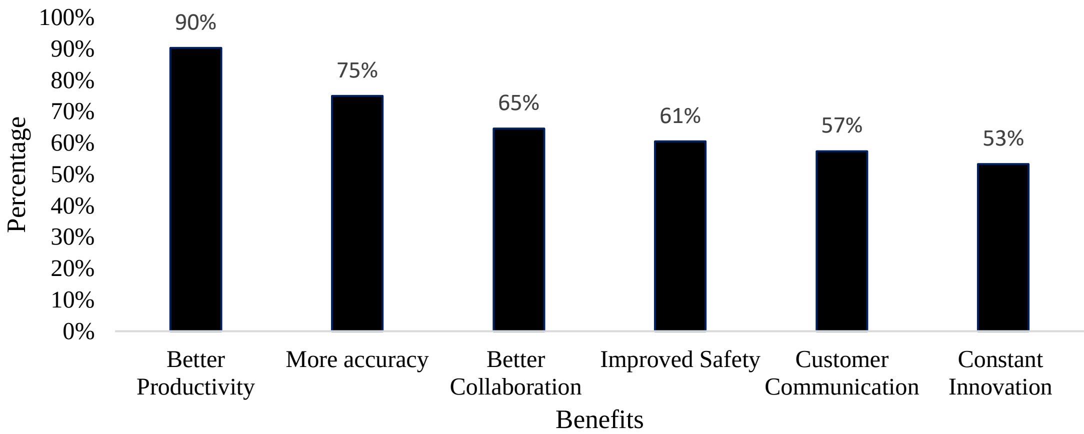


Figure 4: Benefits of implementing digital technology

Table 4 delineates the variances in how different construction professions value these benefits. For engineers and quantity surveyors, the increased productivity afforded by digital tools is paramount. In contrast, architects are more inclined to focus on improvements in customer communication and collaborative processes. The use of technologies such as BIM, Blockchain, and AR/VR are vital for streamlining operations and fostering better collaboration. Additionally, innovations such as laser scanners and UAVs are instrumental in enhancing on-site safety.

Table 4: Benefits of implementing digital technology technologies according to the profession

Benefits	Engineer	QS	Architect	PM	Value
Better Productivity	26	33	4	2	23%
More accuracy	19	32	3	-	19%
Better Collaboration	17	24	5	-	16%
Customer Communication	15	22	5	2	15%
Improved Safety	16	22	3	-	14%
Constant innovation	18	17	3	-	13%

In a survey conducted among AEC industry professionals, participants highlighted the pivotal role of digital technology in enhancing construction efficiency. Responses emphasised the benefits of digital adoption, such as time-saving, improved construction quality, fewer disputes, and enhanced efficiency, especially in the early design stages through project pre-visualisation. Moreover, they noted that embracing digital tools can help avert ambiguities and stakeholder conflicts. These insights underscore the substantial value and transformative potential of digital technology within the construction sector.

4.7 STRATEGIES TO OVERCOME PROBLEMS

Survey results highlighted challenges faced due to the minimal use of digital technology in the construction sector, inviting strategies to address these issues. Participant A proposed in-depth training for technicians and investment in current staff for a resilient workforce. Participant B advocated for brief, intensive seminars to acquaint existing professionals with new digital tools, enhancing project management capabilities. Participant C underlined the need for increased investment in cutting-edge technologies, encouraging stakeholder collaboration to mitigate financial risks and propel technological progress.

5. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Considering the data collection and analysis where 96% of respondents recognised BIM as pivotal, yet only 8% were familiar with UAVs, the study delineates a significant discrepancy in digital technology awareness within the construction sector. This disparity, coupled with formidable barriers such as high maintenance costs (identified by 83% of respondents) and a palpable skill deficit within the workforce (noted by 57%), underscores the nuanced landscape of digital adoption. Furthermore, an inherent resistance to change, cited by 58% of professionals, exacerbates the slow pace of digital integration, illustrating a tripartite barrier to the sector's transformation.

The acute recognition of digital technologies' benefits: enhanced productivity and safety, as acknowledged by 90% and a substantial portion of participants, respectively illuminates the potential gains from overcoming these obstacles. However, the gap between recognition and implementation, highlighted by the 76% concern over costs and 58% noting skill shortages, necessitates targeted strategies to bridge these divides.

To directly tackle the 83% of respondents concerned with high maintenance costs, we advocate for innovative cost management and financing strategies. This includes exploring collaborative investments and leveraging governmental and private sector incentives to alleviate the economic burdens, thereby making digital technologies more accessible across the industry.

Addressing the 58% shortfall in skilled personnel, the study emphasises the development and implementation of specialised training programs. These programs aim to equip both current employees and new entrants with essential digital competencies, directly targeting the skill gaps identified in our analysis. Moreover, in response to the 57% of professionals citing resistance to change, fostering a cultural shift towards innovation and openness to technological advancements is crucial. By promoting a more receptive environment for digital integration, it can counteract historical resistance and facilitate smoother digital transformation pathways.

The findings from this study reveal significant barriers to digital technology adoption in the Sri Lankan construction industry, including high maintenance costs, a lack of skilled personnel, and resistance to change. These barriers are consistent with the challenges identified in previous studies. However, the potential benefits of digital technology, such as improved productivity, efficiency, and safety, underscore the need for targeted strategies to facilitate adoption. These strategies should include professional training, increased investment, and governmental support.

In conclusion, this study highlights the critical need for digital transformation in the Sri Lankan construction industry. The dual focus on identifying barriers and facilitating adoption provides a comprehensive approach to addressing the slow pace of digital integration. By implementing targeted strategies, such as professional training and increased investment, the industry can overcome existing challenges and harness the full potential of digital technologies. Future research should continue to explore these areas, providing further insights and recommendations for enhancing digital adoption in the construction sector.

6. REFERENCES

Arif, I., Aslam, W., & Hwang, Y. (2020). Barriers in adoption of internet banking: A structural equation modeling - Neural network approach. *Technology in Society*, *61*, 101231. https://doi.org/10.1016/j.techsoc.2020.101231.

Balali, V., Noghabaei, M., Heydarian, A., & Han, K. (2018). Improved stakeholder communication and visualizations: Real-time interaction and cost estimation within immersive virtual environments. *Construction Research Congress 2018* (pp. 522-530). American Society of Civil Engineers. https://doi.org/10.1061/9780784481264.051.

Barbosa, F., Woetzel, J., & Mischke, J. (2017). *Reinventing construction: A route of higher productivity*. McKinsey Global Institute.

Baur, C., & Wee, D. (2015). Manufacturing's next act. *McKinsey & Company*. https://www.mckinsey.com/capabilities/operations/our-insights/manufacturings-next-act

Begić, H., & Galić, M. (2021). A Systematic review of construction 4.0 in the context of the BIM 4.0 premise. *Buildings*, *11*(8), 337. https://doi.org/10.3390/buildings11080337.

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., Owolabi, H. A., Alaka, H. A., & Pasha, M. (2016). Big Data in the construction industry: A review of present status, opportunities, and future trends. *Advanced engineering informatics*, *30*(3), 500-521. https://dx.doi.org/10.1016/j.aei.2016.07.001.

Bozeman, B., Rimes, H., & Youtie, J. (2015). The evolving state-of-the-art in technology transfer research: Revisiting the contingent effectiveness model. *Research Policy*, *44*(1), 34-49. https://doi.org/10.1016/j.respol.2014.06.008.

Cai, S., Ma, Z., Skibniewski, M. J., & Bao, S. (2019). Construction automation and robotics for high-rise buildings over the past decades: A comprehensive review. *Advanced engineering informatics*, *42*, 100989. https://doi.org/10.1016/j.aei.2019.100989.

Chen, X., Chang-Richards, A. Y., Pelosi, A., Jia, Y., Shen, X., Siddiqui, M. K., & Yang, N. (2022). Implementation of technologies in the construction industry: a systematic review. *Engineering, Construction and Architectural Management*, *29*(8), 3181-3209. https://doi.org/10.1108/ECAM-02-2021-0172.

Day, G. S., & Schoemaker, P. J. (2000). Avoiding the pitfalls of emerging technologies. *California management review*, *42*(2), 8-33. http://dx.doi.org/10.2307/41166030.

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International journal of production economics*, *210*, 15-26. DOI: 10.1016/j.ijpe.2019.01.004.

Guo, H., Yu, Y., & Skitmore, M. (2017). Visualization technology-based construction safety management: A review. *Automation in Construction*, *73*, 135-144. http://dx.doi.org/10.1016/j.autcon.2016.10.004.

Hamida, E. B., Brousmiche, K. L., Levard, H., & Thea, E. (2017). Blockchain for enterprise: Overview, opportunities and challenges. In *The thirteenth international conference on wireless and mobile communications (ICWMC 2017)*. International Conference on Wireless and Mobile Communications. Retrieved from https://hal.science/hal-0159185

Holgado-Barco, A., Gonzalez-Aguilera, D., Arias-Sanchez, P., & Martinez-Sanchez, J. (2014). An automated approach to vertical road characterisation using mobile LiDAR systems: Longitudinal profiles and cross-sections. *ISPRS Journal of Photogrammetry and Remote Sensing*, *96*, 28-37. http://dx.doi.org/10.1016/j.isprsjprs.2014.06.017.

Holt, E. A., Benham, J. M., & Bigelow, B. F. (2015). *Emerging technology in the construction industry: Perceptions from construction industry professionals.* 2015 ASEE annual conference & exposition, (pp. 26.595.1 - 26.595.10). ASEE Conferences. http://dx.doi.org/10.18260/p.23933.

Ibem, E. O., & Laryea, S. (2014). Survey of digital technologies in procurement of construction projects. *Automation in Construction*, *46*, 11-21. http://dx.doi.org/10.1016/j.autcon.2014.07.003.

Ikediashi, D. I., & Ogwueleka, A. C. (2016). Assessing the use of ICT systems and their impact on construction project performance in the Nigerian construction industry. *Journal of Engineering, Design and Technology*, *14*(2), 252-276. https://doi.org/10.1108/JEDT-08-2014-0047.

Jaselskis, E. J., Gao, Z., & Walters, R. C. (2005). Improving transportation projects using laser scanning. *Journal of construction engineering and management*, *131*(3), 377-384. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:3(377).

Jayalath, A., & Gunawardhana, T. (2017). Towards sustainable constructions: Trends in Sri Lankan construction industry-A review. I*nternational Conference on Real Estate Management and Valuation, Colombo, Sri Lanka.* University of Sri Jayewardenepura. Retrieved from https://www.researchgate.net/publication/320907730_Towards_Sustainable_Constructions_Trends_in_Sri_Lankan_Construction_Industry-A_Review

Lapierre, A., & Cote, P. (2007). Using open web services for urban data management: A testbed resulting from an OGC initiative for offering standard CAD/GIS/BIM services. *Urban and regional data management* (1st ed., pp. 381-394). CRC Press.

Loosemore, M. (2014). Improving construction productivity: a subcontractor's perspective. *Engineering, Construction and Architectural Management*, *21*(3), 245-260. https://doi.org/10.1108/ECAM-05-2013-0043.

Mader, D., Blaskow, R., Westfeld, P., & Weller, C. (2016). Potential of UAV-based laser scanner and multispectral camera data in building inspection. *The international archives of the photogrammetry, remote sensing and spatial information sciences*, *41*, 1135-1142. http://dx.doi.org/10.5194/isprsarchives-XLI-B1-1135-2016.

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, *77*(12), 1321-1329. Retrieved from https://cs.gmu.edu/~zduric/cs499/Readings/r76JBo-Milgram_IEICE_1994.pdf

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in industry*, *83*, 121-139. http://dx.doi.org/10.1016/j.compind.2016.09.006.

Sabol, L. (2008). *Challenges in cost estimating with building information modeling*. Design + Construction Strategies. Retrieved from https://www.academia.edu/3879014/2_sabol_cost_estimating

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers* (3rd ed.). John Wiley & Sons.

Srivastava, A., Jawaid, S., Singh, R., Gehlot, A., Akram, S. V., Priyadarshi, N., & Khan, B. (2022). Imperative role of technology intervention and implementation for automation in the construction industry. *Advances in Civil Engineering*, *2022*(01), 19. https://doi.org/10.1155/2022/6716987.

Takim, R., Harris, M., & Nawawi, A. H. (2013). Building information modeling (BIM): A new paradigm for quality of life within architectural, engineering and construction (AEC) industry. *Procedia-social and behavioral sciences*, *101*, 23-32. https://doi.org/10.1016/j.sbspro.2013.07.175.

Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N. A., Tan, M. J., & Leong, K. F. (2017). 3D Printing trends in building and construction industry: A review. *Virtual and Physical Prototyping*, *12*(3), 261-276. https://doi.org/10.1080/17452759.2017.1326724.

Zheng, Z., Xie, S., Dai, H., Chen, X., & Wang, H. (2017). An overview of blockchain technology: Architecture, consensus, and future trends. *2017 IEEE international congress on big data (BigData congress)* (pp. 557-564). IEEE. https://doi.org/10.1109/BigDataCongress.2017.85.

Kiridana, Y.M.W.H.M.R.R.L.J.B., Abenayake, M.D.E.T. and Eranga, B.A.I., 2024. AI models for predicting construction disputes in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 132-145. DOI: https://doi.org/10.31705/WCS.2024.11. Available from: https://ciobwcs.com/papers/

AI MODELS FOR PREDICTING CONSTRUCTION DISPUTES IN SRI LANKA

Y.M.W.H.M.R.R.L.J.B. Kiridana[1], M.D.T.E. Abeynayake,[2] and B.A.I. Eranga[3]

ABSTRACT

Construction disputes pose persistent challenges in Sri Lanka's construction industry, leading to project delays, cost overruns, and strained professional relations. This research seeks to alleviate these issues by introducing an AI-powered predictive model designed to identify and analyse dispute risks at the project's outset. By offering proactive insights, the AI model aims to enhance decision-making and facilitate the implementation of dispute prevention strategies, thereby improving overall project outcomes. Employing a mixed-methods approach, the study comprehensively examined project features contributing to disputes within the Sri Lankan context. Quantitative data on project characteristics and their correlation with dispute occurrence were gathered through structured questionnaires, while qualitative insights into dispute causes and stakeholder challenges were obtained via in-depth interviews with industry experts. Through meticulous analysis of this combined data, key predictors of construction disputes were identified, including contract ambiguities, unrealistic timelines, payment delays, poor communication, and unforeseen site conditions. These findings drove the development of a machine learning-based predictive model trained to recognise patterns, predict dispute likelihoods, and suggest their nature based on identified risk factors. This innovative AI tool has the potential to revolutionise dispute management practices in Sri Lanka's construction industry. By providing stakeholders with early warnings of potential disputes, the model enables proactive mitigation strategies, such as enhanced contract drafting, optimised communication, and timely alternative dispute resolution. The long-term impact of this research extends to fostering a more collaborative and sustainable construction industry, ultimately contributing to the successful delivery of projects across Sri Lanka.

Keywords: *Artificial Intelligence; Causes of Construction Dispute; Construction Dispute; Construction Industry; Machine Learning.*

1. INTRODUCTION

The construction industry significantly contributes to economic development and overall quality of life. It enhances science and technology, strengthens infrastructure, and supports social and economic growth (Serogina et al., 2022). The construction sector stimulates growth, creates investment opportunities, and helps achieve national social and economic goals (Silva et al., 2018). Moreover, it plays a vital role in fulfilling the United

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, kiridanaymwhmrrljb.19@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mabeynayake@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurue@uom.lk

Nations' Sustainable Development Goals (SDGs) (Fei et al., 2021). Specifically, the industry is crucial for the SDGs related to equitable communities and cities, climate change mitigation, sanitation and water quality, responsible spending and manufacturing, and fostering innovation and infrastructure (Collier, 2020). Additionally, the construction industry is essential for the reconstruction of conflict-affected nations, contributing to employment, revenue generation, and the development of other industries (Serogina et al., 2022). Therefore, identifying common sources of disputes and improving the competency of judicial actors is crucial to making the resolution process more efficient (Marciano & Ramello, 2019). Factors such as risks, uncertainties, inadequate contract documentation, and behavioural issues contribute to the occurrence of construction disputes (Assaf et al., 2019). Moreover, analysing these factors and understanding their interrelationships is essential for effectively preventing and resolving disputes (Abeysinghe & Jayathilaka, 2022).

The financial consequences of building conflicts are substantial. Cost overruns caused by litigation or delays can cripple projects, especially those with limited resources or those that serve important public infrastructure demands (Arfazadeh, 2014). Furthermore, the reputation of organisations involved in conflicts suffers, limiting their capacity to win future business (Ikechukwu et al., 2017). The hostile atmosphere created by conflicts hampers innovation and the development of collaborative working styles, which are increasingly viewed as threatening to the construction industry's long-term health (Walsh & Llp, 2007).

This research aims to equip stakeholders in the Sri Lankan construction industry with a powerful tool for anticipating and managing disputes effectively. By leveraging AI technology, inspiration is not only limited to mitigating the immediate impacts of conflicts yet fostering a more conducive environment for innovation, collaboration, and sustainable development. The creation and use of such technology have the potential to alter how the Sri Lankan construction sector predicts and resolves disputes. It enables project managers, engineers, and stakeholders to make data-driven decisions, promoting proactive dispute resolution (Choi et al., 2021). By anticipating disputes, AI technology might avoid costly escalations, maintain relationships, and ensure that projects are completed on time and within budget.

Finally, this has the potential to boost the overall efficiency, productivity, and reputation of Sri Lanka's construction industry (Sandagomika et al., 2020). Ultimately, by empowering decision-makers with data-driven insights and proactive strategies, the projects strive to contribute to the long-term prosperity and resilience of the construction sector in Sri Lanka, aligning with broader socio-economic objectives and the pursuit of equitable and sustainable growth.

2. LITERATURE REVIEW

2.1 DISPUTES IN CONSTRUCTION

Disputes in construction occur when conflicts between participants exist, and one party makes a claim which is rejected by the other (Yildizel et al., 2016). These disputes can arise from various issues such as contractual problems, delays, lack of communication, and design defects (El-Sayegh et al., 2020). Disputes in the construction industry have negative impacts on projects, leading to delays, loss of money, and occasionally project abandonment (Mashwama et al., 2019). While disputes in construction cannot be entirely avoided, they can be minimised by ensuring that all project details are clearly stated and executed according to the agreed-upon terms (Osuizugbo & Okuntade, 2020). Therefore, a practical approach should be implemented to minimise disputes in the project (Gunarathna et al., 2018).

2.2 AI APPLICATION FOR DISPUTE PREDICTION

According to Agus et al. (2023), an AI-driven system has the potential to transform the prediction of disputes. Machine learning, as defined by El Naqa and Murphy (2015), is a rapidly evolving field of computing algorithms designed to mimic human intelligence by acquiring knowledge from the surrounding environment. Using machine learning, a model could analyse past project data, contractual agreements, communication patterns, and other relevant factors to identify key risk indicators (Agus et al., 2023). This information, presented through a user-friendly interface, enables project teams to monitor potential conflict triggers in real time (Choi et al., 2021). Importantly, the AI models can predict the likely severity of disagreements, helping stakeholders prioritise actions and efficiently allocate resources for dispute resolution (Chou et al., 2014). The development and implementation of such technology can transform how the Sri Lankan construction sector predicts and resolves disputes. It empowers project managers, engineers, and stakeholders to make data-driven decisions, promoting proactive dispute resolution (Choi et al., 2021). By anticipating disputes, AI technology can prevent costly escalations, and unhealthy relationships, and ensure the projects are completed on time and within the allocated budget. Eventually, this could enhance the overall efficiency, productivity, and reputation of Sri Lanka's construction industry (Sandagomika et al., 2020).

Machine learning algorithms designed to mimic human intelligence by acquiring knowledge from the surrounding environment operate as computational procedures, accomplishing tasks using input data without requiring explicit programming for predetermined results, as emphasised in the text (Horvitz & Mulligan, 2015). Unlike algorithms that are "hard-coded," these algorithms are "soft-coded," meaning they can alter and refine their structures based on repeated encounters or training (Molu & Goertz, 2014). During the training process, the input data is matched with the expected results, which enables the algorithm to fine-tune its configuration. This optimisation allows the algorithm to not only produce desirable outcomes using the training data, yet generalise and perform efficiently with the latest, undetected data (Regona et al., 2022). Training is the phase of machine learning that encompasses the process of "learning". Notably, the process of learning described above is not limited to a specific time frame. Like humans, a skilled algorithm can engage in continuous learning, referred to as "lifelong" learning, by consistently analysing fresh data and gaining knowledge from its errors (Liu, 2017). Supervised learning is considered a category of machine learning concept where the model is trained using labelled data in the training dataset, which means that the features which are selected for the training of the model are based on the labelled data (Zhou, 2018). Different algorithms generate functions that establish a correspondence between inputs and desired outcomes. An example involves classification tasks in which the algorithm is learning to estimate a function which maps input vectors to certain classes, identified as dependent on given input-output samples (Regona et al., 2022). Unsupervised learning is referred to as a type of machine learning where a model is trained by considering the unlabelled data without any specific guidance or supervision of the user. It is the process of representing a group of inputs without having any label or categorisation (Zhou, 2018). Furthermore, reinforcement learning is an algorithm that can be used to learn how to make decisions by observing the environment and receiving feedback which can be used to guide the learning process, as the actions taken by the algorithm can lead to an impact on the environment. Learning to learn, the algorithm develops its own predefined biases based on past experiences (Caruana, 1993). In addition to these categories, machine learning algorithms are widely classified as supervised and unsupervised learning. In the context of supervised learning, predetermined categories are assigned to labelled data segments, which can usually be annotated by humans (Carcillo et al., 2021). The algorithm's main objective is to detect patterns and create mathematical models, which can be used to assess based on their predicted accuracy compared to measurements of data variation.

2.3 RESEARCH GAP

This research mainly focused on the construction industry of Sri Lanka because current approaches to dispute prediction in Sri Lanka frequently rely on subjective assessments and expert judgment (Gunarathna et al., 2018). While useful, such methods have limitations in terms of scalability, consistency, and the ability to analyse large amounts of data to find hidden patterns. Further, the traditional approaches may struggle to predict the cumulative impact of several risk factors throughout the various stages of a construction project (Wang et al., 2018). The lack of dependable early warning techniques limits stakeholders' ability to proactively minimise possible disagreements and implement informed contingency plans (Osuizugbo & Okuntade, 2020).

3. METHODOLOGY

This study adopted a mixed-method research approach to develop an AI-powered predictive model for construction disputes in the Sri Lankan context. A mixed methods design strategically combines quantitative and qualitative research techniques to gain a comprehensive understanding of the complex factors contributing to disputes and to provide robust data for model development. Initial quantitative data collection, using a structured questionnaire and survey, allowed for the identification and measurement of key variables influencing dispute occurrence within historical projects. Qualitative insights, garnered through expert interviews, enriched the understanding of these variables and contextualised the Sri Lankan construction industry's unique dispute landscape. This integrated approach provided a rich dataset, subsequently used to train, optimise, and validate the AI-driven dispute prediction model by having a test run with the practically running projects.

3.1 DATA COLLECTION TECHNIQUES

Expert interviews were employed as a qualitative data collection technique to gain in-depth insights into the complex factors contributing to construction disputes within the Sri Lankan context. These semi-structured interviews targeted industry veterans such as project managers, architects, engineers, and legal professionals, whose extensive experience and specialised knowledge provided valuable perspectives on the causes, consequences, and potential mitigation strategies for construction disputes. The qualitative data derived from these interviews was crucial for enriching the understanding of the quantitative findings gathered through the questionnaire and survey, later strengthening the foundation for the AI model's development.

A meticulously designed questionnaire constituted a primary data collection instrument in this study. The questionnaire was developed based on an extensive literature review and insights gathered from expert interviews, ensuring its focus on critical variables influencing construction disputes in Sri Lanka. A systematic distribution of the questionnaire targeted professionals involved in past or ongoing construction projects, yielding a substantial dataset. This dataset provided quantifiable information regarding project attributes, dispute occurrences, resolution methods, and the perceived impact of various factors on dispute likelihood. The structured nature of the questionnaire allowed for statistical analysis, which played a pivotal role in identifying key patterns and predictors for the AI model.

4. ANALYSIS AND FINDINGS

4.1 METHODS FOR ANALYSING AND DEVELOPING COMPLEX DATA SETS

The set of training data for the machine learning model is generated by applying the underlying logic from the data analysis using Python code. This entails defining construction projects as being the location, type, value, time duration, complexity, and claims of a project. Through extrapolation of these logical rules, the dataset is used in capturing pertinent information that is required in training an AI model for purposes of forecasting the occurrence of potential disputes within construction projects. In line with this, the flow diagram of the proposed model was developed, which outlines the stages of obtaining data on the sources and number of disputes as well as the necessary precautions for utilising clean data and minimising the problem of leakage. The concern with the attributes results from the fact that they are significant in profiling projects and having connections with disputes. The paper has extended the model by adding more parameters that are associated with disputes and these additions further enhance its predictiveness. Organisational dynamics and effectiveness are focal in the development process to provide a dependable information set for future construction disputes. Thus, though there are problems with the efficiency of implemented algorithms, the refined dataset and the training strive to approach errors to manage decisions and risks in constructions.

4.1.1 Findings from Questionnaire Survey

The graph compares the disputed amount with project value, project duration, and complexity (Refer to Figure 1). Analysing this graph led to the following logical findings:

- When the project value increases disputed amount also increases showing a positive relationship.
- Similarly, when the duration of the project increases the disputed amount is also increasing therefore those two attributes show a positive relationship.
- Likewise, when the level of complexity of the project increases, it further affects the increase of the disputed amount showing a positive relationship.
- In conclusion, all the attributes that are considered for drafting the graph have a positive relationship with the disputed amount.

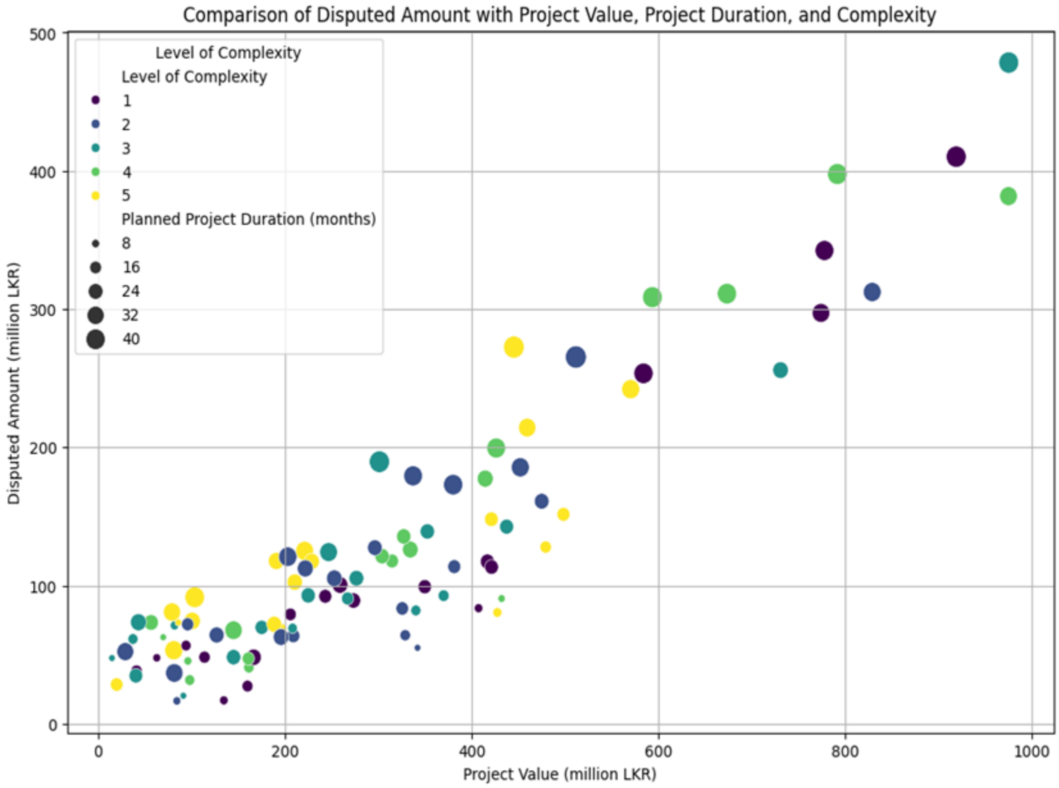


Figure 1: Relationship between disputed amount, project value and complexity

4.1.2 Findings from Expert Interviews

Generic factors that are influenced by the occurrence of construction disputes were analysed through the literature review and expert opinions about the analysed factors were identified using the manual content analysis. These identified factors which are affecting the construction disputes validated by the industry experts, were carried forward to the questionnaire rounds. Then, the finalisation of the conceptual model, intended for use in developing a machine learning model, was undertaken.

4.2 EVOLUTION FROM PRELIMINARY MODEL TO AI MODEL

Figure 2 depicts the sequence of the advancement stages of the model.

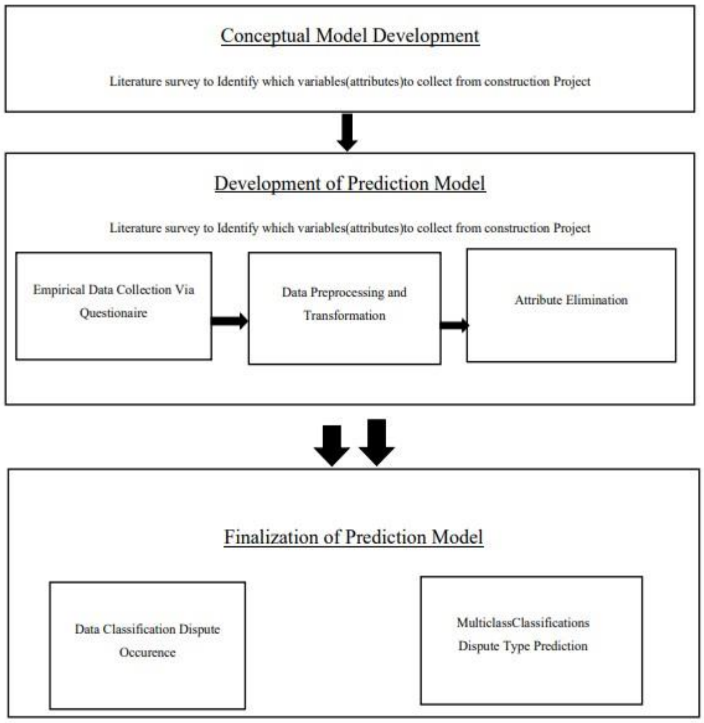


Figure 2: Evolution of models

The stages begin with the ideation phase and gradually progress to the AI implementation stage. This was enabled using well-known data collection techniques such as intensive literature research, and access to a very wide cross-section of experts from within the industry. Each stage of the process involved, was an important milestone that brought about invaluable feedback, many refinements of the model and the model becoming increasingly sophisticated all the time.

This type of iterative journey, as a result, led to the design of a highly satisfying predictive model that represents the intersection of practicality and sophistication. The key point of this approach was the application of data classification machine learning, chosen and adjusted to consider the peculiarities of the domain of a problem. The aim of this algorithmic framework was firstly to maximise the data classification's potential allowing it to go together with the objective of the AI model. Formulating such a strategy signifies our thorough knowledge coupled with awareness about the complexity existing within the issue space thereby, evoking the need for using the latest computational tools to get access to the operational insight from a data set composed of complex sets. The machine learning framework has been established; this model surpasses the limitations of traditional analytics. As a result, it exhibits the potential for growth and scalability and provides a custom solution for the ever-evolving demands of the construction sector. In summary, it is through a necessary blend of theoretical frameworks, empirical observations, as well as computational wizardry that the models combine state-of-the-art innovation and cutting-edge technology, a testimony to the unreserved dedication to the advancement of predictive analytics.

4.3 FINDINGS FROM LITERATURE REVIEW AND EXPERT INTERVIEW

4.3.1 Features Related to Project Characteristics

Project characteristics and contract-related project characteristics make up the first group of input factors which are affecting for happening construction disputes. The results of the literature review indicate that eleven characteristics fall within this group. Namely, the characteristics are as follows:

- Project location
- Project or contract value
- Purpose of the construction
- Category of the contractor (i.e., joint venture, consortium)
- Type of employer (i.e., public, private, PPP)
- Type of contract
- Method of the payment (i.e., unit price, fixed price)
- Delivery system of the project (i.e., DBB, DB)
- Design complexity of the project
- Construction complexity of the project

4.3.2 Features Related to Skills

The category of the skill includes features based on the stakeholders participating in the project and the characteristics of the organisation. According to the literature survey results, this category includes eight attributes:

i. Bond between related stakeholders/individuals,
ii. Years of experience in the construction project (credibility),
iii. Remedies for avoiding disputes,
iv. Communication build-up between stakeholders,
v. Working background cultural features,
vi. Replying rate and community skills,
vii. Relevant project experience, and
viii. Management and coordination skills.

4.3.3 Unexpected Events

The next type of feature selection is 'Changes', which refers to the occurrence of variations, changes, or unforeseen events throughout a construction project. It includes research that discusses the influence of variation on construction conflicts and resolution method selection, as known as the prominence of this variation in the literature, along with the total number of articles that reference them.

4.3.4 Delays

This category examines the influence of delays effect on construction conflicts. It is used to capture the impact of construction project delays. This category considers delays as a factor influencing the type of dispute, and settlement options.

4.3.5 Dispute Background Characteristics

This category of features involves background attributes related to characteristics of a dispute which can be named ‘Dispute Characteristics’. Eleven number of attributes were found in this category from the literature survey. These attributes are:

- Dispute affected party
- Dispute happening phase
- Sources that cause the dispute
- Whether there are any suspensions/termination
- Total amount affected by the dispute (financially)
- Agreed amount to resolve the dispute (financially)
- Rate of success (financially)
- Whether there are any EOT claims.
- Amount affected due to EOT
- Agreed settlement for the EOT claim
- Rate of the success of the EOT claim

4.3.6 Method of Resolution Features

This categorisation of features involves characteristics related to the dispute. Therefore, the category is named ‘Method of Resolution Features’. There can be numerous characteristics in this category, and they mirror the expectation from the resolution method and order of the selected method. These attributes are:

- Cost for the resolution method selected
- Duration taken by the method selected to resolve the dispute
- Satisfaction level of the resolution method
- Level of importance to preserve relationship
- Speed level of resolving the problem
- Considerable cost regarding solving the problem
- Bindingness importance
- Confidential level of the dispute-resolving method
- Level of fairness in the selected process
- Level of flexibility of the selected process
- Level of control over the selected process
- Level of importance of having the remedy
- Level of importance and willingness of the parties to come into a settlement.

4.3.7 Level of Knowledge Related to Resolution Method

This category mainly focuses on the effect of the potential level of knowledge of the parties who are engaged in the process of decision-making about specific resolution methods and the selection of the best matching resolution strategy or method in a systematic order.

4.3.8 Machine Learning Model Development Using Conceptual Model

A web application has been developed using the Python framework Flask and a machine-learning model to predict the occurrence characteristics of disputes based on project inputs (refer to Figure 3).

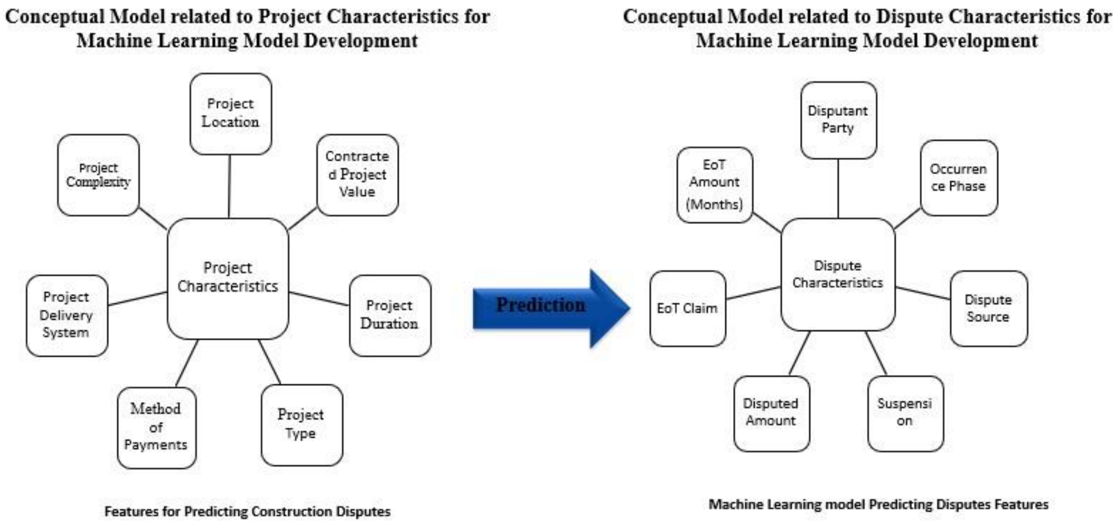


Figure 3: Input data and predicted data

The web application accepts inputs related to project characteristics, which are then passed to the trained machine learning model for prediction. The results from the machine learning model are displayed on the front end of the web application.

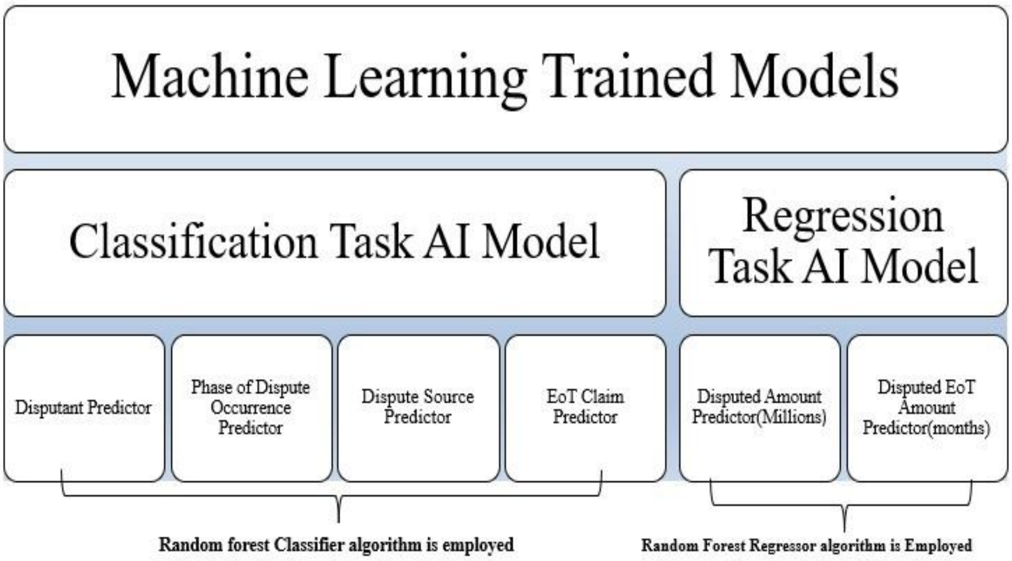


Figure 4: Trained AI models

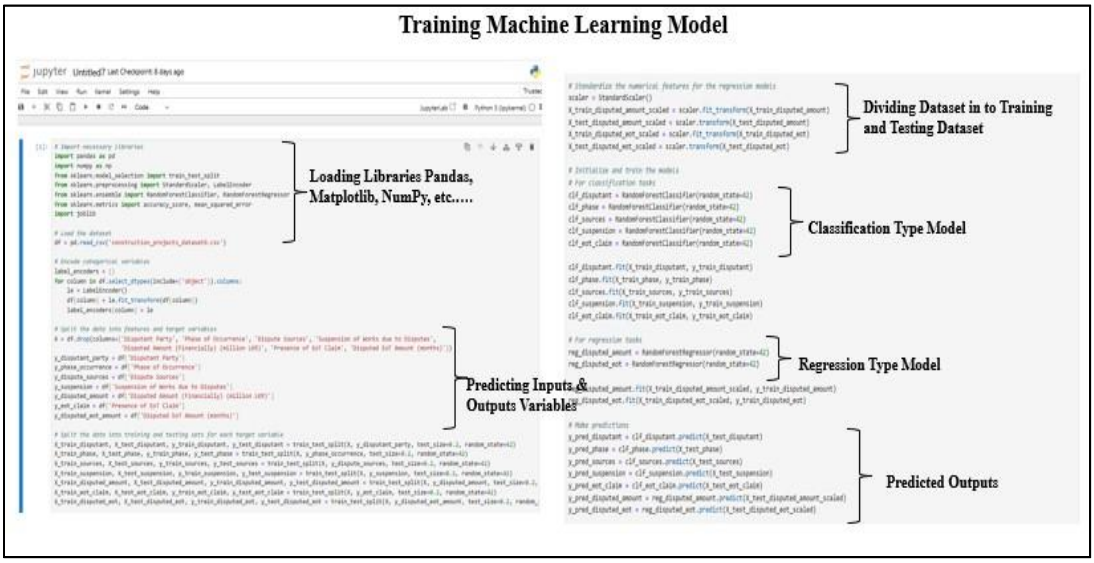


Figure 5: Training machine learning models

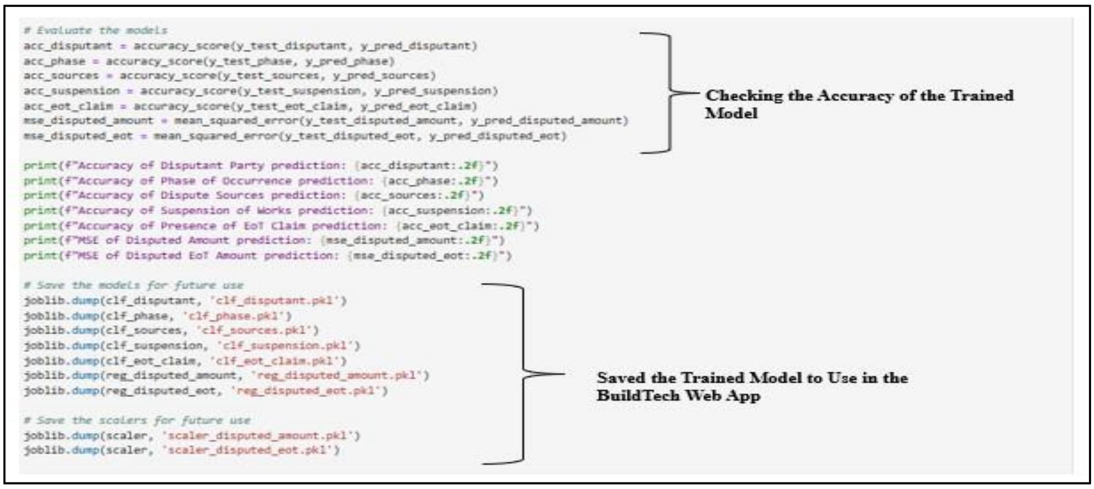


Figure 6: Training machine learning models

4.3.9 Proposed AI Web Application for Dispute Prediction

The recommended solution for applying AI to predict construction disputes is a construction dispute management system designed to serve as an intermediary for dispute avoidance. The system should include:

- Login page where the user can log in to the system using his/her email and a password.
- Registration page where a user can register for the system and can have access to other features in the dispute management system.
- Dashboard which showcases the performance or the accuracy of the dispute prediction model.
- Interface consisted of the reports which are prepared for the project.

- Interface which gives brief details about the project in which the system login party is involved.
- Dispute prediction page where the disputed amount, dispute source, and the dispute occurrence phase are predicted using other variables.
- ‘Build Tech’ is the suggested name for the dispute management system.

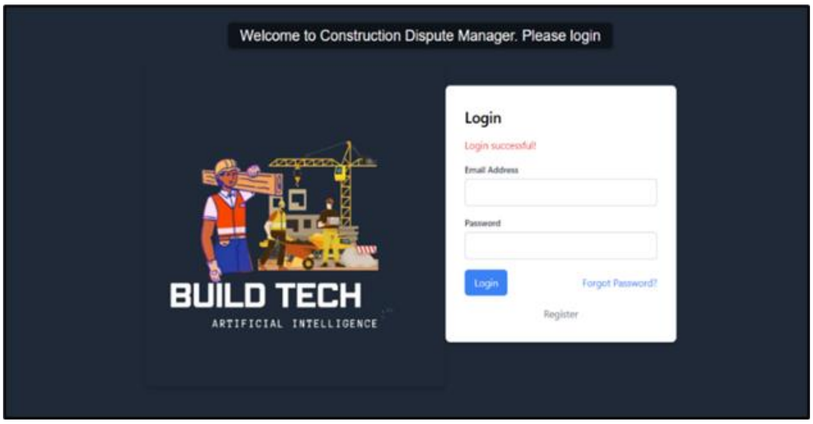


Figure 7: Proposed Flask web app solution

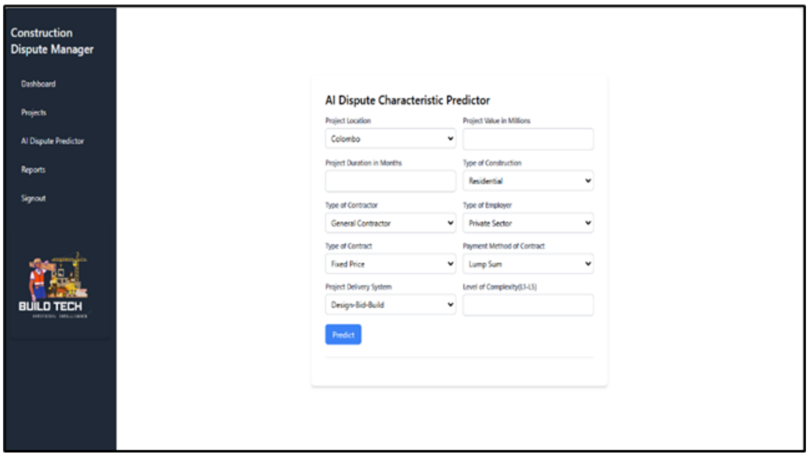


Figure 8: Proposed Flask web app solution

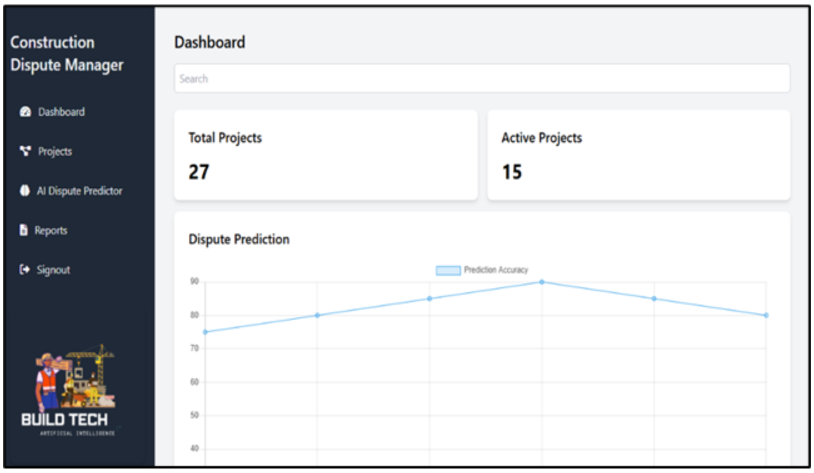


Figure 9: Proposed Flask web app solution

5. CONCLUSIONS

The study has facilitated the successful research of an innovative predictive model for construction disputes in Sri Lanka, which is incorporated with AI technology in the first life cycle phase of a project. The study adopted a mixed-measurement research design where the author conducted a cross-sectional survey and interviewed technical experts in the Sri Lankan construction industry to explore potential sources of dispute.

The predictive model has been calibrated considering the potential of adversarial situations given features that are associated with conflict risks such as breached contractual terms, unrealistic schedules, payment issues, communication breakdowns, and adverse ground conditions. It can aid construction project stakeholders to adopt effective and timely strategies to avoid or minimise possible disputes and enhance the chances of optimising opportunities of post-improvement for the general betterment of the projects, in terms of possible time and cost overrun, as well as deterioration of friendly professional relations.

The long-term implications of this research are significant, as the widespread adoption of this AI model has the potential to reshape dispute management practices and promote a more collaborative and sustainable construction industry in Sri Lanka. By communicating early indicators of impending disputes to project teams, this advanced tool provides an opportunity for proactive response and the implementation of appropriate measures to prevent conflict escalation. This contributes to the successful completion of construction projects in the country.

6. REFERENCES

Abeysinghe, N., & Jayathilaka, R. (2022). Factors influencing the timely completion of construction projects in Sri Lanka. *PLOS ONE*, *17*. https://doi.org/10.1371/journal.pone.0278318

Agus, A., Sudirman, S., Umar, W., & Rustan, A. (2023). The use of artificial intelligence in dispute resolution through arbitration: The potential and challenges. *SASI*, *29*(3), 570. https://doi.org/10.47268/sasi.v29i3.1393

Arfazadeh, H. (2014). Arbitrability under the New York convention: the Lex Fori revisited, *Arbitration International*, *17*(1) 73–88. https://doi.org/10.1023/A:1008994201415

Assaf, S., Hassanain, M. A., Abdallah, A., Sayed, A. M. Z., & Alshahrani, A. (2019). Significant causes of claims and disputes in construction projects in Saudi Arabia. *Built Environment Project and Asset Management*, *9*(5), 597–615. https://doi.org/10.1108/BEPAM-09-2018-0113

Carcillo, F., Le Borgne, Y. A., Caelen, O., Kessaci, Y., Oblé, F., & Bontempi, G. (2021). Combining unsupervised and supervised learning in credit card fraud detection. *Information Sciences*, *557*, 317–331. https://doi.org/10.1016/j.ins.2019.05.042

Caruana, R. A. (1993, June 27). *Multitask learning: A knowledge-based source of inductive bias*. *Machine Learning, 28*, 4175. https://doi.org/10.1016/b978-1-55860-307-3.50012-5

Choi, S. J., Choi, S. W., Kim, J. H., & Lee, E. B. (2021). Ai and text-mining applications for analyzing contractor's risk in invitation to bid (ITB) and contracts for engineering procurement and construction (EPC) projects. *Energies*, *14*(15), 4632. https://doi.org/10.3390/en14154632

Chou, J. S., Cheng, M. Y., Wu, Y. W., & Pham, A. D. (2014). Optimizing parameters of support vector machine using fast messy genetic algorithm for dispute classification. *Expert Systems with Applications*, *41*(8), 3955–3964. https://doi.org/10.1016/j.eswa.2013.12.035

Collier, P. (2020). Embedding the sustainability development goals in Survey Review's remit. *Survey Review*, *52*(373), 287-288. https://doi.org/10.1080/00396265.2020.1746020

El Naqa, I., & Murphy, M. J. (2015). What is machine learning? In *Machine learning in radiation oncology*. Springer International Publishing. https://doi.org/10.1007/978-3-319-18305-3_1

El-Sayegh, S., Ahmad, I., Aljanabi, M., Herzallah, R., Metry, S., & El-Ashwal, O. (2020). Construction disputes in the UAE: Causes and resolution methods. *Buildings, 10*(10), 171. https://doi.org/10.3390/buildings10100171

Fei, W., Opoku, A., Agyekum, K., Oppon, J. A., Ahmed, V., Chen, C., & Lok, K. L. (2021). The critical role of the construction industry in achieving the sustainable development goals (Sdgs): Delivering projects for the common good. *Sustainability*, *13*(16). https://doi.org/10.3390/su13169112

Gunarathna, C., Yang, R. J., & Fernando, N. G. (2018). Conflicts and management styles in the Sri Lankan commercial building sector. *Engineering, Construction and Architectural Management*, *25*(2), 178-201. https://doi.org/10.1108/ECAM-10-2016-0233

Horvitz, E., & Mulligan, D. (2015). Data, privacy, and the greater good. *Science*, *349*(6245), 253–255. https://doi.org/10.1126/science.aac4520

Ikechukwu, A. C., Emoh, F. I., & Kelvin, O. A. (2017). Causes and effects of cost overruns in public building construction projects delivery, in Imo State, Nigeria. *Journal of Business and Management*, *19*(7), 13–20. https://doi.org/10.9790/487x-1907021320

Liu, B. (2017). Lifelong machine learning: A paradigm for continuous learning. *Frontiers of Computer Science*, *11*(3), 359–361. https://doi.org/10.1007/s11704-016-6903-6

Marciano, A., & Ramello, G. B. (2019). Introduction to the symposium on the empirics of judicial institutions. *Journal of Institutional Economics*, *15*(1), 73–80. https://doi.org/10.1017/S1744137418000322

Mashwama, N., Thwala, W. D., & Aigbavboa, C. O. (2019). The impact of construction disputes on projects in the Mpumalanga province of South Africa. In J.S. Miroslaw & M. Hajdu (Eds.), *Proceedings of the Creative Construction Conference* (pp. 454–461). https://doi.org/10.3311/CCC2019-063

Molu, M. M., & Goertz, N. (2014). A comparison of soft-coded and hard-coded relaying. *Transactions on Emerging Telecommunications Technologies*, *25*(3), 308–319. https://doi.org/10.1002/ett.2562

Osuizugbo I. C., & Okuntade, T. F. (2020). Conflict management practice among stakeholders in construction project delivery. *Covenant Journal in Research & Built Environment*, *8*(1). http://journals.covenantuniversity.edu.ng/index.php/cjrbe

Sandagomika, N. M. G. H., Sandanayake, Y., & Ekanayake, Biyanka. (2020). Drivers and barriers of using Internet of Things for successful lean implementation in construction projects in Sri Lanka. *FARU Journal*, *7*(12). https://doi.org/10.4038/faruj.v7i0.26.

Serogina, D., Pushkar, T., & Zhovtiak, H. (2022). The impact of the construction industry on the social and economic development of territories. *Scientific Bulletin of the National Academy of Statistics, Accounting and Audit*, *1*(2), 59–65. https://doi.org/10.31767/nasoa.1-2-2021.08

Silva, G. A. S. K., Warnakulasuriya, B. N. F., & Arachchige, B. J. H. (2018). A review of the skill shortage challenge in construction industry in Sri Lanka. *International Journal of Economics, Business and Management Research*, *2*(1). https://www.researchgate.net/publication/320263862_a_review_of_the_skill_shortage_challenge_in_construction_industry_in_sri_lanka

Walsh, T. W., & Llp, C. (2007). The LCIA court decisions on challenges to arbitrators: An introduction. *Arbitration International*, *1*(3). http://arbitration.oxfordjournals.org/

Wang, L., Zhang, H., Wang, J., & Li, L. (2018). Picture fuzzy normalized projection-based VIKOR method for the risk evaluation of construction project. *Applied Soft Computing Journal*, *64*, 216–226. https://doi.org/10.1016/j.asoc.2017.12.014

Yildizel, S. A., Dogan, E., Kaplan, G., & Ergut, A. (2016). Major constructional dispute causes in Turkey. *Archives of Civil Engineering*, *4*(2). http://archive.sciendo.com/ACE/ace.2016.62.issue-4/ace-2015-0116/ace-2015-0116.pdf

Zhou, Z. H. (2018). A brief introduction to weakly supervised learning. In *National Science Review*. Oxford University Press. https://doi.org/10.1093/nsr/nwx106

Samaranayake, H.S.A.J. and Cooray, S.B.A., 2024. An examination of green space exposure for well-being: A case study of Colombo city. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 146-158. DOI: https://doi.org/10.31705/WCS.2024.12. Available from: https://ciobwcs.com/papers/

AN EXAMINATION OF GREEN SPACE EXPOSURE FOR WELL-BEING: A CASE STUDY OF COLOMBO CITY

H.S.A.J. Samaranayake[1] and S.B.A. Coorey[2]

ABSTRACT

The rapid increase in population density has led to a scarcity of green spaces and limited access to green space for urban dwellers. Green spaces play an important role in promoting human well-being; both socially and psychologically. Ensuring equal access to green spaces is essential for creating equitable cities. When everyone has the opportunity to enjoy parks, gardens, and natural areas, it contributes to a healthier and more inclusive urban environment. However, Colombo, Sri Lanka's bustling city faces challenges in providing habitable and accessible green areas for its residents. This paper aims to assess green space exposure in the city of Colombo. The study examines the provisions, distribution, and accessibility of green areas across CMC's administrative areas, including North Colombo, Central Colombo 1, Central Colombo 2, Colombo East, Colombo West, and Borella. By using a multidimensional approach that combines ArcGIS mapping, spatial tools, population statistics, and remote sensing (via NDVI mapping), the research explores green space availability and proximity-based accessibility for the diverse urban population. This investigation is crucial for informed urban planning and enhancing the quality of life for Colombo's residents.

Keywords: *Green Space; Green Infrastructure; GIS; Green Space Exposure; Remote Sensing; Urban; Wellbeing.*

1. INTRODUCTION

Urbanisation is a worldwide phenomenon that refers to the increasing concentration of populations in urban areas, resulting in the growth and expansion of cities. It encompasses various social, economic, and environmental changes, leading to transformations in landscapes and lifestyles (Teleaga, 2020). The United Nations predicts that by 2050, there will be 6.252 billion people living in urban areas around the world, with an anticipated urbanisation rate of 67.2%. Rapid urbanisation has resulted in an increase in built areas and reduction and loss of urban green spaces and natural environments. The provisions and access to green spaces in cities is a United Nations Sustainable Development Goal (Goal No. 11.7), which aims to provide universal access to safe, inclusive, and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities by the year 2030 (WHO Regional Office for Europe, 2016). The benefits and contributions of green spaces are many. They contribute to improving physical and

[1] Landscape Architecture Graduate, Bachelor of Landscape Programme, Department of Architecture, University of Moratuwa, Sri Lanka, samaranayakahsaj.19@uom.lk
[2] Senior Lecturer, Department of Architecture, University of Moratuwa, scoorey@uom.lk

mental health, social interaction, and opportunity for active lifestyle and relaxation. They provide physical comfort by improving air quality, providing shade, mitigating urban heat island effects and enhancing the overall environmental quality of cities.

The loss of green spaces in cities contributes to decrease in physical activity, increased stress, and decreased social cohesion. International organisations and institutions have expressed the minimum limits for per capita green space, for overall wellbeing. UN expressed that the per capita green space should be more than 30m^2, European Union (EU) says it has to be over 26m^2, while the World Health Organisation (WHO) recommends it should be more than 9m^2. (Lin & Pussella, 2016). However, the per capita green space in Colombo District has been significantly decreasing from 18.047m^2 in 2008 to 13.582m^2 in 2015, with a reduction of 4.46%. Hence, the predicted per capita green space in 2025 is 7.21m^2 (Lin & Pussella, 2016). There is a concern that there is inequality in the provisions and access to green space within Colombo's administrative area. Although Urban Regeneration Projects have been implemented to house significant numbers of urban poor in the North and North-Eastern parts of Colombo, there is a concern over the provision and access to green space, in the form of parks, urban pockets, green walkways, playgrounds, and urban landscapes. Thus, raising concerns on equality across neighbourhoods when considering the provisions and access to urban green space. The study examines the provisions, access and green space exposure across administrative areas within the Colombo Municipal Council.

2. GREEN INFRASTRUCTURE

2.1 INTRODUCTION TO GREEN INFRASTRUCTURE

Many researchers have traditionally defined green infrastructure based on its thematic relevance, use, and real-world applications, as well as terms relating to larger connections between nature and humans in evolutionary biology, psychological evolution, social economics, and conservation (WHO, 2016). Green infrastructure is a collection of natural materials that generates a life support system while also benefiting humans and other animals. Green infrastructure, as described by Benedict and McMahon (2006), is "An interconnected system of natural areas and other open areas that conserves biological ecosystem values and function, maintains clean air and water, and provides a wide range of benefits to people and wildlife".

2.1.1 Typologies of Green Infrastructure

Green infrastructure plays a vital role in providing Eco-System Services (ESS) across different scales. At micro and small scales, elements of green infrastructure contribute to supporting and regulating services, such as improving air quality and modifying microclimates. On a larger scale, green infrastructure extends its functions to provisioning services, including urban agriculture, and cultural services that connect people with nature and enhance well-being (Hansen et al., 2017; Nieuwenhuijsen, 2020).

The concept of green space has garnered significant interest and research, particularly regarding its impact on health and well-being. Despite decades of studies in both urban and rural contexts, a universally agreed-upon definition of green space remains elusive (Nieuwenhuijsen,2020).

WHO has recognised the lack of consensus regarding the definition of green space, especially in urban contexts. Across different academic disciplines, the definition of urban greens pace exhibits substantial variability (Taylor & Hochuli, 2017). Despite the lack of consensus, a few definitions of greens pace have gained traction in various fields. One widely accepted definition, derived from The European Urban Atlas, characterises green space as "public green areas used predominantly for recreation" (WHO, 2016). This definition primarily emphasises vegetated land accessible to the public, including spaces including public parks, gardens, forests, and natural areas.

2.2 GREEN SPACE EXPOSURE

Green space exposure refers to the extent and quality of individuals' interaction with natural environments, including parks, gardens, playgrounds, forests, and other vegetated areas. However, there have been limited studies on measuring green exposure, particularly in terms of proximity, availability, and quality of green space (Quid et al., 2023).

Green space is a broad term that encompasses both recreational and natural components. It includes everything from small urban parks and rivers to vast wilderness areas. Within this context, green spaces are often categorised into two groups: i.e., (i) unstructured green spaces, and (ii) structured green spaces (Markevych et al., 2017; Zhang et al., 2020). Vegetative cover, which encompasses elements such as street trees, residential greenery, and urban agriculture, falls under the category of unstructured green space. Moreover, structured green spaces refer to park-based areas with recreational amenities, such as playgrounds, sports fields, water parks, pocket parks, and squares (Quid et al, 2023).

2.2.1 Importance of Green Space Exposure for Human Health and Wellbeing

Numerous studies worldwide, especially in China, have explored the impact of green spaces on human health and well-being. These studies often focus on the psychological well-being of people in rapidly urbanised cities. Across environmental, social, and health sciences, there is consensus on the positive effects of nature encounters on mental health. As urbanisation continues and global contact with nature decreases, safeguarding and enhancing opportunities for nature experiences become crucial. Green areas hold significant potential for improving public health.

2.2.2 Impact of Green Space Exposure on the Environment

Green spaces in cities improves the overall environmental sustainability. Green spaces help to reduce the impact of the urban heat island effect by providing shade, lowering temperatures, and improving air quality by absorbing pollutants and producing Oxygen.

According to Chiesura (2004; as referenced in Assali, 2015), trees help to purify the air by absorbing Carbon Dioxide and creating Oxygen, as well as boosting quality of life. Green spaces, helps in maintaining biodiversity and promotes ecological balance in urban ecosystems by providing habitat for a variety of plant and animal species. They help manage storm water runoff, reduce flood risk, and improve water quality through natural filtration systems.

2.2.3 Impact of Green Space Exposure on Physical and Mental Wellbeing

Green areas offer valuable opportunities for physical activity, including walking, running, and leisure pursuits. Engaging in these activities contributes to improved physical health and fitness, benefiting both the body and mind. Exposure to green spaces and natural environments has been linked to reduced stress, enhanced mood, and better mental health.

Access to green areas has also been associated with lower rates of obesity, cardiovascular disease, and mental health challenges. Researchers, such as Ward et al. (2016), have found that physical activity and exposure to green spaces are independently connected to various aspects of child development, including emotional well-being and cognitive abilities. Nature also provides specific environmental stimuli necessary for recovering from attention fatigue a state that occurs during sustained cognitive tasks requiring directed attention (Kaplan,1995). Nature facilitates psychophysiological stress recovery through innate, adaptive responses to natural settings. Characteristics such as spatial openness, patterns or structures, and water features trigger positive emotional reactions related to security and survival (Ulrich,1983). Given the global trend of urbanisation and reduced human contact with nature, it is crucial to protect and enhance opportunities for nature experiences. Green areas hold significant potential for improving public health in diverse ways.

2.2.4 Impact of Green Space Exposure on Social Wellbeing

Parks and green spaces play a vital role in fostering social interaction and community building. They serve as meeting places, providing spaces for social gatherings, leisure activities, and get-togethers that promote social cohesion. By reducing social isolation and strengthening community bonds, green spaces contribute to a sense of belonging.

Beyond their social impact, green spaces enhance the aesthetics of urban areas. Amid the built environment, well-designed parks, gardens, and landscapes offer visual respite, evoking feelings of beauty, calm, and relaxation. These aesthetically pleasing settings improve both the surroundings and residents' quality of life. Moreover, green spaces contribute to sustainable urban design. They enhance climate resilience and are critical components of sound design principles.

2.3 ASSESSMENT OF GREEN SPACE

2.3.1 Green Space Availability

Structured Green Spaces

Structured green spaces are planned and managed green spaces within urban environments that serve multiple purposes. These are spaces designed to enhance the quality of life for residents. They contribute to the environmental quality of cities. Typical structured green spaces as parks play areas, grounds, greenways, and conservation areas. In this study the mapping of structured green spaces was done using Google Earth in ArcGIS using data files and digital maps from CMC and Google Earth (refer to Figure 2).

Greenness: measured by Normalised Difference Vegetation Index (NDVI)

The NDVI is a measure of how much live, green vegetation is present in an area; an indicator of an area's 'greenness'(WHO Regional Office for Europe, 2016). NDVI is calculated from the light reflected by vegetation, considering that healthy plants contain more chlorophyll, which increases the absorption of visible light (and thus decreases its reflection) and increases the reflection of near-infrared light, yielding higher NDVI values. Less healthy or densely distributed vegetation, on the other hand, reflects more visible light and less near-infrared radiation, resulting in a lower NDVI rating. This index considers every element of vegetation from satellite imagery, thus measuring far more than just urban green spaces. It is based on vegetation health, which may be affected by the season in which the images were captured as well as the plants' life cycle (Martinez

& Labib, 2023). For the NDVI analysis, satellite imagery was downloaded from land sat data using Earth Explorer website (downloaded data in time 2022-2023) and applied in ArcGIS with the equation of NDVI analysis in the field calculation option. The reclassify tool was used to analyse the high and low areas of the NDVI output map (refer to Figure 5).

2.3.2 Proximity-Based Accessibility

The buffer and network analysis approaches are the most commonly used methods for computing green space accessibility. Nicholls (2001) examined the two methods and determined that the latter is the most accurate. The buffer analysis is a Euclidean distance-based method that assumes people can move in straight lines within urban tissue, which is not typical of reality and may result in overestimation. Proximity-based accessibility is another parameter that green exposure studies used, when measuring accessibility within a 15-minute walking time distance, the alternative of using green areas' centroids as starting points of service areas is shown to have no significant impact compared to using public green spaces' access points (Giuliani et al., 2021).

Buffer Analysis

A buffer formed around a green area from a centroid method merely provides an estimate of how accessible a green space is to a group of people or a community (Nicholls, 2001). Kabisch et al. (2016) uses the buffer approach only estimate the amount of green space available to inhabitants by getting an idea of proximity to green spaces. Kabisch et al. (2016) built a boundary of 500m and 300m around the UGS examined for the study using data from Urban Atlas and municipal land-use data, and then intersected grid cells containing population data with these buffers, aggregating the result per city. WHO suggests that the consistent service distance of green space is 300 m hence this study uses a buffer range of 100m-300m. For the purpose of this study buffer analysis maps was created by using multiple buffer analysis, giving a 100m-300m radius from green space centroid (refer to Figure 4). Euclidean distance of 100m-300m was applied to identify how green spaces covered the buffer area of each district.

Network Service Analysis

The network analysis (Nicholls, 2001) is a more appropriate alternative considering space accessibility because it uses actual travel distances (in time and distance) and can be measured from starting points to urban green areas in a much more realistic way by using accurate road networks. Furthermore, it evaluates the green area's periphery rather than its centre, considering its shape, Both Nicholls (2001) and Gupta et al. (2016) compared both methods in previous papers, with the exception that the latter used remote sensing data; however, both concluded that the straight-line method and network measures have distinct differences in the level of accessibility (Nicholls, 2011). For this study, a pedestrian network was constructed using road network data (refer to Figure 4). Centroids were created for each green space and mapped the ranges of 100m-500m considering the WHO recommended human comfortable walking distance which is 400m-500m. Due to the absence of data on the location access points, centroids were constructed for each urban green space, as these provided a proxy for green space access point.

3. RESEARCH METHODOLOGY

The case study of Colombo administrative area was selected and six divisions i.e. (i) Colombo-North, (ii) Colombo-Central 1, (iii) Colombo-Central 2, (iv) Borella, (v) Colombo-West, and (vi) Colombo-East was explored for their open spaces and accessibility. This study was conducted by mapping the relevant data using the Arc GIS (version 10.8) tool. Parameters of green space availability and proximity is assessed. Using Arc GIS and remote sensing data, structured green space i.e. parks, playgrounds, communal gardens, and cemeteries were mapped through NDVI calculations and structured green space locations to explore green space exposure and availability. Proximity-based accessibility and network service analysis was done through the analysis of multiple buffer rings using Arc GIS spatial analysis tools. The spatial data (from 2010-2020) was obtained from the Urban Development Authority and Survey Department and Colombo Municipal Council. Census data of the year 2010 was obtained from Census and Static Department and remote sensing methods were used to obtain shape files (https://extract.bbbike.org/, Landsat imagery).

4. CASE STUDY AND ANALYSIS

4.1 CASE STUDY

Colombo city is located in the West coast of Sri Lanka between Northern latitudes 6◦55 to 6◦59 and Eastern longitudes 79◦50 to 79◦53 (refer to Figure 1). CMC administrative area is the region that encompasses the entire Colombo metropolitan area. It is the most significant local administrative authority in the country with an area over 37 km^2. The city is one of the oldest in South Asia (Senanayake at el., 2013). CMC area consists of 55 GN administrative divisions, the minor administrative units in the country. The study focuses on the Colombo municipal wards district, which encompasses various urban and densely populated areas. The selection of this study area is based on its significance as a central urban region in Sri Lanka, where green space exposure is of particular importance due to high population densities and urbanisation.

4.2 DATA ANALYSIS

The distribution of residential areas are shown in Figure 01 indicating a diverse distribution of residential clusters across Colombo-North, Central 1, Central 2, Borella, Colombo-East, and Colombo-West. However, Figure 02: the structured green space map shows that the green spaces are not equally distributed in the residential areas. It shows that Borella and Colombo-East has more provisions of green space as opposed to the other areas, where there are predominant residential clusters. The distribution of residential population, and amount of structured green spaces shows that there is a significant lack of green space availability in Colombo-North, Colombo Central-1 and Colombo-West. However, Colombo-West being in close proximity to the coast has the benefits of blue infrastructure as an alternative to green infrastructure. Colombo-North and Colombo-Central 1 are most deprived from green infrstarcture although observed as areas with high density of vulnerable low-income residents living in informal settlements and multistorey housing.

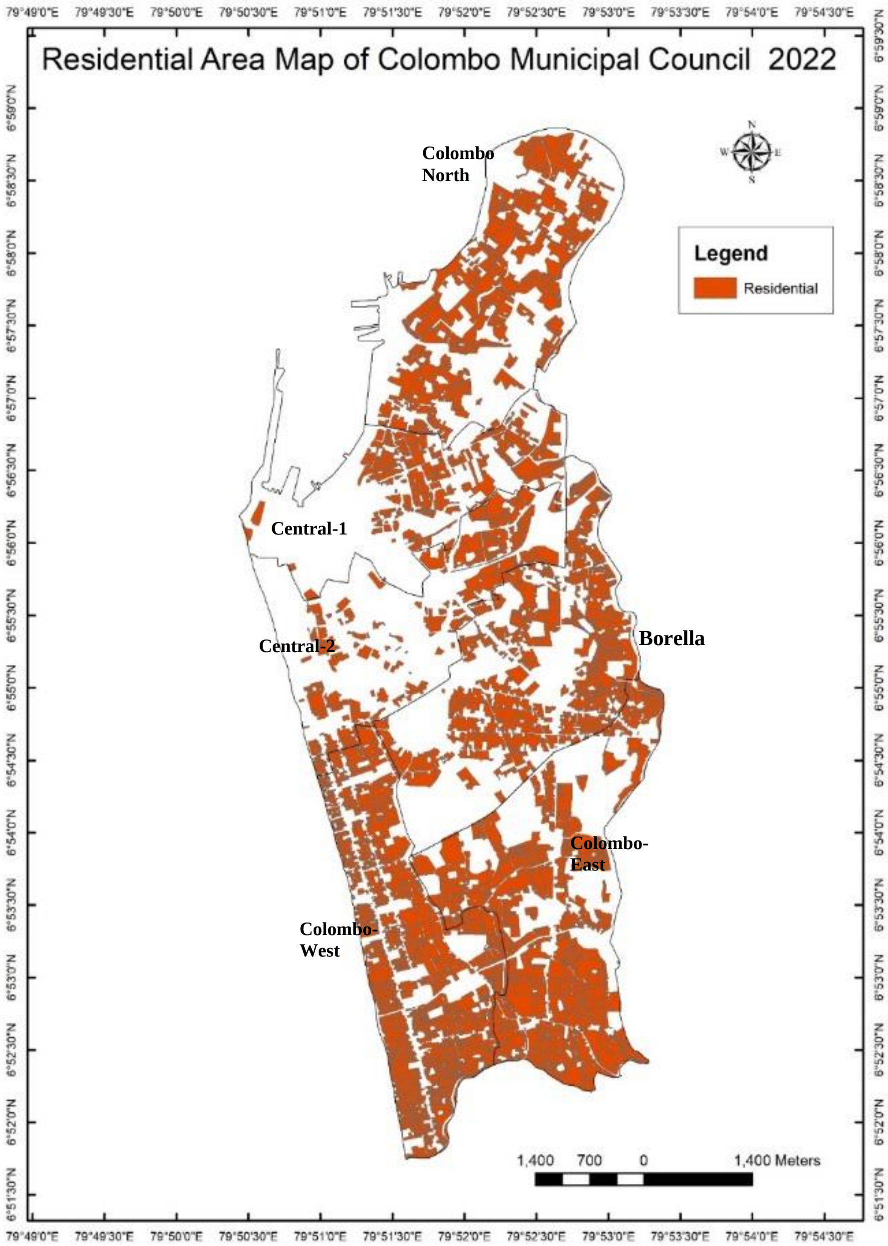


Figure 1: Residential distribution map in CMC area
Source: by author using GIS data

WHO recommended a minimum of $9m^2$ of green space per capita with an ideal UGS value of $50m^2$ per capita. As per Table 1, when comparing the green space per capita values across the Wards in CMC area it shows that only Borella is fulfilling the minimum green space standard set by the WHO while all other wards green space per capita is below the expected standards. As per Table 1 and Figures 1 and 2, it shows that high population sizes are in Colombo-North, Colombo-Central 1 and Colombo-Central 2 and they also have the lowest Green Space per capita.

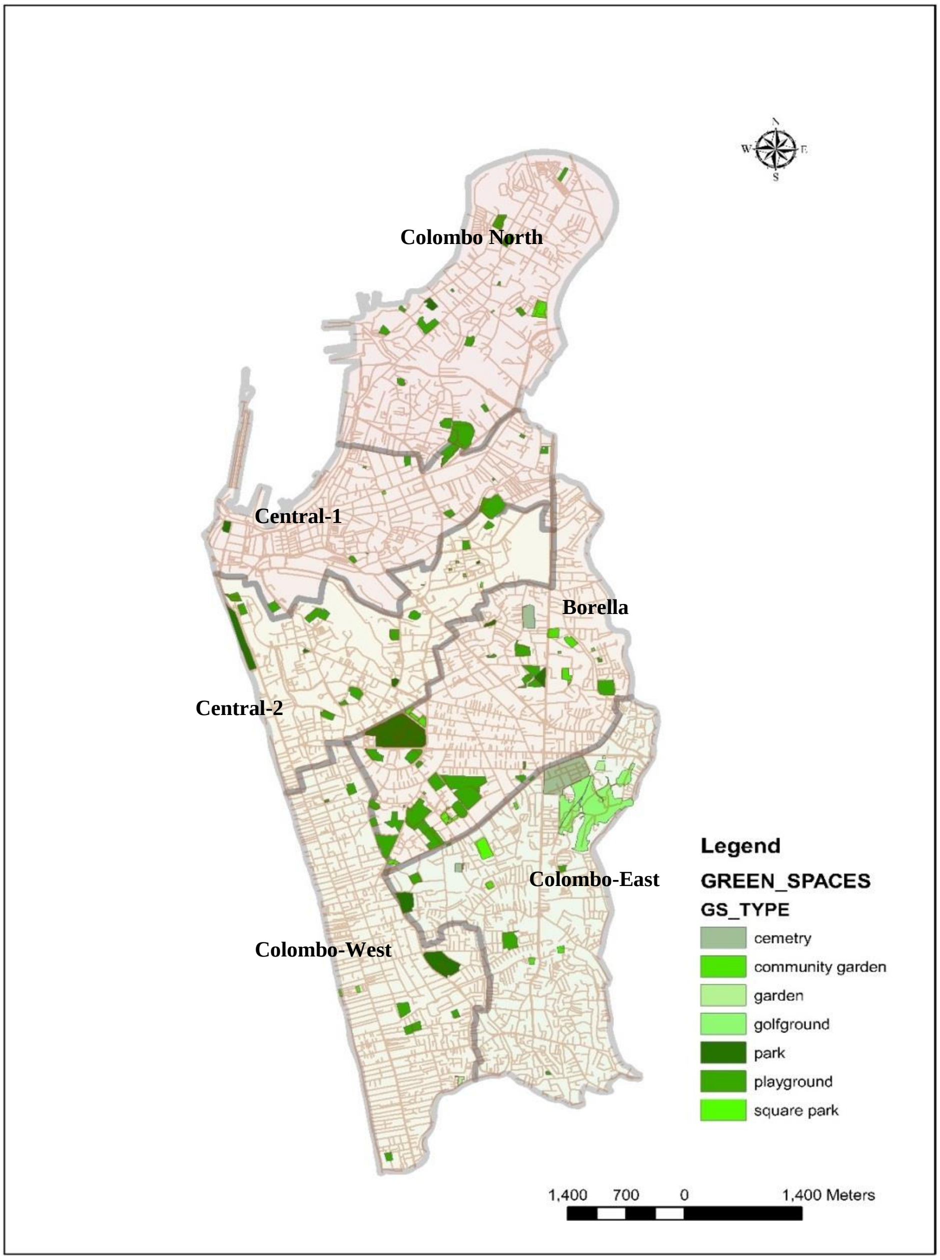


Figure 2: Structured green space distribution map in CMC area
Source: by author using GIS data

Table 1: Population and green cover across CMC area
Source: Data obtained by author using GIS maps (2024)

Municipal Ward	Total cover area (m^2)	Population	Green Space Cover Area (m^2)	Green Space per Capita
Colombo-North	7,343,928.23	123,799	332,975.75	2.689648139
Colombo-Central 1	3,835,416.72	117,693	141,924.5	1.205887351
Colombo-Central 2	5,856,100.96	131,723	224,139.68	1.701598658
Borella	7,559,916.18	94,907	910,763.32	9.596376663
Colombo-West	6,366,193.09	57,999	190,282.3	3.280785876

Colombo East	7,816,323.36	98,535	744511.81	7.555810727

As show in Figure 3, the structured green space network service map shows a 100-500m walking distance to green spaces considering road networks. Colombo-Central 1, Colombo-West, and Colombo-East areas significantly lack green space within 300-500m walking distance. Since Colombo-West is in close proximity to the coastal belt residents have access to "blue infrastructure" as an alternative. Some of the residential areas with a lack of access to green space are Kotahena East, Kotahena West, north of Mattakkuliya, and Blumedhal in Colombo-North. Figure 4; Buffer Analysis map highlights the green space buffer zones that indicate a Euclidean distance of 300m from the green spaces. This shows the 300m radius from green space irrespective of the road network walking distance. Several residential clusters in Colombo-North, Colombo-Central 1, Colombo-East, and Colombo-West lack green space distribution within 300m from residential areas. Colombo Central-2 and Borella areas have a comparatively better distribution of green space as per Figures 3 and 4.

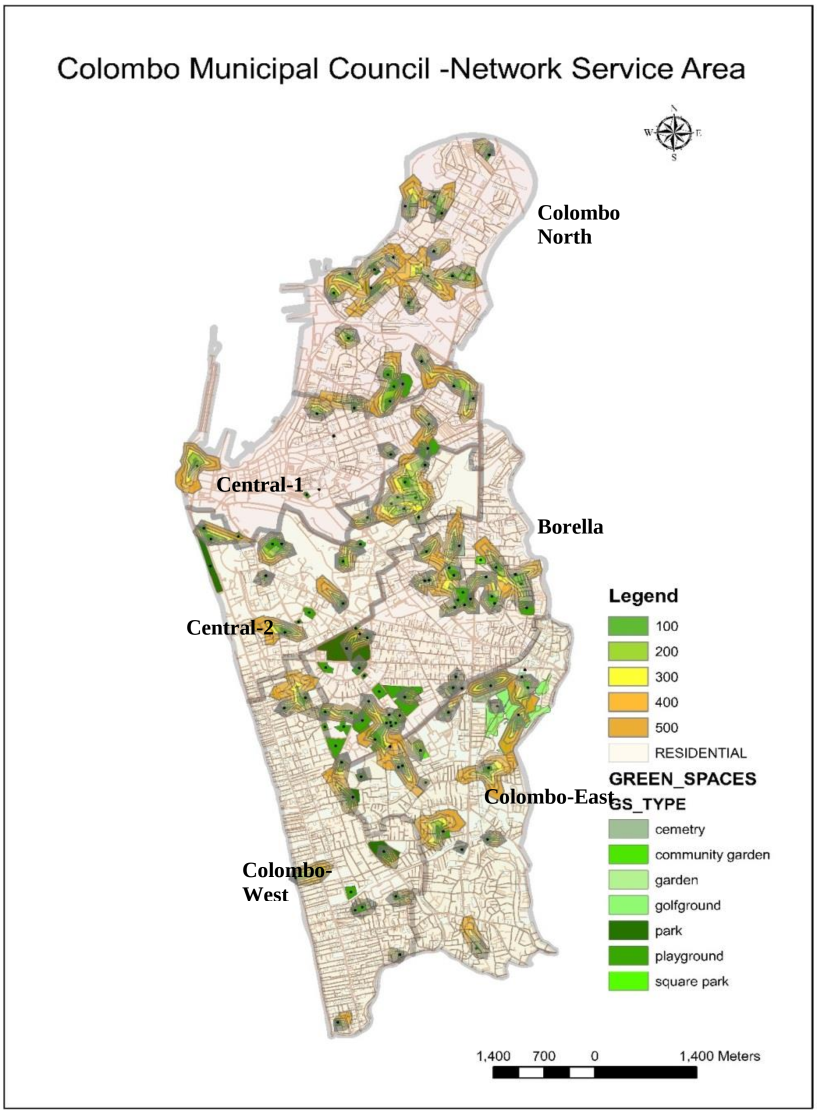


Figure 3: Network service from structured green space map in CMC area
Source: by author using GIS data

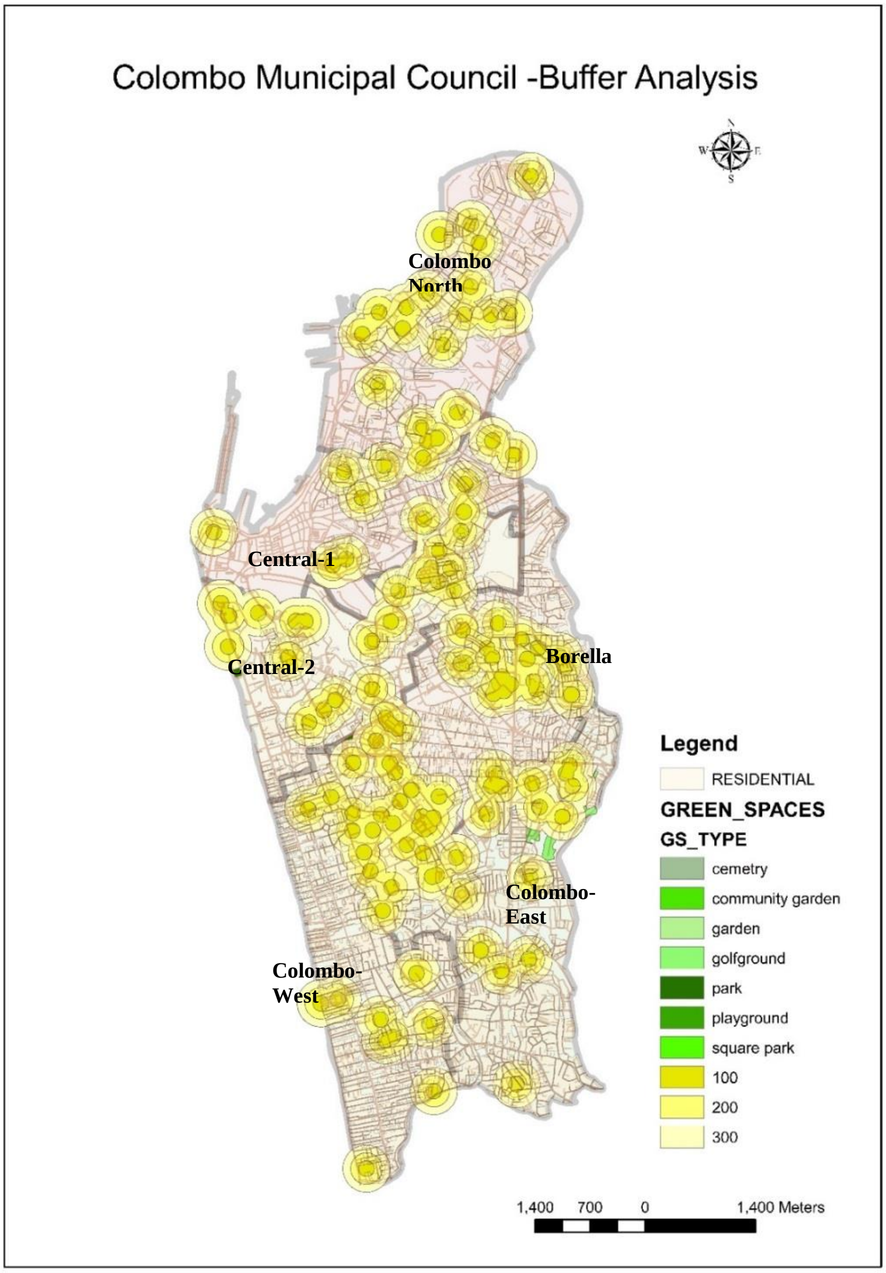


Figure 4: Euclidean radius distance buffer from structured green space map in CMC area
Source: by author using GIS data

NDVI map given in Figure 5 shows the exposure to both structured and unstructured green spaces. The high exposure is shown in green while lowest exposure is shown in red. The highest green space exposure is observed in Borella and Colombo-West. Colombo-North, Colombo-Central 1 and Colombo-West, has least exposure to green.

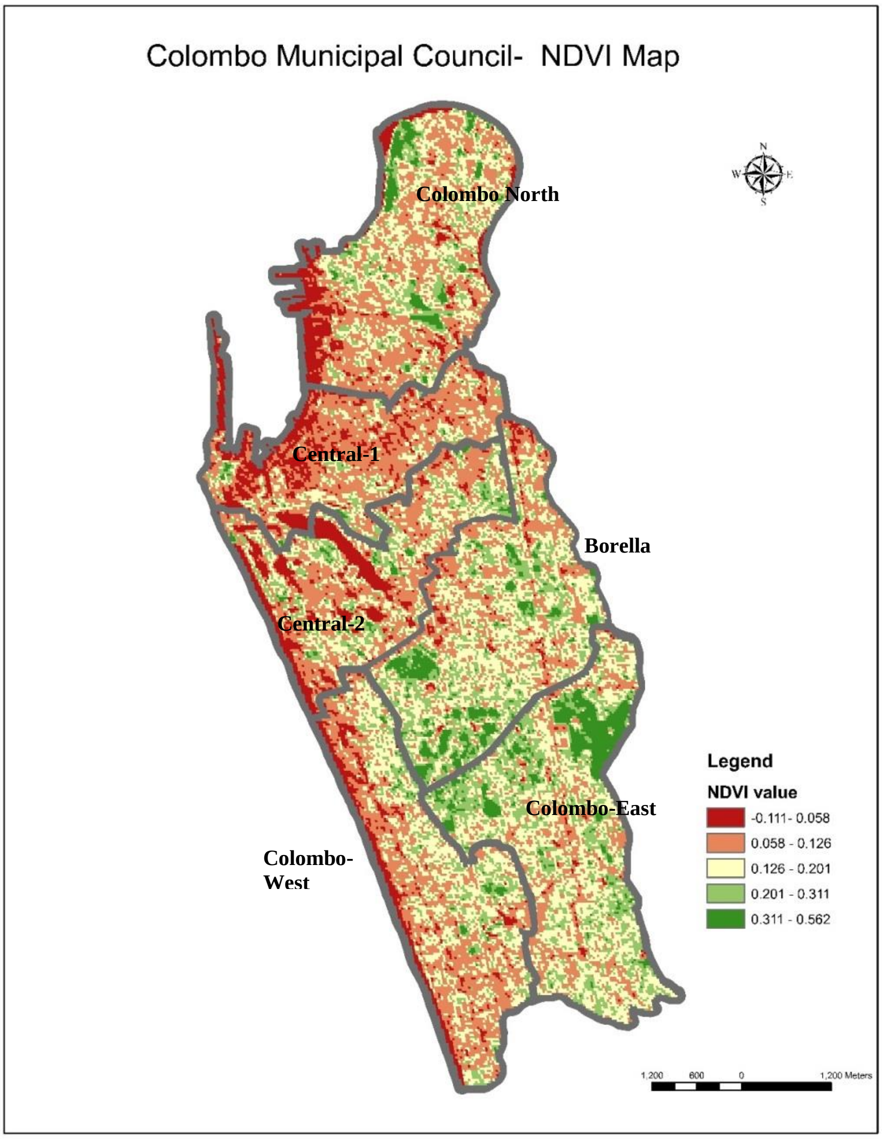


Figure 5: NDVI map in CMC area
Source: by author using GIS data

5. CONCLUSIONS

Green spaces are important components of urban infrastructure because they promote mental and physical health, social interaction, and provide a respite from the hustle and bustle of city life.

This study takes into account the green infrastructure within the CMC area and examines the buffer zones within a 300-meter radius and network analysis within a 500-meter radius. Notably, when compared to other CMC wards, North of Colombo, Colombo-West and Colombo-Central 1 has minimum green space coverage within the buffer zone, indicating these areas as possible focal locations for future green space development. Crow Island Park in North Colombo shows the possibility for green space development to satisfy the requirement for more exposure. Significantly, the results of network analysis strongly coincide with the findings of buffer zones, emphasising the necessity of permitting reasonable walking distances to green space. Borella and Colombo East emerge as areas with significant green space coverage and green space exposure. However, due to the distinct locations and nature of green space the presence of urban green areas does not necessarily translate into fair accessibility for all inhabitants. The private or public nature and the functions of green space also play an important role in accessibility. The analysis, as shown in above maps, highlights the presence of parks inside each district, yet emphasises the need for strategic planning to improve citizens' access to these green havens. Despite the availability of green areas in Borella, it is clear that the distribution throughout other divisions is not consistent, necessitating a critical review of allocation practices. Special emphasis is required in the provisions and access to green space in Colombo-North, Colombo-Central 1 and Colombo-West. CMC administrative areas need to improve proximity-based accessibility to green space by constructing green spaces within walking distance to residential clusters and enhancing the accessibility to green spaces and creating “green space equity” for the diverse and vulnerable, such as the elderly, women, children and the urban poor.

The access to green space within walking distance can significantly enhance their exposure to green and promote overall wellbeing. This research highlights the need for provisions and access to green space in specific areas within the CMC boundaries and suggests the need for strategic planning to ensure fair access to these natural havens. Hence careful consideration of green space availability and accessibility in the development and formation of urban neighbourhoods can result in healthier, happier, and sustainable urban communities.

6. REFERENCES

Benedict, M. A., & McMahon, E.T. (2006). Green infrastructure: Linking landscapes and communities. Island Press

Chiesura, A. (2004). The role of urban parks for the sustainable city. Landscape and Urban Planning, 68(1), 129-138. https://www.scirp.org/reference/referencespapers?referenceid=2632322

Costanza, R., Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., & Grasso,M. (2017). Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosystem Services, 28, 1-16. https://doi.org/10.1016/j.ecoser.2017.09.008

Hansen, R., Olafsson, A.S., Jagt, A., Rall, E. and Pauleit, S.(2017). Planning multifunctional green infrastructure for compact cities: What is the state of practice? Ecological Indicators, 96(2), 99-110. http://dx.doi.org/10.1016/j.ecolind.2017.09.042

Giuliani, G., Petri, E., Interwies, E., Vysna, V., Guigoz, Y., Ray, N., & Dickie, I. (2021). Modelling accessibility to urban green areas using open earth observations data: A novel approach to support the urban SDG in four European cities. Remote Sensing, 13(3), 422. https://doi.org/10.3390/rs13030422

Gupta, K., Roy, A., Luthra, K., Maithani, S., & Mahavir. (2016). GIS based analysis for assessing the accessibility at hierarchical levels of urban green spaces. *Urban Forestry & Urban Greening*, *18*, 198-211. https://doi.org/10.1016/j.ufug.2016.06.005

Kabisch, N., Qureshi, S., & Haase, D. (2016). Human–environment interactions in urban green spaces—A systematic review of contemporary issues and prospects for future research. *Environmental Impact Assessment Review*, *50*, 25-34. https://doi.org/10.1016/j.eiar.2014.08.007.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169-182. https://doi.org/10.1016/0272-4944(95)90001-2

Lin, L., & Pussella, P. (2016). Temporal changes of per capita green space of Colombo district, Sri Lanka, *Preprints*. https://doi.org/10.20944/preprints201612.0144.v1

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., De Vries, S.,Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J., & Lupp, G. (2017). Exploring pathways linking greenspace to health: Theoretical and methodological guidance. *Environmental Research*, *158*(8), 301-317. DOI: https://doi.org/10.1016/j.envres.2017.06.028

Martinez, A. de la I., & Labib, S. M. (2023). Demystifying normalized difference vegetation index (NDVI) for greenness exposure assessments and policy interventions in urban greening. *Environmental Research*, *220*(10). .https://doi.org/10.1016/j.envres.2022.115155

Nicholls, S. (2001). Measuring the accessibility and equity of public parks: a case study using GIS. *Managing Leisure*, *6*(4), 201-219. https://doi.org/10.1080/13606710110084651

Nieuwenhuijsen, M.J. (2020). *Green infrastructure and health. annual review of public health,* '42'.DOI: https://doi.org/10.1146/annurev-publhealth-090419- 102511

Quid, D., Heng, L., Xiaohong, L., Pengman, H., Di AU, L., Linjia, W., Yundi, W., & Xuli, C. (2023). Evaluation and optimization of green space fairness in urban built-up areas based on an improved supply and demand model: A Case Study of Chengdu, China. *Sustainability*, *15*(20), https://doi.org/10.3390/su152015014

Senanayake, I. P., Welivitiya, W. D. D. P., & Nadeeka, P. M. (2013). Urban green spaces analysis for development planning in Colombo, Sri Lanka, utilizing THEOS satellite imagery – A remote sensing and GIS approach. *Urban Forestry & Urban Greening*, *12*(3), 307–314. https://doi.org/10.1016/j.ufug.2013.03.011

Teleaga, G. (2020). Urbanization and health. *Arta Medica*, *77*(4). https://doi.org/10.5281/zenodo.4174848

Taylor, L. and Hochuli, D.F. (2017). Defining greenspace: Multiple uses across multiple disciplines *Landscape and Urban Planning*, 158, 25-38. https://doi.org/10.1016/j.landurbplan.2016.09.024

Ulrich, R. (1984). View through a window may influence recovery. *Science*, *224*(4647), .224-225. doi:10.1126/science.6143402

Ward, J. S., Duncan, J. S., Jarden, A., & Stewart, T. (2016). The impact of children's exposure to greenspace on physical activity, cognitive development, emotional well-being, and ability to appraise risk. *Health & Place*, *40*, 44–50. https://doi.org/10.1016/j.healthplace.2016.04.015

World Health Organization Regional Office for Europe. (2016). *Urban green spaces and health.* https://www.who.int/europe/publications/i/item/WHO-EURO-2016-3352-43111-60341

Zhang, Y., Mavoa, S., Zhao, J., Raphael, D., & Smith, M. (2020). The Association between green space and adolescents' mental well-being: A systematic review. In*ternational Journal of Environmental Research and Public Health*, *17*(18), 6640. https://doi.org/10.3390/ijerph17186640

Wijayasenaratne, K.A.S.H., Rathnayake, R.M.D.I. and Rajakaruna, A.G.H.M., 2024. Analysing people's behaviour towards indoor air quality management: A case study in Kandy, Kurunagala and Hambanthota. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 159-170. DOI: https://doi.org/10.31705/WCS.2024.13. Available from: https://ciobwcs.com/papers/

ANALYSING PEOPLE'S BEHAVIOUR TOWARDS INDOOR AIR QUALITY MANAGEMENT: A CASE STUDY IN KANDY, KURUNAGALA AND HAMBANTHOTA

K.A.S.H. Wijayasenaratne[1], R.M.D.I. Rathnayake[2], A.G.H.M. Rajakaruna[3], W.K.T. Dulanjana[4], R.A.K.S. Ranasinghe[5] and R.T.K. Ariyawansha[6]

ABSTRACT

Indoor air quality (IAQ) management is crucial for ensuring a healthy and comfortable living environment. This study aimed to assess people's behaviours on IAQ management by investigating their awareness, attitudes, and practices. A questionnaire-based survey was conducted to gather data on IAQ-related habits and practices of individuals in Kurunagala-Abanpola, Kandy-Bothota, and Hamabnthtoa-Thangalle. The sample population was 156. The awareness of respondents regarding indoor air quality varied among the sampling locations. Awareness levels in Ambanpola, Bothtoa, and Thanagalle were 80%, 34.62%, and 82.14% respectively. Major sources of indoor air pollution also varied, with tobacco smoke usage (34.62%) and cooking emissions being predominant in Kandy-Bothota, while pollution associated with household cleaning products (32%) was identified as a major source in Kurunagala-Ambanpola. In contrast, cooking smoke (25%) and, cleaning products (21.43%) were identified as major indoor air pollutant sources in Hambanthtoa-Thangalle. In addition, outdoor activities such as the open burning of plastic waste, also impact indoor air quality. The majority of the respondents (42.31%) in the Kandy-Bothota region burned their plastic waste close to their dwellings, whereas the Kurunegala-Abanpola region had the lowest proportion, at 3.57%. The findings underscore varying levels of awareness among participants, largely attributed to a lack of information accessibility. The attitudes towards IAQ management were generally positive. However, the survey revealed that practical implementation of IAQ measures often fell short, indicating a gap between intention and behaviour.

Keywords: *Behaviours; Indoor Air Quality Management; Indoor Air Pollution; Indoor Air Quality.*

---

[1] Teaching Assistant, Department of Environmental Technology, Sri Lanka Technological Campus, Sri Lanka, harshaniwi@sltc.ac.lk
[2] Undergraduate Student, Department of Environmental Technology, Sri Lanka Technological Campus, ,Sri Lanka, dewminirathnayake541@gmail.com
[3] Undergraduate Student, Department of Environmental Technology, Sri Lanka Technological Campus, ,Sri Lanka, mandaraharini@gmail.com
[4] Undergraduate Student, Department of Environmental Technology, Sri Lanka Technological Campus, Sri Lanka, dulanwitharana2000@gmail.com
[5] Undergraduate student, Department of Environmental Technology, Sri Lanka Technological Campus, Sri Lanka, kashenranasingha@gmail.com
[6] Senior Lecturer, Department of Environmental Technology, Sri Lanka Technological Campus, Sri Lanka, renukaa@sltc.ac.lk

1. INTRODUCTION

The quality of indoor air significantly impacts the health and well-being of individuals, since approximately 80-90% of their total time is spent in indoor environments (Kumar et al., 2022). The cumulative impact of both ambient air pollution and household air pollution accounts for 6.7 million premature deaths every year (World Health Organisation, 2022). Indoor air pollutants encompass a diverse range of elements, including particulate matter, biological agents (such as allergens, bacteria, mold, fungi, and spores), physical factors like temperature and electromagnetic fields, and over 400 distinct chemical compounds, predominantly volatile organic compounds (VOCs) and inorganic compounds (VICs Approximately one-third of the world's population, (nearly 2.4 billion people), depends on open fires or inefficient stoves fuelled by kerosene, biomass (including wood, animal dung, and crop waste), and coal for cooking, resulting in the production of detrimental household air pollution (World Health Organisation, 2022). Nearly 40% of all households, and a significant 90% of rural households in Low- and Middle-Income Countries (LMICs), primarily rely on biomass as their primary domestic energy source (Raju et al., 2020). Although over 80% of households in Sri Lanka have electricity access, the majority limit its usage primarily to lighting, predominantly influenced by cost considerations and cooking preferences (Chartier et al., 2017).

Traditional solid fuel burning methods, such as open fireplaces and unvented stoves, are inefficient and ineffective, more pollutants such as NO_2 and Carbon Monoxide (CO), as well as particulate matter, are emitted into the indoor environment (Zhang & Smith, 2003). Household pollutant concentrations can still rise in residences that do not rely on solid fuels, due to other prevalent heating and cooking methods (Raju et al., 2020). For instance, kerosene stoves and devices emit significant amounts of PM2.5, CO, NO_2, and SO_2 (Nandasena et al., 2013). Further to the authors, environmental tobacco smoke (ETS), commonly referred to as second-hand smoke (SHS) or passive smoke, is a combination of more than 4,000 chemicals, with more than 40 of them recognised as carcinogens in both vapour and particle phases. Vapor-phase numerous common household products such as personal care items, household cleaning products like finishes, rug and oven cleaners, paints, lacquers, paint strippers, pesticides, mosquito repellents, dry-cleaning fluids, building materials, and home furnishings can also be sources of indoor air pollutants (Nandasena et al., 2013). Further to the authors, very fine asbestos fibres can be released into the air when materials containing asbestos, such as roof sheets and insulation for heating systems, are utilised.

Indoor air quality is influenced by a variety of factors, including behavioural factors, housing characteristics, environmental conditions, and indoor and outdoor pollution sources. The levels of indoor air pollutants can be influenced by the presence of outdoor air pollution arising from both human activities and natural occurrences, such as emissions from road traffic, wildfire smoke, and the resuspension of dust (Vardoulakis et al., 2020). Moreover, sources of pollutants and their emission rates undergo rapid changes over time (González-Martín et al., 2021). These sources include both constant contributors, such as building materials, adhesives, paints, and varnishes, as well as occasional ones like furniture, cleaning and disinfection products, cooking, personal care products, and even human metabolism (González-Martín et al., 2021). Additionally, the intrusion of outdoor pollutants is strongly dependent on human activities like road traffic and industrial processes (González-Martín et al., 2021). Lastly, indoor gas-phase reactions among various compounds present in indoor air can also lead to the formation of secondary pollutants (González-Martín et al., 2021). Multiple adverse respiratory health outcomes such as preterm birth, low birth weight, compromised lung function, childhood respiratory infections, an elevated risk of developing conditions like asthma, chronic obstructive pulmonary disease (COPD), lung cancer, and worsening of existing respiratory ailments have been linked to Household Air Pollution (HAP) in LMICs (Raju et al., 2020). This study aimed to assess indoor air quality awareness, perceptions, knowledge gaps, motivators and barriers, and attitudes toward management. It also examined the impact of health events, technology adoption, policy awareness, and the effectiveness of educational campaigns.

2. MATERIALS AND METHOD

2.1 STUDY AREA SELECTION

This study aimed to investigate the perception of the rural population towards indoor air quality. So, Bothota in the Kandy district, Tangalla in the Hambanthota district, and Ambanpola in the Kurunegala district were selected for this study (Refer to Figure 1).

Figure 1: Areal view of the study area (Google Earth)

The selection of Kandy, Kurunegala, and Hambantota for studying people's behaviour towards indoor air quality management is influenced by their diverse geographical and climatic conditions, different air quality challenges, and cultural and behavioural insights. Kandy, in the central highlands, has a cooler, humid climate. Kurunegala, in the North Western Province, has a temperate, relatively dry climate. Hambantota, in the southern coastal region, experiences a hot, arid climate. These locations also represent varied socioeconomic statuses and demographic profiles, allowing for a comprehensive understanding of indoor air quality management across different community settings. This selection ensures a thorough analysis of environmental, social, and economic contexts, leading to more generalisable findings. A questionnaire-based study was conducted to collect data on indoor air quality.

2.2 DATA COLLECTION

A population of 156 respondents was selected. 52 respondents were selected from each sampling location. The questionnaire consisted of 6 main sections with 68 questions, Section 1 - demographic information (Q1.1-1.7); Section 2 - awareness and knowledge about indoor air quality and Management (Q2.1-Q2.7); Section 3 - sources of indoor air pollution (Q3.1-3.30); Section 4 - potential health impacts (Q4.1-4.5); Section 5 - indoor air quality management practices (Q5.1-5.8) and Section 6 - future considerations (6.1-6.2). Section 3 identified various sources of indoor air pollution that the respondents might encounter. The survey was conducted both physically and virtually to accommodate different preferences and accessibility issues. The questionnaires were initially written in English and then translated into Sinhala to ensure better understanding and accurate responses from the participants. Data collection took place over two weeks in September 2023.

3. RESULTS AND DISCUSSION

3.1 DEMOGRAPHIC CHARACTERISTICS

Table 1 provides the demographic characteristics of the surveyed population across different areas.

Table 1: Demographic information

Demographic features		Kandy (Bothota)	Kurunegala (Abanpola)	Hambanthota (Tangalle)
Gender	Female	62.75%	52.94%	59.62%
	Male	37.25%	47.06%	40.38%
Age	15-30	31.37%	70.59%	86.27%
	30-45	23.53%	33.33%	13.73%
	45-60	5.88%	7.84%	0%
	60-75	7.83%	0%	0%
Residence	Rent	58.82%	19.61%	5.88%
	Own	31.37%	68.63%	94.11%
	Other	29.41%	11.76%	0%
Highest education qualifications	Advanced level	35.29%	70.59%	49.02%
	Bachelor’s degree	17.65%	23.53%	45.1%
	Master’s degree	7.84%	0%	0%
	Doctorate	1.96%	0%	0%
	Other	52.94%	5.88%	5.88%
Where do you spend most of your time?	Home/boarding place	33.33%	60.78%	86.27%
	Workplace	23.53%	27.45%	9.08%
	Outdoor environment	33.33%	11.76%	3.92%

3.2 AWARENESS AND KNOWLEDGE

Kurunegala-Ambanpola showed the lowest level of awareness (11.76 %) of indoor air quality. In Bothota 34.62% of respondents expressed awareness of indoor air quality, and 15.38% admitted to a lack of awareness. In contrast, Hambanthota-Tangalle had a significantly higher awareness level, with 84.31% of respondents reporting awareness. In the Kurunegala-Ambanpola area, 29.41% of respondents had encountered health problems attributed to indoor air quality. In Kandy-Bothota (54.32%) of respondents reported health issues associated with indoor air quality, Tangalle exhibited a different pattern, with 23.53% of respondents indicating health issues. Kurunegala-Ambanpola indicated the highest level of awareness (90.2%) of indoor air pollutant sources. In Kandy-Bothota the situation contrasted with the lowest level of awareness of indoor air pollutant sources (17.08%). Respondents in Hambanthota-Tangalle exhibited a significant level (68.63%) of awareness of indoor air pollution. These findings provide valuable insights into the varying degrees of awareness and understanding of the significance of indoor air quality among different regions. The findings underscore the divergence in attitudes and apprehensions across the surveyed areas.

As shown in Figure 2, factors that were identified as potential influencers on indoor air quality varied across the surveyed areas.

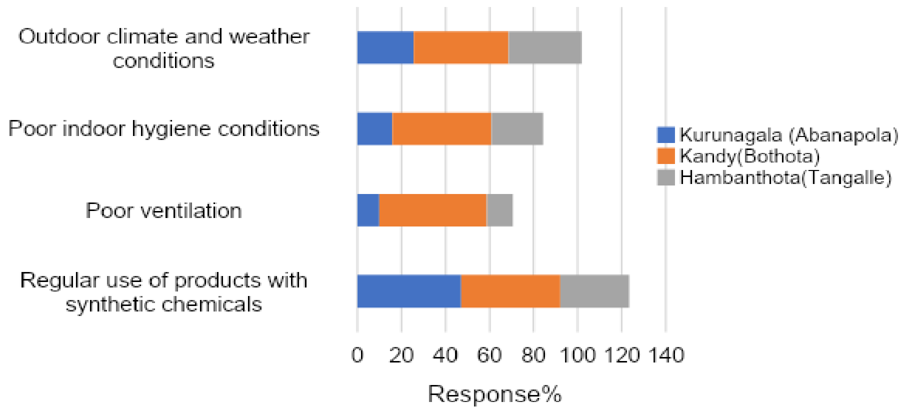


Figure 2: Factors affecting indoor air quality

In Ambanpola, 28% of respondents attributed the regular use of products containing synthetic chemicals as a factor affecting indoor air quality. Additionally, 12% identified poor ventilation, 24% cited poor indoor hygiene conditions, and 32% recognised outdoor climate and weather conditions as contributors to indoor air quality. In Bothota the figures showed a slightly different perspective, with 19.23% of respondents attributing synthetic chemical products, 19.23% acknowledging poor ventilation, 26.92% associating poor indoor hygienic conditions, and 38.46% pointing to outdoor climate and weather conditions as factors impacting indoor air quality.

In Hambanthota-Tangalle area, 35.71% associated synthetic chemicals, 14.29% acknowledged poor ventilation, 21.43% recognised poor indoor hygiene conditions, and 28.57% cited outdoor climate and weather conditions as factors affecting indoor air quality. These findings shed light on the multifaceted nature of factors perceived to impact indoor air quality, emphasising the importance of understanding regional variations in perceptions and awareness.

3.3 INDOOR AIR POLLUTION SOURCES

The data provided in Figure 3, as reported by the respondents, reveals the sources of indoor air pollution across different areas.

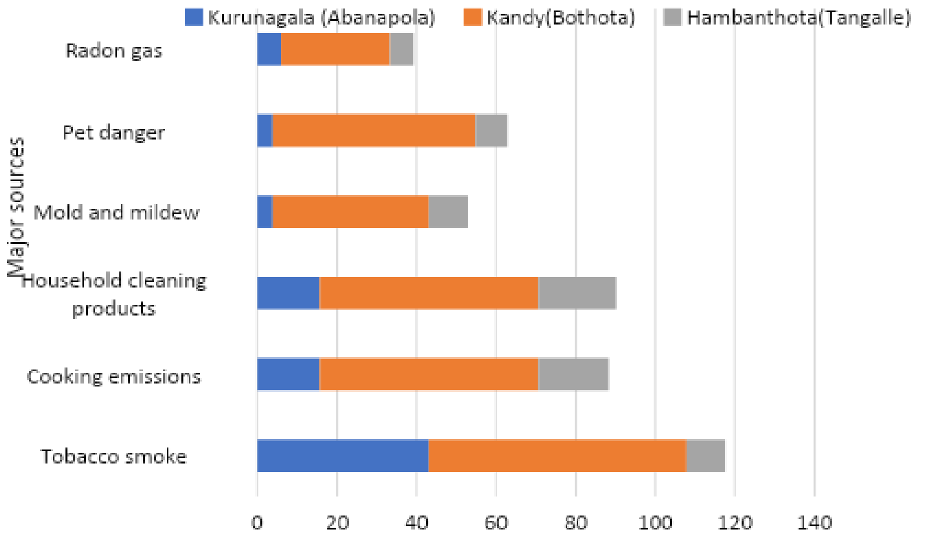


Figure 3: Major sources of indoor air pollution according to the responded population

Notably, the Kandy-Bothota area exhibits a higher prevalence of tobacco smoke usage, accounting for 34.62% of respondents, and it also records the highest percentage of cooking emissions. Interestingly, an equal number of respondents, approximately 8% identified, pet dander, mold, and mildew as sources of indoor air pollution. In Kurunagala-Ambanpola, pollution associated with household cleaning products (32%) can be identified as the major source of indoor air pollution. In contrast, cooking smoke (25%) and cleaning products (21.43%) were identified as major indoor air pollutant sources. Furthermore, most respondents (53.85%) in the Kandy-Bothota area used biogas for cooking while Kurunegala-Ambanpola reports a substantial 84% usage of LPG gas, and Hambanthota-Tangalle records 82.14% usage of LPG gas (Refer to Figure 4).

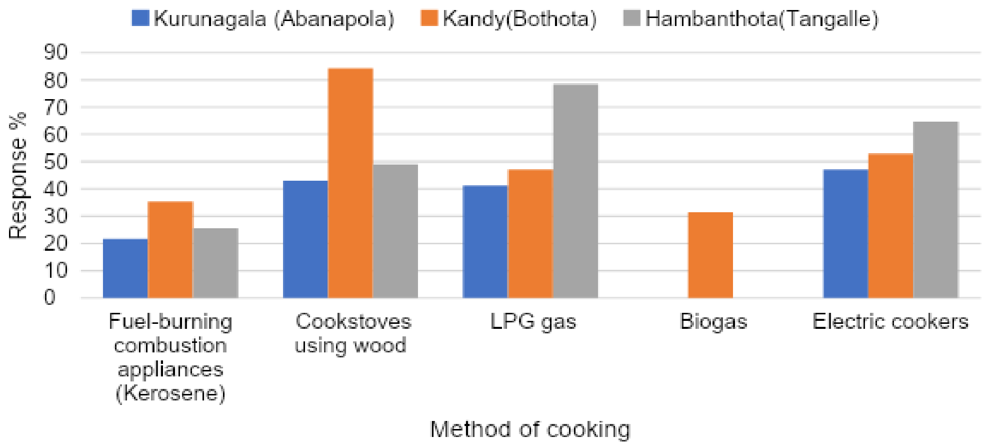


Figure 4: Methods of cooking foods of the respondent population

When cooking with traditional solid fuels over open flames or in traditional cooking stoves, exposure lower-income individuals can lead to ambient concentrations exceeding ten times the allowed EPA level in a 24-hour period (150µg/m^3) (Duflo et al., 2008). In comparison to burning solid fuels, burning gaseous fuels in basic machines results in a greatly reduced pollution emission. This comprises carcinogens such as benzene, 1,3-

butadiene, and polycyclic aromatic hydrocarbons, as well as CO, particulate matter (PM), and volatile organic chemicals that irritate the eyes (such as aldehydes) (Zhang & Smith, 2003).

Additionally, the concentration of pollutants is influenced by kitchen attributes such as ventilation, the existence of a chimney, and the design of the stove (Nandasena et al., 2013). Sri Lanka predominantly employs two types of stoves: traditional stoves and improved cook stoves, exemplified by the "Anagi" stove (Nandasena et al., 2013). Traditional stoves, crafted by users from locally sourced materials like the "three stone stove", have been a fixture in households for generations. In contrast, Anagi stoves are commercially produced lightweight clay units capable of accommodating one or two cooking utensils simultaneously (Nandasena et al., 2013).

According to a study conducted by Phillips et al (2016), indoor PM2.5 concentrations typically exceeded personal concentrations, especially when the stove lacked a chimney, trapping smoke inside the structure. For instance, an Anagi stove used without a chimney yielded an indoor PM2.5 concentration of 222 $\mu g/m^3$. Women who utilised Anagi stoves with chimneys in cooking areas integrated with their homes had the lowest personal exposures, measuring 47 $\mu g/m^3$. In contrast, those who relied on traditional stoves without chimneys in separate structures faced the highest PM2.5 concentrations, reaching 216 $\mu g/m^3$(Phillips et al., 2016). Approximately 50% of the respondents in both Kurunagala (Abanpola) and Kandy (Bothota) use polythene to initiate the flame in their wooden furnaces. 27.47% of respondents in Hambanthota-Tangalle use polythene to initiate the flame in their furnaces. Solvents, microplastics, and hazardous gases are released into the air during the burning of polythene in cooking stoves (Handley, 2022). These findings shed light on the diverse sources of indoor air pollution in various regions, highlighting the need for targeted interventions and awareness campaigns to address these concerns. The prevalence of indoor air pollution sources, beyond the primary ones, is detailed in Table 2.

Table 2: Other sources of indoor air pollution

Source		Percentage of the responded population		
		Kurunagala (Abanapola)	**Kandy (Bothota)**	**Hambanthota (Tangalle)**
Wooden furniture		76.47	66.67	62.75
Wall paintings		17.65	47.06	49.02
Disinfection agents		15.69	58.82	13.73
Air fresheners		49.02	54.90	50.98
Personal care products	Perfumes	76.47	62.75	82.35
	Nail polish removers	39.22	45.10	39.22
	Nail polish	45.10	37.25	39.22
	Hair sprays	9.80	56.86	23.53
	Deodorants	47.06	60.78	72.55

Most respondents across all three locations reported having wooden furniture in their households. In Bothota-Kandy and Tangalle-Hambanthota, 47.06% and 49.02% of respondents, respectively, reported having wall paintings in their homes, whereas only

17.65% of respondents in Abanpola-Kurunagala reported the same. Bothota-Kandy recorded the highest use of disinfection agents at 58.82%, while Tangalle-Hambanthota had the lowest at 13.73%. Approximately 50% of respondents in all three locations use air fresheners. Additionally, the use of personal care products such as perfumes, nail polish, nail polish removers, hair sprays, and deodorants was more prevalent among respondents in Bothota-Kandy than in the other two locations.

Awareness of respondents regarding the indoor air pollution associated with personal care products varied from 60.78% (Kurunegala-Abanpola), 58.82% (Kandy-Bothota), and 33.33% (Hambanthota-Tangalle) respectively. Awareness of respondents regarding the indoor air pollution associated with the use of grilling machines under poor ventilation conditions varied from 80.39% (Kurunegala-Abanpola), 56.86% (Kandy-Bothota)- and 35.29% (Hambanthota-Tangalle) respectively.

Incense materials have been employed for centuries in Asia for ceremonial and indoor fragrance purposes. However, many individuals remain unaware of the potential indoor air quality issues associated with incense smoke (Verma et al., 2016). The burning of incense can lead to a slow and incomplete combustion process, resulting in the emission of dense smoke, which in turn contributes to indoor air pollution concerns (Verma et al., 2016). The use of incense sticks was also high in the Kurunagala-Amanpola area compared to the remaining areas. Most of the respondents (65%) in Kurunagala-Amanpola burned incense sticks daily while the lowest daily burning (25%) was recorded in the Kandy-Bothota area (Refer to Figure 5).

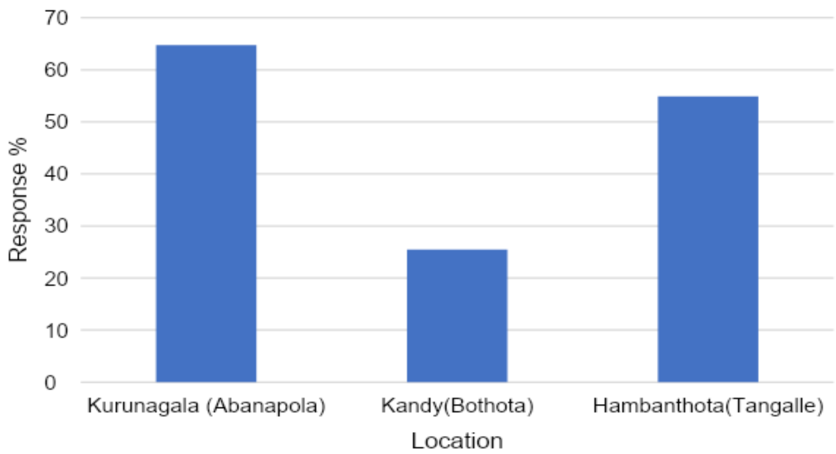


Figure 5: Daily use of incense sticks of the respondent population

Awareness of respondents regarding the indoor air pollution associated with burning incense sticks can act as indoor air pollution varied 60.78% (Kurunegala-Abanpola), 31.37% (Kandy-Bothota)- and 88.24% (Hambanthota-Tangalle) respectively. Mosquito coils are commonly used in Asia to repel mosquitoes (Verma et al., 2016). These coils typically contain pyrethrin insecticides, which play a crucial role in their effectiveness but pyrethrins have low chronic toxicity for humans (Verma et al., 2016). However, the combustion of the remaining materials in mosquito coils generates significant amounts of particulate matter (Verma et al., 2016). The toxicological effects of inhaling mosquito coil smoke can lead to health issues such as asthma, lung cancer, and persistent wheezing in children (Verma et al., 2016). In contrast, Kandy-Bothota exhibits a higher prevalence at 58.82%, while Hambantota-Tangalle and Kurunegala-Ambanpola record the lowest percentages at 23.53% and 25.49%, respectively. The highest daily burning of mosquito coils was recorded in Kandy-Bothota at 27.45%, while the lowest was recorded in Kurunegala-Ambanpola at 3.92%, as shown in Figure 6.

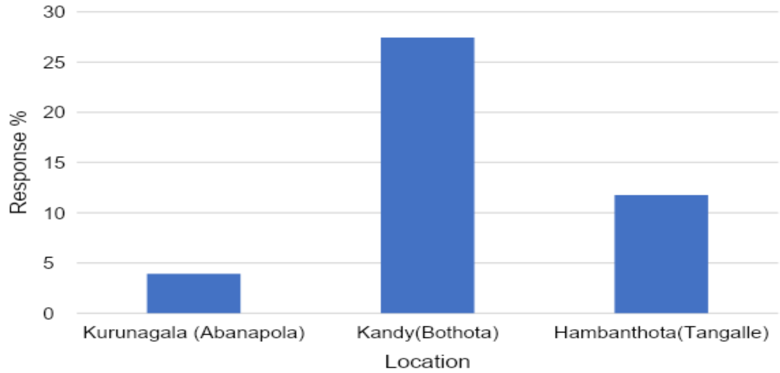


Figure 6: Daily use of mosquito coils of the respondent population

No respondents in Kurunagala-Amanpola observed tobacco smoking inside their houses. In contrast, Kandy-Bothota exhibited the highest percentage (52.94%) of tobacco smoking inside their house. Few respondents (5.88%) observed tobacco smoking inside their house in Hambantota-Tangalle. In addition to sources in the indoor environment, outdoor air pollution also influences indoor air quality. For instance, outdoor activities such as the open burning of plastic waste also impact indoor air quality. Most of the respondents (56.81%) in the Kandy-Bothota region burned their plastic waste close to their dwellings. 7.84% of respondents burnt plastic waste at a very short distance to their house in Kurunagala-Bothota In contrast, the Hambanthota-Tangalle region, has the lowest proportion, at 3.92%. In, Kandy-Bothota, respiratory problems have been reported in 35.29% of residents due to the open burning of plastics. 27.45% of respondents in Kurunagala-Abanpola reported respiratory illness related to the open burning of plastics. In contrast, Hambanthota-Tangalle displays the majority 43.14% with relation to health difficulties. Appropriate ventilation techniques are being used to lessen the amount of contaminated air coming from Tangalle, which accounts for 41.18% of the total, Bothota for 60.78%, and Ambanpola for 64.71%. Roofs were covered with asbestos in houses of 66.67%, 68.63%, and 50.98% of respondents in Kurunagala (Abanpola), Kandy (Bothota), and Hambanthota (Tangalle) respectively. 68.63%, 64.71%, and 41.18% of respondents were aware of the harmful health impacts of asbestos sheets in Kurunagala (Abanpola), Kandy (Bothota), and Hambanthota (Tangalle) respectively. 72.55%, 60.78%, and 40.06% of respondents replace the damaged asbestos on their roofs in Kurunagala (Abanpola), Kandy (Bothota), and Hambanthota (Tangalle).

3.4 POTENTIAL HEALTH IMPACTS

The survey results also provided a comprehensive overview of respondents' awareness of health risks associated with indoor air pollution in various areas. In Ambanpola, 78.43% of respondents acknowledged their awareness of these potential health risks, while 19.61% were not cognizant of the health issues related to indoor air pollution. 52.95% and 37.25% of respondents exhibited awareness of these potential health risks in Kandy-Bothota and Hambanthota-Tangalle respectively. Interestingly, in the Bothota village of Kandy, a substantial 69.23% of respondents reported facing health risks due to indoor air pollution. Conversely, in the Hambanthota-Tangalle area, only 28.57% of respondents acknowledged these risks. Second, hand smoke, a notable source of indoor air pollution, also exhibited variations in awareness across areas. In Ambanpola 72% of respondents reported their awareness of secondhand smoke, while Kandy-Bothota had a lower awareness rate of 19.23%. Tangalle demonstrated a high level of awareness at 78.57%. In terms of allergies or sensitivities exacerbated by indoor air quality, respondents in Ambanpola (32%), Bothota (46.15%), and Hambanthota-Tangalle (32.14%) reported their awareness of this situation. These allergies commonly manifest as skin rashes, pollen allergies, and pet dander sensitivities.

Furthermore, the survey revealed the prevalence of health issues associated with poor indoor air quality. Kurunegala-Ambanpola reported that 60% of respondents had experienced health problems, primarily respiratory issues. Bothota displayed the highest rate at 92.31%. The long-term health effects of indoor air pollution, including respiratory disorders, cancers, and allergies, were recognised by 100% of respondents in Kurunegala-Ambanpola. In Kandy-Bothota 34.62% were aware of these risks, while Tangalle reported lower awareness rates of 92.86%, respectively. These differences in awareness levels can be attributed to varying levels of education and information dissemination about indoor air quality, highlighting the need for increased public awareness and concern for health issues related to indoor air pollution.

3.5 INDOOR AIR QUALITY MANAGEMENT PRACTICES

The preceding section delves into the measures adopted by respondents to mitigate indoor air pollution. Notably, in Kurunegala-Ambanpola, most respondents, accounting for 76%, reported the regular practice of ventilating their indoor spaces. This emphasises the significance of maintaining proper airflow as an effective method to combat indoor air pollution. Furthermore, 58.82%, 54.90%, and 41.17% of respondents have taken steps to reduce indoor air pollution from cooking or heating in Abanpola, Bothota, and Hambanthota respectively. 54.91%, 50.98%, and 50.98% of respondents use exhaust fans in their kitchens in Abanpola, Bothota, and Hambanthota. 62.75%, 50.98%, and 43.14% of respondents utilise chimneys to escape the polluted air in Abanpola, Bothota, and Hambanthota, respectively.

Table 3: Air quality management practices

Measures	Percentage of the responded population		
	Kandy (Bothota)	Kurunegala (Ambanpola)	Hambanthota (Tangalle)
Regular ventilating	58.82%	88.24%	70.59%
Air purifiers and filters	23.53%	7.84%	27.45%
Removing or reducing sources	60.78%	72.55%	47.06%
Natural cleaning product	47.18%	72.55%	54.90%
Control of dust and allergens-Mop hard floor	54.90%	92.16%	19.61%
Control of dust and allergens Dust and vacuum	39.22%	54.90%	92.16%
House plant to improve indoor air quality	52.94%	72.55%	52.94%
Modification to enhance indoor air quality (Sealing gaps, VOC product)	15.68%	15.68%	39.22%
Follow any guidelines or recommendations	74.51%	62.75%	33.33%

In contrast, a noteworthy observation was made in the Hambantota-Tangalle area, where 100% of respondents reported the practice of mopping hard floors. This underscores the simplicity and feasibility of employing methods such as floor cleaning and regular ventilation as part of daily routines to enhance indoor air quality. These practices, being relatively easy to implement, have the potential to mitigate the negative impacts of indoor air pollution. Encouraging the adoption of such daily practices can serve as an essential step toward improving indoor air quality and minimising its detrimental effects on health and well-being.

3.6 FUTURE CONSIDERATIONS

As previously noted, the interplay between outdoor air quality and indoor air quality is a complex issue with varying levels of recognition among respondents. In Abanpola-Kurunegala, 7.82% of respondents perceive outdoor air quality as a major factor influencing indoor air quality, compared to 50.98% in Bothota-Kandy and 3.92% in Tangalle-Hambanthota. This highlights the need for enhanced awareness and education regarding the interconnectedness of these two environmental factors. Furthermore, 19.61% of respondents in Abanpola-Kurunegala, 35.29% in Bothota-Kandy, and 17.65% in Tangalle-Hambanthota have received guidance or information on indoor air quality management from local authorities or health organisations. This underscores the necessity to implement strategies to increase awareness of indoor air quality among rural communities. Interestingly, the majority of respondents (60%) across all three locations sought information from academic institutions rather than relying on government agencies as their primary source of knowledge. This trend suggests a higher degree of trust in academic institutions and underscores their importance in disseminating information and raising awareness about air quality issues, both indoors and outdoors. Consequently, academic institutions have the potential to play a key role in educating the public and promoting measures to enhance air quality.

4. CONCLUSIONS

This study underscores the critical role of IAQ management in fostering healthy living environments. Through an examination of behaviours, awareness, attitudes, and practices related to IAQ among residents of Kurunagala-Abanpola, Kandy-Bothota, and Hambanthota-Thangalle, significant regional disparities have been uncovered. Awareness levels of IAQ varied widely, with Kurunagala-Abanpola and Hambanthota-Thangalle demonstrating high awareness (80% and 82.14%, respectively), while Kandy-Bothota exhibited notably lower awareness (34.62%). Despite generally positive attitudes towards IAQ management across all regions, there remains a notable gap between awareness and practical implementation of effective measures. The findings highlight this crucial gap, primarily attributable to limited access to information and resources. Thus, there is an urgent need to develop and implement targeted strategies aimed at bridging this divide, enhancing IAQ management practices, and promoting sustained behavioural changes. Addressing these disparities and fostering improved IAQ practices holds the potential to significantly enhance the health and comfort of rural communities.

5. REFERENCES

Chartier, R., Phillips, M., Mosquin, P., Elledge, M., Bronstein, K., Nandasena, S., Thornburg, V., Thornburg, J., & Rodes, C. (2017). A comparative study of human exposures to household air pollution from commonly used cookstoves in Sri Lanka. *Indoor Air*, *27*(1). https://doi.org/10.1111/ina.12281

Duflo, E., Greenstone, M., & Hanna, R. (2008). Indoor air pollution, health and economic well-being. *Sapiens*, *1*(1). https://doi.org/10.5194/sapiens-1-1-2008

González-Martín, J., Kraakman, N. J. R., Pérez, C., Lebrero, R., & Muñoz, R. (2021). A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control. *Chemosphere*, *262*. https://doi.org/10.1016/j.chemosphere.2020.128376

Handley, M. A. (2022). Confronting the plasticine: Promise in a world wrapped in plastic. *The Lancet Planetary Health*, *6*(9). https://doi.org/10.1016/S2542-5196(22)00194-2

Kumar, P., Singh, A. B., & Singh, R. (2022). Comprehensive health risk assessment of microbial indoor air quality in microenvironments. *PLoS One*, *17*(2). https://doi.org/10.1371/journal.pone.0264226

Nandasena, S., Wickremasinghe, A. R., & Sathiakumar, N. (2013). Indoor air pollution and respiratory health of children in the developing world. *World journal of clinical pediatrics*, *2*(2). https://doi.org/10.5409/wjcp.v2.i2.6

Phillips, M. J., Smith, E. A., Mosquin, P. L., Chartier, R., Nandasena, S., Bronstein, K., Elledge, M. F., Thornburg, V., Thornburg, J., & Brown, L. M. (2016). Sri Lanka pilot study to examine respiratory health effects and personal PM2.5 exposures from cooking indoors. *International Journal of Environmental Research and Public Health*, *13*(8). https://doi.org/10.3390/ijerph13080791

Raju, S., Siddharthan, T., & McCormack, M. C. (2020). Indoor air pollution and respiratory health. *Clinics in chest medicine*, *41*(4), 825-843. https://doi.org/10.1016/j.ccm.2020.08.014

Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Sleeuwenhoek, A., Galea, K. S., Dixon, K., & Crawford, J. O. (2020). Indoor exposure to selected air pollutants in the home environment: A systematic review. *International Journal of Environmental Research and Public Health*, *17*(23). https://doi.org/10.3390/ijerph17238972

Verma, R., Patel, K. S., & Verma, S. K. (2016). Indoor polycyclic aromatic hydrocarbon concentration in central India. *Polycyclic Aromatic Compounds*, *36*(2), 152-168. https://doi.org/10.1080/10406638.2014.957407

World Health Organization. (2022, November 28). Household air pollution. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health?gclid=CjwKCAjwkY2qBhBDEiwAoQXK5Y7cj4rGDvkkkEpeiwji_QYu_hI8Z2R_BE74SPFnOGQvjTICzrpHoRoC8XAQAvD_BwE

Zhang, J., & Smith, K. R. (2003). Indoor air pollution: A global health concern. *British medical bulletin*, *68*(1), 209-225. https://doi.org/10.1093/bmb/ldg029

Wijesundara, P.M., Hadiwattege, C. and Chandani, G.G.N., 2024. Applicability of the atmospheric water generation: The case of hotel industry in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 171-184. DOI: https://doi.org/10.31705/WCS.2024.14. Available from: https://ciobwcs.com/papers/

APPLICABILITY OF THE ATMOSPHERIC WATER GENERATION: THE CASE OF HOTEL INDUSTRY IN SRI LANKA

P.M. Wijesundara[1], Chandanie Hadiwattage[2] and G.G.N. Chandani[3]

ABSTRACT

The proliferation of plastic drinking water bottles poses significant environmental, economic, and social challenges globally. In response, many countries are seeking alternative methods to provide safe drinking water. Atmospheric Water Generators (AWGs) have emerged as a promising solution, yet their implementation remains novel, particularly in countries like Sri Lanka. This paper explores the feasibility of implementing AWGs in the hotel industry in Sri Lanka to mitigate reliance on bottled water. Through a comprehensive literature review and quantitative research methodology including questionnaire surveys, the functional requirements, constraints, drivers, barriers, and strategies for AWG implementation were identified and analysed. The findings underscore the critical importance of factors such as low relative humidity, wide temperature range functionality, energy efficiency, water quality, and appropriate design in selecting AWGs. While drivers like higher efficiency, governmental support, and public awareness propel AWG adoption, barriers such as high initial investment, energy consumption, and mineral deficiency pose challenges. Strategies to overcome these barriers include lifecycle cost analysis, renewable energy integration, vendor selection, and mineral supplementation. The research contributes to understanding successful AWG implementation in the Sri Lankan hotel industry, addressing water bottle consumption's environmental and socio-economic impacts. This study highlights the urgency of transitioning to sustainable water solutions and provides practical insights for stakeholders to navigate the implementation of AWGs effectively.

Keywords: *Atmospheric Water Generators; Bottled Water Consumption; Drinking Water; Drivers and Barriers; Hotels; Sri Lanka; Strategies.*

1. INTRODUCTION

Drinking-water is essential for survival, and everyone should have access to an appropriate, clean, and readily available supply (Chang, 2015). Improving the quality of drinking-water is a significant concern to protect human health globally (Garfí et al., 2016). World Health Organisation (WHO, 2019) stated that in 2017, 71% of the world's population (5.3 billion people) relied on an adequately regulated drinking-water system, which is on-site, accessible when required, and free of contamination.

[1] Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, pavithrawijesundara.pw@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, chandanieh@uom.lk
[3] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, navodag@uom.lk

The current trend of drinking-water from bottles reveals remarkable adaptation in each part of the world, varying with geographical location, lifestyle, needs, and comfort of people in nature, and the theme behind these kinds of societal changes is the scarcity of contaminated water and its effect on human health and livelihood results (Dasinaa & Delina, 2015). Further, the authors mentioned that, in Sri Lanka, the Western Province has a higher percentage of people involved in the handling of bottled water than the other provinces. Still, in recent years, the Southern and Central Provinces have played a vital role over the Eastern Province. Every minute, a million plastic bottles are purchased worldwide, and resulting in an environmental crisis that some activists say will be as bad as climate change (Laville & Taylor, 2017). Toxic chemicals are released as the plastic degrades over hundreds of years, potentially contaminating groundwater (Fresh Outlook Foundation (FOF, 2021). Feng (2019) stated, according to an estimate is done by an expert for Eco-Business amid many anti-plastic announcements by major hotel chains, a single 200-room four-star hotel will use around 300,000 pieces of single-use plastic in a month if it is at total capacity and does not invest in any eco-friendly alternatives. About 20,000 plastic water bottles per month are used in a single 200-room four-star hotel (Feng, 2019). When considering the cost, bottled water is about more expensive per gallon than tap-water. Water harvesting has been done in various ways worldwide, including desalination, groundwater harvesting, and rainwater capture and storage. Liquid water must already be sufficient for this to operate, but when such sources are scarce, atmospheric water generating becomes necessary (Jarimi et al., 2020). The atmosphere contains a large amount of water in the form of vapour, moisture, and other states. This amount of water can be used with the help of an Atmospheric Water Generator (AWG) (Tripathi et al., 2016). AWG stands out as a significant advancement that can address the issue of pure water shortage by generating liquid water from the air (Shourideh et al., 2018). Air is a cleaner platform than soil, and water production from the air eliminates the need for groundwater pumping and the fear of soil contamination; because of that, the quality and taste of the water that is processed using air-to-water technology is of the highest standard (Watergen, 2024). Besides that, Akvo (2018) elaborates that atmospheric water generators are cost-efficient devices.

Currently, the Sri Lankan hotels does not use AWGs for their water needs. Instead, hotels primarily rely on bottled water to ensure a safe and reliable supply of drinking water for their guests, posing considerable environmental and economic concerns. AWGs provide an extended solution to the growing problem of water scarcity. AWGs generate water from the atmosphere, reducing dependency on traditional sources and eliminating the need of plastic bottles. They deliver reliable, high-quality water while resolving environmental concerns and cutting expenses. Implementing AWGs can improve sustainability and assure a consistent supply of safe drinking water in Sri Lankan hotels.

2. LITERATURE FINDINGS

2.1 ATMOSPHERIC WATER GENERATORS

The atmospheric water generator is a device that harvests water from the humidity in the air using dehumidification/condensing technology (Tripathi, et al., 2016). Dehumidification is the process of removing vapour from gas-vapour combination, specifically the separation of water vapour molecules from ambient air in this project (Bolsinger & Ralphs, 2019). AWG uses the principle of latent heat to convert water vapour molecules into water droplets. Therefore, it works on the similar principle that is used in refrigerators and air conditioners, the principle of cooling through evaporation (Tripathi, et al., 2016). The atmospheric air that consists of vapour pass several filters while entering the AWG. Then the water vapour in the air condenses to water drops because the surface temperature of the evaporator is lower than the dew point temperature of the atmosphere (Balaganapathi, et al., 2020). The condensate water accumulates in the water collector and drains to the bottom tank for storage and activated Carbon and reverse osmosis treatments, Ultra-Violet (UV) sterilisation, and a couple of other processes to make this water portable and drinkable (Eastern Research Group, 2018).

2.2 BENEFITS OF THE AWG

Water scarcity solutions include various water-saving measures, reclaiming used water, and water production (Inbar, et al., 2020). The authors stated that atmospheric water production is an efficient and eco-friendly source of potable drinking-water. Some of the benefits of using AWG are briefly described below.

Energy-efficiency **-** AWG is more energy-efficient than the other feasible methods available in the modern world (Elliott, 2021). AWG uses most solar energy and battery backup as the primary source, and it will reduce the high energy consumption (James, et al., 2018).

Less environmental impact **-** Atmospheric air is a renewable source of energy; due to the temperature, different AWG will be able to produce the water without producing waste (Moghimi, et al., 2021). When considering the water bottles, it is stored mostly in PET-type bottles, but there is no problem with AWG (Smuts, 2015). Delgado (2020) stated that the AWG creates water on demand, reducing the requirement for plastic storage containers that would otherwise end up in a landfill or river.

Cost-effectiveness **-** According to the case study of Eastern Research Group (2018), when comparing the cost per 1 litre of bottled water and AWG, AWGs require more upfront capital compared to bottled water. Still, when considering the entire useful life of the AWG unit, it is lower than the bottled water (AWG total cost per 1litre - $ 0.07-0.14 and bottled water total cost per 1 litre - 0.38).

Water quality **–** AWG has a decentralised production method; therefore, the diseases are borne, and contaminants of existing water sources will not spread (Moghimi, et al., 2021). The water generates from AWG is microbiologically safe, which means it is free from potentially harmful contaminants because it has both UV, air filtration, and other kinds of different filtration methods (Brigano & Kapustin, 2021).

No-water transport infrastructure required - Another benefit of using atmospheric water as a source of drinking-water is that no water-transport infrastructure is required; harvesting equipment can be put practically everywhere (away from the coastline) (Inbar, et al., 2020).

2.3 REQUIREMENTS AND CONSTRAIN TO BE CONSIDERED WHEN SELECTING THE AGW

There are some factors to be considered when selecting AWG (Moradi, 2019). According to Moradi (2019), the main factors are the need for and availability of a high percentage of Relative Humidity (RH) in the air and air temperature and the AWG's geological area.

Correspondingly, Moradi (2019) mentioned that yield and cost are two other factors that should be considered

Table 1: Requirements and constraints to be considered when selecting an AWG

Factor	Unit of measure
Functional Requirements	
Should be used when the RH is low.	30% RH
Should utilise about the same amount of power as a typical industry appliance.	<1000W
Should be able to provide adequate water for the facility.	>200 litres per day
Alternative energy sources should be used to power it.	Using power other than electricity
Water should be filtered, and minerals added	At least one filter and mineral adder
Design should be appropriate for the facility	According to the client requirement
Functional Constraints	
To draw moisture, air should be used.	No input of water to the machine is needed
The water produced should meet EPA standards in terms of quality.	TDS[2] < 500 ppm pH ~8
Operation processes should be safe	No hazardous/ harmful elements or parts
Should be operated at a low volume.	< 50 dB
Minimum production costs are required	Depending on the organisation

Adapted: (Moradi, 2019)

2.4 DRIVERS AND BARRIERS RELATED TO THE AWG IMPLEMENTING PROJECT

Drivers and barriers to implantation are presented in Table 2.8. These details elaborate according to the countries that already use AWG, since it will help evaluate drivers and barriers regarding the Sri Lankan context.

Table 2: Drivers and Barriers of the AWG implementation

Drivers and Barriers	Sources
Driver	
Higher efficiency with lower environmental impact	(Market Research Team, 2021)
Declining freshwater level	
Supportive government regulations (FCAU)	
Several governments throughout the world have expressed an interest in developing infrastructure for commercial atmospheric water purposes.	(Market Research Team, 2021)
Growing adaptation for alternative water sources	(Kulkarni, 2019)
The power supply can be shifted to renewable energy (Ex. Solar)	
Should be able to produce water continually for drinking purposes anywhere that have sufficient RH%	(Maida, 2019)

Drivers and Barriers	Sources
Driver	
Increased public awareness of waterborne diseases and the legislation that governs them.	(Dublin, 2020)
User-friendly technological advancement and future growth opportunities	
Development in novel technologies in AWGs (advanced filtration systems, electrically improved harvesting, advanced Oxidation processes, and automatic variable filtration technology)	(Industry ARC, 2019)
AWGs are becoming more common in a variety of end-use industries.	
The demand for AWG is predicted to increase significantly because of Asia's scarcity and depleted freshwater resources.	(IPS News Agency, 2020)
Barriers	
The high initial investment for implementing	(Market Research Team, 2021)
Cooling condensation systems require high amounts of grid electricity	
Not sufficient to use for all water requirements such as laundry, gardening, etc.	(Zhou, Lu, Zhao, & Yu, 2020)
To maintain and operate inside of the AWG, expert knowledge is needed.	
No proper system to balance the requirement of moisture concentration and water release.	
Difficulty in choosing a suitable vendor for purchasing the AWG	(The United Abrahamic Family, 2019)
AWG's do not work in every climate type	
Difficulties in obtaining approval from the top management board	
Lack of minerals compared to the groundwater.	

3. RESEARCH METHODOLOGY

A quantitative approach was selected to achieve research objectives. The Quantitative research entails gathering and analysing numerical data objectively to characterise, predict, or regulate factors of interest, and it aims to explore causal correlations between variables, make predictions, and generalise findings to a larger group of people (McLeod, 2019). This research design includes a comprehensive literature review, questionnaire surveys, data analysis, and discussion of research findings, respectively. The questionnaire survey was conducted to gather the details on the negative impacts of water bottle usage and the overall idea of implementing AWG in the Hotel industry in the Sri Lankan context. Due to the lack of realistic practices of the AWG in Sri Lanka, the main concern of the questionnaire survey was to validate the information identified in the literature review regarding the global context. The sample was chosen to include 30 professionals working in up to 3-star hotels across various districts, specifically targeting those in executive and managerial positions with extensive experience in the hotel industry for a questionnaire survey. This selection was made to ensure the insights gathered are from individuals with substantial industry knowledge and expertise. Professionals at these levels are typically responsible for strategic decision-making and have a comprehensive understanding of both operational challenges and opportunities within their hotels. Their extensive experience ensures that the feedback and data collected are reliable, informed, and reflective of the industry's best practices and current trends. Due to the study is going to investigate the applicability of implementing the AWG in Hotels, separate opinions from different hotels in several districts were collected. The demographic distribution of the survey respondents is shown in Table 3.

Table 3: Demographic Distribution of Survey Respondents

Variable	Categories	Frequency	Percentage
District	Anuradhapura	2	6.7
	Batticaloa	3	10
	Colombo	8	26.7
	Galle	2	6.7
	Hambantota	1	3.3
	Kalutara	3	10
	Kandy	2	6.7
	Matale	3	10
	Matara	2	6.7
	Nuwara Eliya	1	3.3
	Puttalam	2	6.7
	Trincomalee	1	3.3
Experience	Less than 5	2	6.7
	5 – 10	10	33..3
	10 - 15	13	43.3
	More than 15	5	16.7

The table presents the distribution of professionals participating in a questionnaire survey, categorised by the district they work in and their years of experience in the hotel industry. The percentage column in the table indicates the proportion of total respondents for each category within the "District" and "Experience" variables. The Relative Importance Index (RII) was utilised to analyse the significance of various factors related to the adoption of AWGs in the Sri Lankan hotel industry. Respondents rated each factor on a scale from 1 to 5, with 1 indicating "highly disagree" and 5 indicating “highly agree”. The RII was calculated using the formula RII = $\sum W / A \times N$ where W represents the weight given to each factor, A is the highest weight on the scale (5), and N is the total number of respondents (30). This analysis provided a quantitative measure of each factor's significance, aiding in strategic decision-making for the implementation of AWGs in hotels.

Table 4: Importance Levels Based on the RII Value Range

Maximum RII value	RII Value Range	Importance Level
1	1.0 – 0.8	High
0.8	0.8 – 0.6	Significant
0.6	0.6 – 0.4	Moderate
0.4	0.4 – 0.2	Low

4. RESEARCH FINDINGS AND ANALYSIS

4.1 FUNCTIONAL REQUIREMENTS AND CONSTRAIN OF IMPLEMENTING AWG

According to the literature review, there were functional requirements and constraints when implementing the AWGs in any location. Tables 4 and 5 are illustrated the responses with the percentages and the status of critical or non-critical gathered from the questionnaire survey.

Table 5: Critical or non-critical status of the identified functional requirements

Functional Requirements	Percentages (%)		Critical or Non-critical Status
	Critical	Non-Critical	
Should be used when the RH is low	100	-	Critical
Should be able to function at a wide range of temperatures	96.67	3.33	Critical
Should utilise about the same amount of power as a typical industry appliance	100	-	Critical
Should be able to provide adequate water for the facility	100	-	Critical
Alternative energy sources should be used to power it	100	-	Critical
Water should be filtered, and minerals added	100	-	Critical
Design should be appropriate for the facility	73.33	26.67	Critical

Table 6: Critical or non-critical status of the identified functional constraints

Functional Constraints	Percentages (%)		Critical or Non-critical Status
	Critical	Non-Critical	
To draw moisture, air should be used	100	-	Critical
Should be able to generate water within a specific temperature range	100	-	Critical
The water produced should meet EPA standards in terms of quality	86.67	13.33	Critical
Operation processes should be safe	100	-	Critical
Should be operated at a low volume	96.67	3.33	Critical
Minimum production costs are required	100	-	Critical

4.2 DRIVERS FOR IMPLEMENTING AWG AT HOTEL INDUSTRY

As identified in the literature review, there are several drivers to implement the AWG in hotels in the Sri Lankan context. Figure 1 presents the graphical representation of the drives.

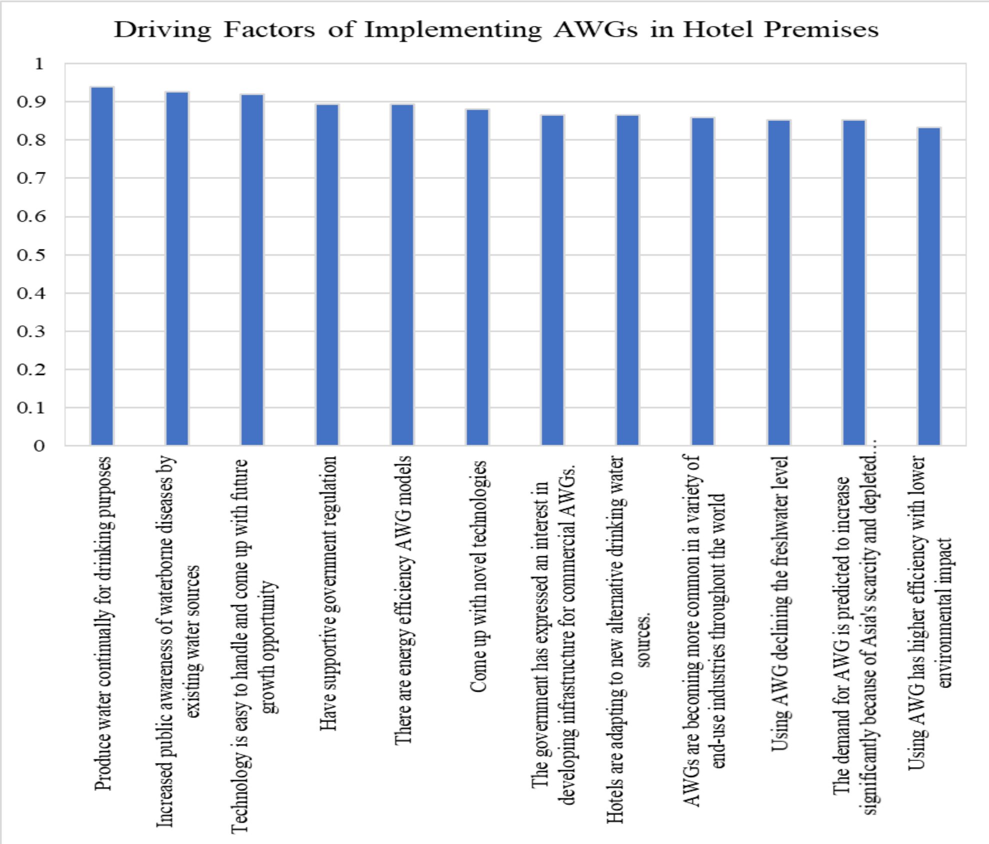


Figure 1: Driving factors of implementing AWGs in hotel industry according to the RII value

The survey exposed that "Produce water continually for drinking purposes" as the most important driver to implement AWG in hotels. As the alternative for the drinking-water bottles, providing the required capacity of water continually is an essential driver for hotels and AWG can fulfil that goal. According to Moghimi et al. (2021), AWGs offer an alternative water resource, especially in water-scarce regions. The second one is "Increased public awareness of waterborne diseases by existing water sources". These strategies focus on improving water quality, sanitation, and hygiene practices (Kumar et al., 2022). Not awareness of water treatments methods and water sources of water bottles and other alternatives of drinking-water, makes the requirement of well-known treated water. Since the AWG can provide fresh water without waterborne diseases, it will be great a solution for the alternative method for hotels. "Technology is easy to handle and come up with future growth opportunity" was ranked as the third driver. Sadowski et al. (2023), stated that AWGs extract water from the air using refrigeration, sorption, or fog harvesting technologies. Their ease of operation makes them accessible to a wide range of users, even after reading the user manual. The literature review identified twelve key drivers for implementing AWGs, which can be categorised into opportunities and strengths for hotels. These drivers include supportive government regulations and the development of energy-efficient AWG models, as noted by Sadowski et al. (2023). Governments are increasingly recognising the importance of AWGs for a sustainable water supply and expressing interest in developing infrastructure for commercial AWGs. Technological advancements such as advanced filtration systems, electrically improved harvesting, advanced oxidation processes, and automatic variable filtration technology are also driving the adoption of AWGs. Hotels are adapting to new alternative drinking-water sources, benefiting from AWGs' reliable on-site water production, which reduces dependence on external sources (Banerjee et al., 2023). AWGs are becoming more common across various end-use industries worldwide, including residential buildings, military installations, disaster relief efforts, remote communities, and industrial facilities, as highlighted by Inbar et al. (2020). The utilisation of AWGs helps mitigate the decline in freshwater levels by providing an additional water source, with their efficiency depending on climatic conditions and technology (Potyka et al., 2024). The demand for AWGs is expected to increase significantly in Asia due to the region's severe freshwater scarcity (Zia, 2020). Furthermore, AWGs offer higher efficiency with lower environmental impact, with all identified drivers having high importance levels according to the RII ranges, indicating their critical role in the successful implementation of AWGs. All the above drivers have higher rates of RII (<0.83). That means, all drivers identified have high importance levels according to the RII ranges.

4.3 BARRIERS FOR IMPLEMENTING AWG IN HOTEL INDUSTRY

As well as drivers, several barriers were identified through the literature review. Figure 2 illustrates the graphical representation of the results of identified barriers.

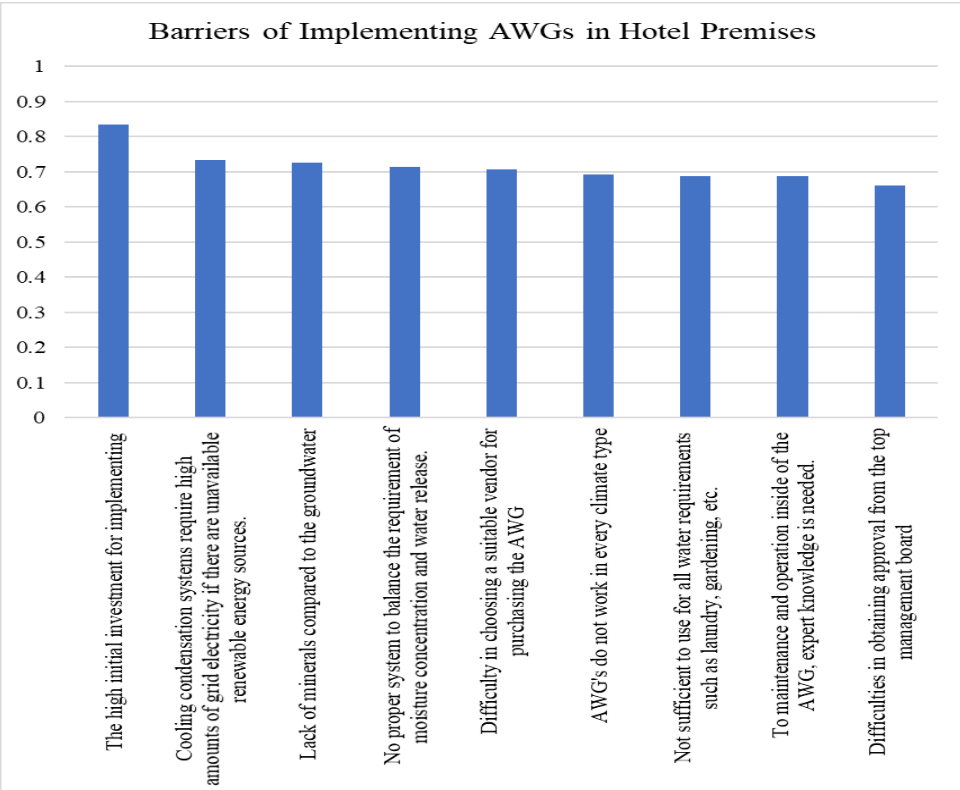


Figure 2: Barriers of implementing AWGs in hotel industry according to the RII value

"The high initial investment for implementing" is ranked as the most identified barrier (RII = 0.8333) among 9 barriers. This indicates that, high investment costs prevail as the most prominent barrier to the implementation of AWGs in hotels. The cost of buying the generator, transportation cost to the facility, and installing the solar power system for power generation are highly contributing to the initial costs. Therefore, it is clearly can be identified as the most important barrier, because when implementing a new strategy to mitigate an existing problem, that alternative should be more cost-effective than the previous method. However, assuming a perfect substitution between AWG machines and bottled water, the financial performance of AWG machines demonstrates an attractive substitute product in the majority of locations (Moghimi et al., 2021). ‘Cooling condensation systems require high amounts of grid electricity if there are unavailable renewable energy sources” was ranked as the second barrier with RII value 0.7333. Cooling condensation AWGs use a compressor to cool the air and condense water vapor (Siddiqui et al., 2023). If renewable energy sources are unavailable, reliance on grid electricity can be high (Aravind, 2023). Using electrical power from the grid will increase the energy consumption because AWGs need to operate throughout the day and the condensing process needs a high amount of energy. Therefore, it will become another major obstacle to implementing the AWGs. As the third barrier, “Lack of minerals compared to the groundwater” was identified. Whether, AWG can provide fresh water, the percentages of the mineral required in drinking-water are not available in the atmosphere water vapour, when compared with the ground water. The mineral content in AWG water depends on the source air and the materials used in the system (Watergen, 2024). Some AWGs add essential minerals (such as calcium and magnesium) to improve water quality (drinkableair technologies, 2024). However, AWG water may still have lower mineral content compared to groundwater. The fourth and fifth barriers, “No proper system to balance the requirement of moisture concentration and water release” and “Difficulty in choosing a suitable vendor for purchasing the AWG” got the RII value of 0.7133 and 0.7067 respectively. Selecting a vendor for purchasing an AWG becomes a barrier because, as the newly invented strategy of making drinking-water, there are not many manufacturers and distributors in Sri Lanka.

The remaining barriers to implementing AWGs are notably significant but rated as moderate in importance compared to higher-level barriers. These barriers include the limitation that AWGs do not work in every climate type, as their performance is highly dependent on humidity and temperature (Sadowski et al., 2023). Consequently, not all regions would achieve the same level of water production due to these climatic constraints. Additionally, AWGs are not sufficient for all water requirements, such as laundry and gardening, because their capacity depends on factors like humidity levels and machine specifications. Maintaining and operating AWGs requires expert knowledge, including understanding system components, performing filter replacements, and troubleshooting. Furthermore, obtaining approval from top management boards can be challenging due to initial investment costs and operational considerations (Raveesh et al., 2023). These barriers have RII values between 0.7 and 0.6, indicating a significant level of importance.

4.4 STRATEGIES TO OVERCOME BARRIERS

To overcome the barriers of implementing AWGs in the Hotel industry in the Sri Lankan context, respondents were asked to suggest strategies. For the first barrier, it was suggested to analyse the overall life cycle cost comparison between bottled water consumption vs AWG. So, it will be easy to find the most cost-effective method between those two methods is. According to the case study of Eastern Research Group (2018), it was mentioned that there is a significant cost difference when considering the entire useful life of the AWG. Moreover, it can be used new technologies and manufacturing processes to minimise the overall production cost. When using the AWG, throughout the day it consumes a high amount of grid electricity and it will directly increase the operational cost of the AWG. Hence the respondent’s suggestion was to implement the

AWGs with a solar power system. Due to the tropical country Sri Lanka always have solar power. In the hotel industry, there are plenty of other water requirements. However, this study is focused on drinking-water consumption, it is not needed to consider other water requirements like laundry, gardening, washrooms etc. Besides, respondents stated that as the first step, it is sufficient to fulfil the drinking-water consumption. Since AWG is a novel concept and technology to Sri Lanka, the respondents had not much knowledge about the maintenance and operation inside of the AWGs. Therefore, respondents did not suggest any strategy to overcome the issue. However, the AWG water generation project is similar to the HVAC system (Tripathi, et al., 2016). Therefore, by giving training to the technicians on the basic functions of AWG, it will be easy to mitigate the barrier. 'No proper system to balance the requirement of moisture concentration and water release', for this barrier also none of the respondents mentioned a strategy, due to the lack of knowledge of AWG's process. According to Zhou, et al. (2020), sorbent materials can be used as moisture harvesters if the water affinity is adjusted to allow for moisture concentration at low RH and water release with little energy input.

In Sri Lanka there are no details on who manufactured or distributed commercial type AWGs that can provide more than 1000 litres per day. Therefore, the strategy that was suggested by the respondent is to make contact with an international vendor to import AWGs. By referring to the feedback of previous customers, and doing the technical and commercial evaluations, suitable vendor can be selected. In literature synthesis it was identified that there are factors that need to be considered when selecting AWGs. According to the Eriksson and Hashemi (2008), there should be more than 30% RH levels and the temperature should be varied between 20℃ – 40 ℃. Respondents did not mention any strategy to overcome because Sri Lanka is a tropical country and the required level of RH and temperature levels are available in most of the areas in Sri Lanka. The average monthly RH level is higher than 70% and the mean annual temperature varies between 26.5℃ – 28.5℃ (Department of Meteorology, 2019). To implement a new strategy, it is a must to take approval from top management. As the first step, it is needed to prepare the proposal for the reason of implementing the AWG and submit it to the top management. Then discussed with them the drivers, and benefits that can be gained through the implementation. When compared to the ground water, there is a lack of minerals in atmospheric vapour. The remedy that was suggested by the respondents was to add minerals other nutrition to the generated water. According to Brigano and Kapustin (2021), there is an in-building filtration system in several AWGs and for others it can be added. Thus, to mitigate this barrier, the generated water should pump through the filters and then add minerals to the water to increase and maintain healthy pH levels.

5. CONCLUSIONS

The study underscores the significant potential of AWGs as an alternative to bottled water in Sri Lanka's hotel industry. Globally, there is a growing urgency to find sustainable drinking-water solutions, driven by the environmental impact of bottled water and the need for reliable water sources. In Sri Lanka, the adoption of new technologies has been relatively slow compared to more developed countries. The negative impacts of bottled water, such as the lack of transparency in water sources and treatment methods, and its high contribution to the carbon footprint, have led to a search for better alternatives. The AWG method has emerged as a promising solution. While many countries have begun implementing AWGs, this technology remains novel in Sri Lanka. Introducing AWGs to the hotel industry, which is a major consumer of bottled water, represents a strategic starting point. The research highlights the importance of addressing environmental conditions, efficiency, government support, and public awareness to facilitate the adoption of AWGs in Sri Lanka's hotel sector. Overcoming challenges like high initial costs, energy consumption, and maintenance requirements through incentives, collaboration, and education is crucial for the successful implementation of AWGs and promoting sustainable water management.

6. REFERENCES

Aravind, K. (2023). Investigation of the technological advancements and future prospects of atmospheric water Generator Systems. *Journal of Student Research, 12*(3), 1–5. Retrieved from https://doi.org/10.47611/jsrhs.v12i3.4684

Balaganapathi, Parthasarathy, Kumaresan, Kamil, A., & Ganesh. (2020). Experimental analysis of atmospheric water generator using surface sondensation technique. *Journal of Interdisciplinary Cycle Research, 12*(3), 250- 253.

Banerjee, U., Kaushik, H., Garg, H., & Sikarwar, B. S. (2023). Design and fabrication of an atmospheric water generator for water harvesting from moist air BT. In R. Sharma, R. Kannojiya, N. Garg, & S. S. Gautam (Eds.), *Advances in engineering design*. (pp. 169–178). Springer Nature Singapore.

Bolsinger, C., & Ralphs, S. (2019). *Atmospheric water generation.* Worchester Polytechnic Institute. https://digital.wpi.edu/pdfviewer/nc580q66g

Botto, S., Niccolucci, V., Rugani, B., Nicolardi, V., Bastianoni, S., & Gaggi, C. (2011). Towards lower carbon footprint patterns of consumption: The case of drinking water in Italy. *Environmental Science & Policy,* 14(4), 388-395.

Brigano, F. A., & Kapustin, E. A. (2021, September 28). *Applications & Evolution of Atmospheric Water Generation Technologies*. Water World. https://www.wqpmag.com/one-water/applications-evolution-atmospheric-water-generation-technologies

Chang, C.W. (2015). *A study on the social and the environmental impacts of bottled water & a design solution to improve the user experience of water reusable water bottles.* [Thesis, Rochester Institute of Technology] RIT Libraries. https://repository.rit.edu/theses/8720

Dasinaa, S., & Delina, E. (2015). *Spatial Distribution of Mineral Water Bottle Usage in Batticaloa District: A Case Study.* South Eastern University Sri Lanka.

Delgado, M. (2020, February 20). *The importance of atmospheric water technology in the face of global water scarcity.* Smart Water Magazine. Retrieved June 27, 2024 from https://smartwatermagazine.com/blogs/mildred-delgado/importance-atmospheric-water-technology-face-global-water-scarcity

Department of Meteorology . (2019, June 20). *Climate of Sri Lanka.* Department of Meteorology , Retrieved June 22, 2024 from https://www.meteo.gov.lk/index.php?option=com_content&view=article&id=94&Itemid=310&lang=en

Drinkableair Technologies. (2024, June 22). *Atmospheric Water Generator Technology - Drinkableair Technologies*. Drinkableair Technologies, Retrieved June 22, 2024 from https://drinkableair.tech/awg-technology/atmospheric-water-generator-technology/

Eastern Research Group. (2018). *Life cycle and cost assessments of atmospheric water generation technologies and alternative potable water emergency response options.* (EPA Contract No. EP-C-15-010 Work Assignment 2-32 & 3-32). United States Environmental Protection Agency

Elliott, S. (2024, May 2). *What are Atmospheric Water Generators?* HowStuffWorks, Retrieved June 22, 2024 from howstuffworks: https://home.howstuffworks.com/atmospheric-water-generators.htm

Eriksson, D., & Hashemi, R. (2008). *Evaluation of suitable methods for water generation* . [Masters Thesis, KTH Industrial Engineering & Mnagment, Sweden].

Feng, Z. (2019, November 8). Going plastic-free: How hotels are joining the anti-plastic fight. Eco-business. Eco Business. Retrieved June 22, 2024from https://www.eco-business.com/news/going-plastic-free-how-hotels-are-joining-the-anti-plastic-fight/

Fresh Outlook Foundation (2021). *More people are hitting the bottle.* Fresh Outlook Foundation. Retrieved June 27, 2024 from https://freshoutlookfoundation.org/more-people-are-hitting-the-bottle/

Garfí, M., Cadena, E., Sanchez-Ramos, D., & Ferrer, I. (2016). Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. *Journal of Cleaner Production*, *137*, 997-1003. Retrivied from https://doi.org/10.1016/j.jclepro.2016.07.218

Global Market Monitor. (2020, August 25). *Atmospheric Water Generator Global Market Study Focus on Top Companies and Crucial Drivers*. IPS News Agency, https://ipsnews.net/business/2020/08/25/atmospheric-water-generator-global-market-study-focus-on-top-companies-and-crucial-drivers/

Inbar, O., Gozlan, I., Ratner, S., Aviv, Y., Sirota, R., & Avisar, D. (2020). Producing safe drinking water using an atmospheric water generator (AWG) in an urban environment. *Water*, *12*(10), 2940, Retrieved from https://doi.org/10.3390/w12102940

Industry ARC. (2019). *Atmospheric Water Generator Market Report – Forecast (2020-2025).* (Report code ITR 85735) Atmospheric water generator market. https://www.industryarc.com/Research/Atmospheric-Water-Generator-Market-Research-504142

James, S., Normand, G., Pike, A., & Agulier, A. (2018). Novel Low-Cost Portable Solar-Powered Atmospheric Water Generator. *Calfornia State University.* Fullerton.

Jarimi, H., Powell, R., & Riffat, S. (2020). Review of sustainable methods for atmospheric water harvesting. *International Journal of Low-Carbon Technologies,* 15(2), 253-276. Retrieved from https://doi.org/10.1093/ijlct/ctz072

Kulkarni, S. (2019, September 17). *Atmospheric water generator : water from thin air - part III*. Tahaan.Retrieved June 22, 2024 from https://tahaanefforts.org/blog/atmospheric-water-generator-part-three

Kumar, P., Srivastava, S., Banerjee, A., & Banerjee, S. (2022). Prevalence and predictors of water-borne diseases among elderly people in India: Evidence from longitudinal ageing study in India, 2017–18. *BMC Public Health*, *22*(1), 993. https://doi.org/10.1186/s12889-022-13376-6

Laville, S., & Taylor, M. (2017, June 28). *A million bottles a minute: World's plastic binge 'as dangerous as climate change'.* Guardian. Retrieved June 27, 2024 from https://www.theguardian.com/environment/2017/jun/28/a-million-a-minute-worlds-plastic-bottle-binge-as-dangerous-as-climate-change

Maida, J. (2019, January 28). *Global atmospheric water generator market 2019-2023:New technological developments in awg market to boost growth Technavio*. Businesswire, Retrieved June 22, 2024 from https://www.businesswire.com/news/home/20190128005501/en/Global-Atmospheric-Water-Generator-Market-2019-2023-New-Technological-Developments-in-AWG-Market-to-Boost-Growth-Technavio

Market Research Team. (2021, September). *Atmospheric water generator market - global industry analysis, size, share, growth, trends, and forecast, 2021-2031*. Transparency Market Research, Retrieved June 22, 2024 from https://www.transparencymarketresearch.com/atmospheric-water-generator-market.html

McLeod, S. (2019). *What's the difference between qualitative and quantitative research?* Simply Physhology. Retrieved June 22, 2024 from https://www.simplypsychology.org/qualitative-quantitative.html

Mendoza-Escamilla, J. A., Hernandez-Rangel, F. J., Cruz-Alcántar, P., Saavedra-Leos, M. Z., Morales-Morales, J., Figueroa-Diaz, R. A., . . . Martinez-Lopez, F. J. (2019). A feasibility study on the use of an Atmospheric Water Generator (AWG) for the harvesting of fresh water in a semi-arid region affected by mining pollution. *Applied Science*, *9*(16), 3278. DOI:10.3390/app9163278

Moghimi, F., Ghoddusi, H., & Asiabanpour, B. (2021). Is atmospheric water generation an economically viable solution? *Clean Techn Environ Policy, 23,* 1045-1062. Retrieved from https://link.springer.com/article/10.1007/s10098-020-02015-6

Moradi, S. (2019). *Reviewing and designing an Atmospheric Water Generator.* [Masters thesis, Aalto University]. https://aaltodoc.aalto.fi/items/3bf8ad85-e3a9-4764-ad93-6a4edb0d1dea

Potyka, J., Dalibard, A., & Tovar, G. (2024). Energetic analysis and economic viability of active atmospheric water generation technologies. *Discover Applied Sciences*, *6*(4), 153. Retrieved from https://doi.org/10.1007/s42452-024-05746-z

Research and Markets (2020, October 14). *Global Atmospheric Water Generator Market Report 2020: A $3 Billion Industry - Forecast to 2025.* Globenewswire, Retrieved June 22, 2024 from https://www.globenewswire.com/news-release/2020/10/14/2108155/28124/en/Global-Atmospheric-Water-Generator-Market-Report-2020-A-3-Billion-Industry-Forecast-to-2025.html

Raveesh, G., Goyal, R., & Tyagi, S. K. (2023). *Atmospheric Water Generation: Concepts and Challenges.* Thermopedia. https://www.thermopedia.com/content/10265/

Sadowski, E., Mbonimpa, E., & Chini, C. M. (2023). Benchmarks of production for atmospheric water generators in the United States. *PLOS Water*, *2*(6), e0000133. Retrieved from https://doi.org/10.1371/journal.pwat.0000133

Shourideh, A. H., Ajram, W. B., Lami, J. A., & Salem, H. (2018). A comprehensive study of an atmospheric water generator using Peltier effect. *Thermal Science and Engineering Progress, 6,* 14-26. Retrieved from https://doi.org/10.1016/j.tsep.2018.02.015

Siddiqui, M. A., Azam, M. A., Khan, M. M., Iqbal, S., Khan, M. U., & Raffat, Y. (2023). Current trends on extraction of water from air: an alternative solution to water supply. *International Journal of Environmental Science and Technology*, *20*(1), 1053–1080. Retrieved from https://doi.org/10.1007/s13762-022-03965-8

Smuts, K. (2015, July 3). *Atmospheric water provides bottled water alternative*. Engineering News. Retrieved June 22, 2024 from https://www.engineeringnews.co.za/print-version/atmospheric-water-provides-bottled-water-alternative-2015-07-03

The United Abrahamic Family. (2019). *Why atmospheric water generator technology by TUAFI?* TUAFI. Retrieved June 22, 2024 from https://tuafi.com/why-tuafi/

Tripathi, A., Tushar, S., Pal, S., Lodh, S., Tiwari, S., & Prof. Desai, R. (2016). Atmospheric water generator. *International Journal of Enhanced Research in Science, Technology & Engineering, 5*(4), 69-72.

Watergen (2024). *GEN-M PRO world's most efficient water from air generator.* Watergen. Retrieved June 22, 2024 from https://us.watergen.com/commercial/gen-m/

World Health Organisation (WHO). (2019, June 14). *Drinking-water.* Retrieved September 12, 2023 from https://www.who.int/news-room/fact-sheets/detail/drinking-water

Zhou, X., Lu, H., Zhao, F., & Yu, G. (2020, May 7). Atmospheric water harvesting: A review of material and structural designs. *ACS Materials Letters, 2*(7), 671-684. Retrieved from https://doi.org/10.1021/acsmaterialslett.0c00130

Zia, Q. (2020 February 25). *Technology and the future of growth: Challenges of change.* Brookings. Retrieved June 22, 2024 from https://www.brookings.edu/blog/up-front/2020/02/25/technology-and-the-future-of-growth-challenges-of-change/

Silva, F.H.Y.D., Perera, B.A.K.S., Atapattu, A.M.D.S., Jayanetti, J.K.D.D.T. and Wijewickrama, M.K.C.S., 2024. Application of biomimicry concept to improve the sustainability of the construction industry: A literature review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 185-199. DOI: https://doi.org/10.31705/WCS.2024.15. Available from: https://ciobwcs.com/papers/

APPLICATION OF BIOMIMICRY CONCEPT TO IMPROVE THE SUSTAINABILITY OF THE CONSTRUCTION INDUSTRY: A LITERATURE REVIEW

F.H.Y.D. Silva[1], B.A.K.S. Perera[2], A.M.D.S. Atapattu[3], J.K.D.D.T. Jayanetti[4], and M.K.C.S. Wijewickrama[5]

ABSTRACT

The growing need for urbanisation has resulted in the intense development of the construction industry, which has negatively impacted the conservation of the environment. In this regard, to preserve the ecosystems, the concept of sustainable development was introduced, however, the effectiveness of the existing sustainability practices in the construction industry is at a questionable level. Meanwhile, the evolving concept of biomimicry, which inspires and learns from natural processes, has proven the capacity to achieve sustainable parameters when incorporated into construction processes. Yet, there is a noticeable gap in applying the biomimicry concept to improve the sustainability of the construction industry. Therefore, this study aims to comprehend the applicability of the biomimicry concept in improving the sustainability of the construction industry. Accordingly, a comprehensive literature review was conducted on existing studies related to the biomimicry concept. The content analysis method was used to analyse the collected data. The findings suggested that the biomimicry concept can contribute to sustainable parameters such as material efficiency, energy efficiency and zero-waste concept. Accordingly, this study reveals the potential to improve the sustainability of the construction industry by comprehending the application of the biomimicry concept in detail. In this regard, the study discovers the enablers, barriers and strategies for biomimicry application in the construction industry. Accordingly, this study contributes to the theory and bridges the knowledge gap in utilising biomimicry applications to enhance the sustainability of the construction industry. It demonstrates how various biomimicry inspirations can positively impact sustainable parameters such as material efficiency, energy efficiency, and zero waste, thereby revealing the concept's applicability in developing a sustainable built environment.

Keywords: *Barriers; Biomimicry; Construction Industry; Enablers; Strategies.*

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, fhyohandilushasilva@gmail.com
[2] Professor in Quantity Surveying, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk
[3] PhD Researcher in Construction Management, School of Architecture and Civil Engineering, The University of Adelaide, Australia, atapattu.atapattu@adelaide.edu.au
[4] PhD Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, qsthamasha@gmail.com
[5] Lecturer, School of Architecture and Civil Engineering, The University of Adelaide, Australia, chamitha.wijewickrama@adelaide.edu.au

1. INTRODUCTION

The construction industry contributes to the development of a country as a key contributor to the national economy (Oguntona & Aigbavboa, 2020). Nonetheless, the excessive resource consumption and waste generation of construction activities have termed the industry as one of the most disastrous industries in the world (Huo et al., 2018). According to research, 40% of the natural resources are consumed by the construction industry while accounting for 40% of the global waste generation and 33% of harmful emissions (van Stijn & Gruis, 2020). Thus, a worldwide concern was developed focusing on the sustainability of the construction industry to minimise the industry's harmful impact on nature (Chua et al., 2018).

With the growing interest in sustainable construction practices, resource minimisation practices, including the use of secondary materials (recycled or used materials), were greatly followed in construction projects as a solution to excessive resource consumption (Singh, 2018). Additionally, a clear focus was driven towards creating a healthy and non-toxic environment, formation of sustainable construction standards, pursuing quality in the built environment and establishing sustainable construction technologies (Seferlis et al., 2021). Furthermore, education and training opportunities on sustainable construction activities were implemented to increase the sustainability of the construction sector (Mikhno et al., 2021). Besides employing sustainable practices in the construction industry has a proven capacity to offer numerous benefits mainly including the progression of a firm's competitiveness and profitability (Ahamed et al., 2022). Additionally, sustainable construction practices provide further benefits including reduction of expenses, increased energy efficiency, and health and safety benefits (Hosseini et al., 2019).

Even if sustainable construction practices provide numerous benefits, the successful adoption of sustainable practices is hindered in the construction industry due to several challenges (Ogunsanya et al., 2022). Availability issues of sustainability materials and technologies are a key issue for the successful establishment of a sustainable construction industry (Opoku et al., 2019). Additionally, lack of focus, shortage of rules and regulations and economic barriers impact the effective implementation of sustainable construction practices (Al-Otaibi et al., 2022). Furthermore, limited government support is considered a key reason for the lower adoption rate of sustainable practices in the construction industry (Pham et al., 2020). Besides, the lack of effectiveness in sustainability practices is considered a key barrier to the successful adoption of sustainable construction practices (Ogunsanya et al., 2022). Unlike other barriers such as regulatory barriers and economic barriers, the issues on the effectiveness of sustainability practices are more prevalent since the successful employment of sustainable construction practices strictly relies on this matter (Williams, 2022). Accordingly, the need to introduce new concepts to enhance the effectiveness of sustainable practices was heightened to stimulate the transition to a sustainable built environment (Moshood et al., 2022).

In this context, the concept of biomimicry was introduced, mimicking nature's philosophies to resolve human problems (Beermann & Austin, 2021). The biomimicry concept emulates models, elements, and systems of nature to develop innovative and sustainable design solutions (Khoja & Waheeb, 2020). Accordingly, the biomimicry concept has been integrated into structural material creation, and examples include the functionally graded concrete, which is inspired by porcupine quill and sea urchins' spines, and sandwich structures, which are inspired by the wings of the green hairstreak butterflies (Ahamed et al., 2022). Furthermore, integrating the biomimicry concept has led to improvements in building shapes. A notable example is the Eastgate Shopping Centre in Zimbabwe, which was designed by mimicking the shape of termite mounds (Yacubov & Smith, 2020). Additionally, the biomimicry concept follows peculiar techniques such as incorporating diversity, combining modular and nested components, and using multi-functional designs (Ahamed et al., 2022; Austin et al., 2020; Oguntona & Aigbavboa, 2019a), which are highly significant in improving the effectiveness of sustainable practices in the construction industry.

Nevertheless, the shortage of biomimicry experts and lack of biomimicry education and training opportunities have hindered the successful adoption of the biomimicry concept in the construction industry (Oguntona & Aigbavboa, 2019a). Furthermore, research is still underway on the biomimicry concept's performance and technical requirements (Zari & Hecht, 2020). Accordingly, studies have been conducted on integrating biomimicry applications into the transportation industry (Kong et al., 2020), healthcare sector (Chairiyah, 2021), agriculture industry (Stojanovic, 2019) and automation industry (Kazasidis et al., 2021). Meanwhile, the studies on integrating biomimicry applications into the construction sector rather focus on applying the biomimicry concept to industrial mechanisms regardless of assessing the role of biomimicry in improving the sustainability of the construction industry (Oguntona & Aigbavboa, 2019a). However, preliminary investigations have been conducted on the intervention of biomimicry applications in achieving the sustainability of the construction industry, including the areas of sustainable construction projects where biomimicry principles can be applied (Adekunye & Oke, 2023), the link between the biomimicry concept and sustainable principles such as repairing, maintaining retrofit and reusing existing buildings (Sai & Lakshmi, 2020) and the connection of organism-based and eco system-based biomimicry applications with sustainable buildings (Syed, 2021). Accordingly, earlier research focused only on specific applications and none of these studies have consolidated all these applications to comprehend the potential of applying the biomimicry concept in improving the sustainability of the construction industry. Nevertheless, it is highly significant to assess the role of the biomimicry concept in enhancing the effectiveness of existing sustainability practices to ensure the endurance of a sustainable built environment (Williams, 2022). Accordingly, to fill this knowledge gap, this study aims to comprehensively investigate the applicability of the biomimicry concept to enhance sustainability in the construction industry based on existing literature.

2. RESEARCH METHOD

The research method is a way of providing accurate responses to the research problem (Pandey & Pandey, 2015). The methodological process of research is developed by stabilising the background of the study, reviewing the existing literature related to the study, and ultimately analysing the collected data related to the identified research problem (Edwards & Brannelly, 2017). Accordingly, the research process followed in this study is illustrated in Figure 1.

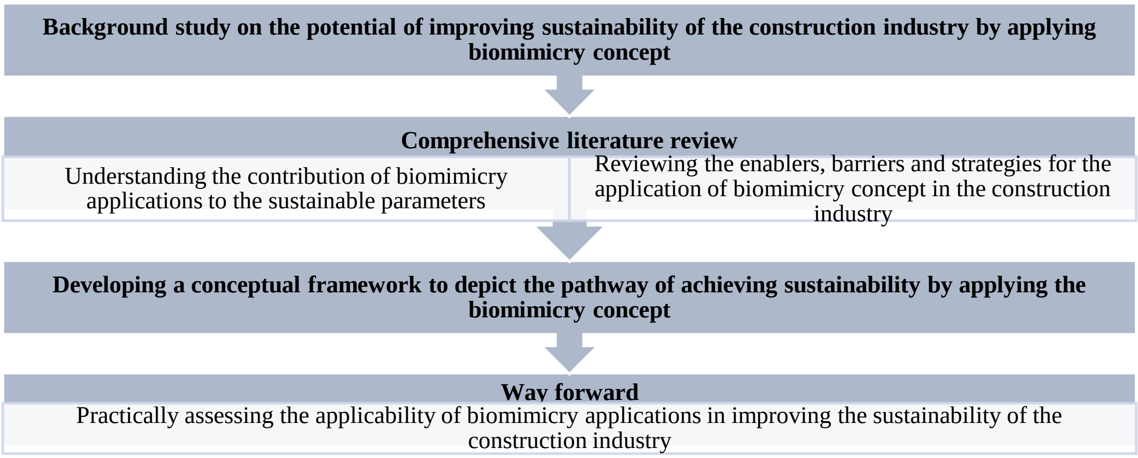


Figure 1: Research process

As explained in Figure 1, a background study was conducted to understand the potential of improving the sustainability of the construction industry by applying the biomimicry concept. From the background study, the importance of conducting a study on applying the biomimicry concept to enhance sustainability was revealed. Herein, a comprehensive literature review was conducted on the research area since reviewing literature assists researchers in distinguishing the updated and structured overview of the existing body of knowledge related to the specific area of the research (Pautasso, 2019). Accordingly, the existing studies were searched in three databases, i.e. (i) Google Scholar, (ii) Web of Science, and (iii) Scopus by filtering through the key terms of "biomimicry", "sustainability" and "construction". Approximately 150 journal articles, conference papers and theses were referred to. The gathered data from the literature review was analysed using the content analysis method since this method has a straightforward criterion for categorising data to improve the contextual significance (Kyngäs, 2020). A conceptual framework was developed from the findings since it acts as an important research element that assists further investigations on the research area (Martín et al., 2019).

3. FINDINGS

The existing sustainability practices in the construction industry and the issues related to their effectiveness were revealed from the literature review on the study area which is presented in this section. Furthermore, the approaches and applications of the biomimicry concept were discovered by literature findings with their capability to achieve sustainable parameters that were supported by real-life example projects. Moreover, the enablers, barriers and strategies for biomimicry applications were revealed by literature findings which are comprehensively presented in this section.

3.1 SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY

Sustainability in the construction industry refers to the creation and accountable upkeep of a healthy built environment based on ecological and resource-efficient principles (Ahiabu et al., 2022). Sustainable construction projects develop into a sizable competitive advantage, increasing the profitability of the venture through higher rents and reduced life cycle costs, which is highly valued by investors (Sanchez et al., 2020). Simultaneously, it has been demonstrated through empirical research that the presence of environmentally friendly production correlates with the firm's profitability and competitiveness (Ahamed et al., 2022). Due to the wide range of benefits offered by integrating sustainability into the construction industry, construction practitioners are highly motivated to execute sustainability practices in construction projects (Mensah, 2019). Accordingly, Table 1 provides the sustainability practices that are implemented in the construction industry.

Table 1: Existing sustainability practices in the construction industry

Sustainable Practices	Authors																	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Resource minimisation				✓											✓			
Maximisation of resource reuse	✓		✓		✓	✓		✓	✓		✓		✓	✓		✓	✓	
Utilisation of renewable or recyclable resources			✓	✓			✓				✓	✓			✓			✓
Protection of the natural environment	✓	✓			✓				✓	✓			✓				✓	
Creation of a healthy and non-toxic environment			✓	✓							✓	✓						✓
Enforcement of sustainable legal		✓				✓		✓		✓				✓		✓		
Standards, guidelines or policies for sustainable construction				✓	✓		✓					✓	✓		✓			✓
Designing based on sustainability principles	✓	✓				✓		✓	✓	✓				✓		✓	✓	✓
Technologies, processes and innovations based on sustainability principles		✓				✓				✓				✓				✓
Achievement of quality in creating the built environment		✓		✓	✓			✓		✓		✓	✓			✓		✓
Measurement and reporting based on sustainability principles																		✓
Education and training based on sustainability principles	✓			✓	✓		✓		✓			✓	✓		✓		✓	

A - (Mikhno et al., 2021), B - (Wuni et al., 2019), C - (Sanchez et al., 2020), D - (Singh, 2018), E - (Cedeño et al., 2018), F - (Hossain et al., 2020), G - (Darko et al., 2019), H - (Ghisellini et al., 2018), I - (Khoshnava et al., 2020), J - (Oyebode, 2018), K - (Athapaththu & Karunasena, 2018), L - (Silvestre & Ţîrcă, 2019), M - (He et al., 2018), N - (Kim et al., 2018), O - (Rai et al., 2021), P - (Yu et al., 2020), Q - (Parn & Edwards, 2019), R - (Seferlis et al., 2021)

As Table 1 suggests, numerous sustainability practices are currently implemented in the construction industry to increase the quality of the industrial processes (Xia et al., 2018). Designing based on sustainability principles is one of the most well-recognised sustainability practices in the construction industry to reduce the effects of building on the environment (Fianko et al., 2021). According to Singh (2018), sustainable building designs focus on using energy-efficient heating, lighting, air conditioning systems, and wastewater recycling technologies to improve the building's environmental performance. Besides, following sustainability guidelines such as using renewable energy sources for construction (e.g., solar power) will improve the sustainable features of the buildings while reducing carbon dioxide and other harmful emissions (Lin & Zhu, 2019).

Even if sustainable construction has captured the attention of the construction industry, it is not effectively practised (Rajamanickam et al., 2019; Ahamed et al., 2022). One of the major reasons for this issue is that sustainable practices frequently have a high initial cost (Aramesh & Shabani, 2020). There are many difficulties incorporated with adapting to sustainable designs (Ogunsanya et al., 2022). For instance, renewable energy sources mostly depend on location and weather conditions because of their natural characteristics, and they are less capable compared to fossil-powered energy sources (Opoku et al., 2019). In addition, some sustainable materials need chemical treatments to perform effectively on fire resistance and durability (Zhang et al., 2023). Sustainable practices lack effectiveness based on such issues; thus, to increase the effectiveness of sustainability principles, it is highly significant to comprehend the integration of sustainability principles with novel concepts that consider the conservancy of the environment (Tanwar et al., 2022).

3.2 THE CONCEPT OF BIOMIMICRY AND THE CONSTRUCTION INDUSTRY

According to research, nature has the best organisation in terms of form and function, which can produce practical and long-lasting designs (Austin et al., 2020). Therefore, academics, architects, and designers known as Bioneers believe that insights from nature can be used to inform their design processes (Jalil & Kahachi, 2019). Accordingly, an applied science known as "biomimicry" was introduced. Herein, biomimicry uses natural patterns, mechanisms, and systems to generate concepts for solving problems (Sadegh et al., 2022). The word 'biomimicry' became well-known in 1997 with the publication of "*Biomimicry: Innovation Inspired by Nature*," authored by the biologist and co-founder of the biomimicry guild Janine M. Benyus (Jalil & Kahachi, 2019). Afterwards, the biomimicry concept was instituted with several corresponding definitions. Table 2 lists various definitions of "biomimicry" that thoroughly explain the concept and are supported by prior research.

Table 2: Definitions of biomimicry concept

Definition	Authors
A relatively new field of science called "**nature as a model**" utilizes natural phenomena as models for human problems and seeks to replicate or be inspired by them.	(Pathak, 2019)
A novel perspective on and assessment of nature is that of **nature as a mentor.** This new understanding explains where we have faltered thus far and what we can take away from it.	(Beith, 2021)
3.8 billion years of **natural evolution as a measure**, along with ecological norms, quality assurance, and standards, are used to assess the sustainability of inventions. The laws of sustainability have already been discovered by nature. The "rightness" of our inventions is assessed using a biomimicry standard.	(Wan & Subri, 2021)
To solve human issues, biomimicry involves observing nature's most successful innovations and then modelling systems after them. It can be described as **"innovation inspired by nature."**	(Alanbari et al., 2022)

As elaborated by the definitions in Table 2, biomimicry studies natural models and then copies their forms, processes, systems, and tactics to address human problems sustainably (Pathak, 2019). It is an innovation strategy that seeks long-lasting solutions by mimicking proven patterns and processes found in nature (Anwar et al., 2018).

Simultaneously, the studies that have been conducted on the biomimicry concept specifically focusing on the construction context define biomimicry as a concept that gets inspiration from nature for designing, producing and maintaining building systems, elements and processes (Adekunye & Oke, 2023). It is referred to as "imitation engineering" (p.514), which integrates natural science with construction engineering (Sai & Lakshmi, 2020). Moreover, construction projects inspired by the biomimicry concept can be considered a major contributor to developing a regenerative built environment (Syed, 2021). Furthermore, there are several methodologies for applying the biomimicry concept in the construction industry from its inception to its depletion (Adekunye & Oke, 2023). In this vein, the two main methodologies that researchers have introduced for the implementation of the biomimicry concept are; (i) the problem-based (top-down) approach, and (ii) the solution-based (bottom-up) approach (Sadegh et al., 2022).

The problem-based (top-down) approach is initiated by the design problem, where the designers identify the issue and then look for remedies (Jamei & Vrcelj, 2021). The authors further mentioned that this approach encourages biologists to compare the issue to a natural process that has resolved a comparable issue. Therefore, the problem-based (top-down) approach depends on the clear identification of objectives and constraints of the design problem (Austin et al., 2020). Conversely, in the solution-based (bottom-up) approach, the design process depends on the factual knowledge of biologists and scientists rather than problems with human design (Beermann & Austin, 2021). In this approach, natural solutions inspire the design of a process or system, and natural techniques will be converted into technical answers (Abedanzadeh et al., 2021). Accordingly, many inventors follow both biomimicry approaches to optimise their designs with inspiration from nature (Prianka et al., 2018). Consequently, biomimicry is currently at the forefront of scientific and technological research since it offers novel views on the synthesis of ecologically compatible, environmentally non-threatening, and dynamically efficient materials for multiple industries over the globe (Katiyar et al., 2021).

3.3 BIOMIMICRY APPLICATIONS IN THE CONSTRUCTION INDUSTRY

The use of biomimicry in the construction industry focuses mostly on enhancing the built environment through advancements in construction and operation, as well as the reduction in environmental consequences by incorporating insights from nature (Ahamed et al., 2022). Research suggests that the use of biomimicry innovation techniques allows construction professionals and their associated partners to develop high-performance, sustainable, and energy-efficient buildings that adhere to advanced waste management practices (Dash, 2018). Amer (2019) pointed out that while there are numerous historical examples of biomimicry applications in the construction industry, their implementation varies based on the project's specific circumstances and demands. Certain solutions offer design flexibility, while others enhance structural stability by incorporating biomimicry principles into architectural elements, thereby contributing to sustainable construction (Othmani et al., 2018). Accordingly, Table 3 lists several examples of construction projects that utilised biomimicry inspirations to increase the sustainability of the projects.

Table 3: Construction projects that utilised biomimicry inspirations

Name of the building	Biomimicry inspiration	Application to the project	Positive environmental/ economic/ social attainment	Contribution to the sustainable parameters
Eiffel Tower	Thigh Bone	The flare on the outside mimics a femur bone.	Withstand thermal expansion	Material efficiency, functionality and aesthetics in design
Beijing national stadium	Bird's Nest	Contains ETFE panels that act as insulation by cramming tiny pieces of material inside the twigs.	Cost reduction, durable and recyclable materials	Energy efficiency, material efficiency, zero waste, cost-efficient technology
L'institute Du Monte Arabe	Iris of Eye	Cladded with a screen with an automated lens to control light.	Natural lighting and ventilation	Renewable energy usage, energy efficiency, passive design strategy
Sinosteel International Plaza	Beehive	The windows are made in five various hexagonal sizes and arranged in an energy-efficient way.	Energy efficiency achieved by 75%	Renewable energy usage, energy efficiency, passive design strategy
Rafflesia House	Rafflesia Flower	Concave and convex internal walls regulate the flow of air inside.	Utilised zero waste energy	Energy efficiency, zero waste, functionality and aesthetics in design

Name of the building	Biomimicry inspiration	Application to the project	Positive environmental/ economic/ social attainment	Contribution to the sustainable parameters
The Esplanade Theatre, Singapore	Durian Fruit	Use of geometric structure and shape, heat protection for spikes.	Lowered HVAC levels, Durian's form allows for optimum view of the bay	Energy efficiency, material efficiency, passive design strategy
Lily pad, Floating city	Lily pad	An idea for a floating city that is entirely self-sufficient and is meant to offer protection from potential climate change.	Able to process carbon dioxide in the atmosphere and absorb it	Renewable energy usage, energy efficiency, zero waste, passive design strategy
Shi Ling Bridge	Shell Lace Structure	Uses an optimized curvilinear geometry in conjuncture with corrugation to provide stiffness.	Formed an incredibly expressive, unique and economically intuitive bridge	Passive design strategy, functionality and aesthetics in design
Lotus Temple	Lotus Flower	Shapes were translated into formulae using thin concrete shells and used in engineering drawings and structural analysis.	Adequate light and ventilation, structurally efficient design	Material efficiency, passive design strategy, functionality and aesthetics in design
Sydney Opera House	Shell-like sails	Comprise three groups of interlocking vaulted 'Shells' that roof two main performance halls.	Temperature to be 22.5 degrees Celsius to ensure the instruments stay in tune	Energy efficiency, passive design strategy, functionality and aesthetics in design

Source: (Dash, 2018)

According to Table 3, different applications of biomimicry can be identified in the construction industry, which has contributed to the achievement of different sustainability parameters. It is rather clear that to address any construction-related challenge, biomimicry applications need to be comprehended and designed relevant to a specific context and then may be applied to other construction scenarios (Sá & Viana, 2023).

3.4 ENABLERS, BARRIERS AND STRATEGIES TO THE APPLICATION OF BIOMIMICRY CONCEPT

In comprehending the optimum application of the biomimicry concept in the construction industry, it is of utmost significance that the enablers, barriers and strategies are identified for the effective implementation of the concept. Accordingly, Table 4 summarises the enablers, barriers and strategies for the application of the biomimicry concept as identified by the previous studies.

Table 4: Enablers, barriers and strategies for the application of the biomimicry concept

Enablers	Barriers	Strategies
Using readily available materials	Shortage of biomimetic technology	Providing education and training
Incorporating diversity	Absence of biomimicry in the university curriculum	Increasing stakeholder awareness
Recycling all materials	Limited availability of biomimetic materials	Improving the availability of biomimetic technology
Using low-energy processes	Shortage of incentives for adopting biomimicry	Improving the availability of biomimetic materials
Fitting form to function	The absence of a database and information on biomimicry	Improved affordability of biomimetic materials
Building from the bottom-up concept	Absence of a well-defined biomimicry approach	Increasing client demand
Doing chemistry in water	Shortage of client demand	Providing economic incentives
Breaking down products into benign constituents	Risks associated with the implementation of biomimicry	Improving multi-disciplinary collaboration
Maintaining integrity through self-renewal	Time commitment	Improving government support and intervention

Enablers	Barriers	Strategies
Embodying resilience through decentralization	Shortage of real-life examples	Improving the availability of biomimetic framework/ measurement standard
Building selectively with a small subset of elements	Perceived high cost of adopting biomimicry	Providing biomimicry innovation and certification
Embodying resilience through redundancy	Absence of biomimicry training and education programme	Developing a policy monitoring system
Combining modular and nested components	Lack of awareness	Developing a legal and regulatory framework
Reshuffling information	Lack of governmental and regulatory support	Providing motivation and commitment (at individual and corporate levels)
Leveraging cyclic processes	Lack of professional knowledge in biomimicry	
Using multi-functional design	Absence of building codes and regulations	
	Shortage of biomimicry measurement framework	

Sources: (Ahamed et al., 2022; Varshabi et al., 2022; Jamei & Vrcelj, 2021; Oguntona & Aigbavboa, 2019a; Beermann & Austin, 2021; Zari & Hecht, 2020; Blanco et al., 2021; Oguntona & Aigbavboa, 2019b; Bumgardner & Nicholls, 2020; Austin et al., 2020; Soteriou et al., 2021)

As Table 4 suggests, there are various enablers, barriers and strategies for applying the biomimicry concept in the context of the construction industry. Accordingly, using readily available materials, incorporating diversity (e.g. in the biomimicry concept, benefits are obtained by bringing designers from diverse backgrounds and expertise for construction planning and designing) and recycling the materials will effectively enable the successful implementation of the biomimicry concept in the construction industry (Ahamed et al., 2022). Besides, combining modular and nested components, leveraging cyclic processes and using multi-functional designs will require complex technologies, yet they will stimulate the successful adoption of the biomimicry concept in the construction industry (Varshabi et al., 2022). At the same time, there are numerous technology-related barriers, including a shortage of biomimetic technology, the absence of databases and information on biomimicry and the absence of a well-defined biomimicry approach, which hinders the successful adaption of biomimicry applications in the construction industry (Blanco et al., 2021). Furthermore, regulatory barriers, including the absence of building codes and regulations and the shortage of biomimicry labelling/measurement framework, obstruct the effective implementation of biomimicry applications in the construction industry (Jamei & Vrcelj, 2021). In this regard, strategies such as developing a policy monitoring system, developing a legal and regulatory framework, and improving government support and intervention can be performed since it will positively impact overcoming the regulatory barriers for the implementation of the biomimicry concept in the construction industry (Oguntona & Aigbavboa, 2019a). Moreover, providing biomimicry education and training, increasing stakeholder awareness and improving multi-disciplinary collaboration will enhance the success rate of biomimicry adaption in the construction context, which will eventually increase the sustainability of the construction industry (Soteriou et al., 2021).

4. CONCEPTUAL FRAMEWORK

A conceptual framework detailing how to study the research problem can be created by evaluating the literature on the research area (Guo et al., 2020). Additionally, it describes the crucial considerations to make while conducting research in either a graphical or narrative manner, which may involve diagrams, flow charts, mind maps, and other visual aids (Ahmadi et al., 2020). Accordingly, Figure 2 illustrates the conceptual framework for assessing the applicability of biomimicry applications to improve the sustainability of the construction industry.

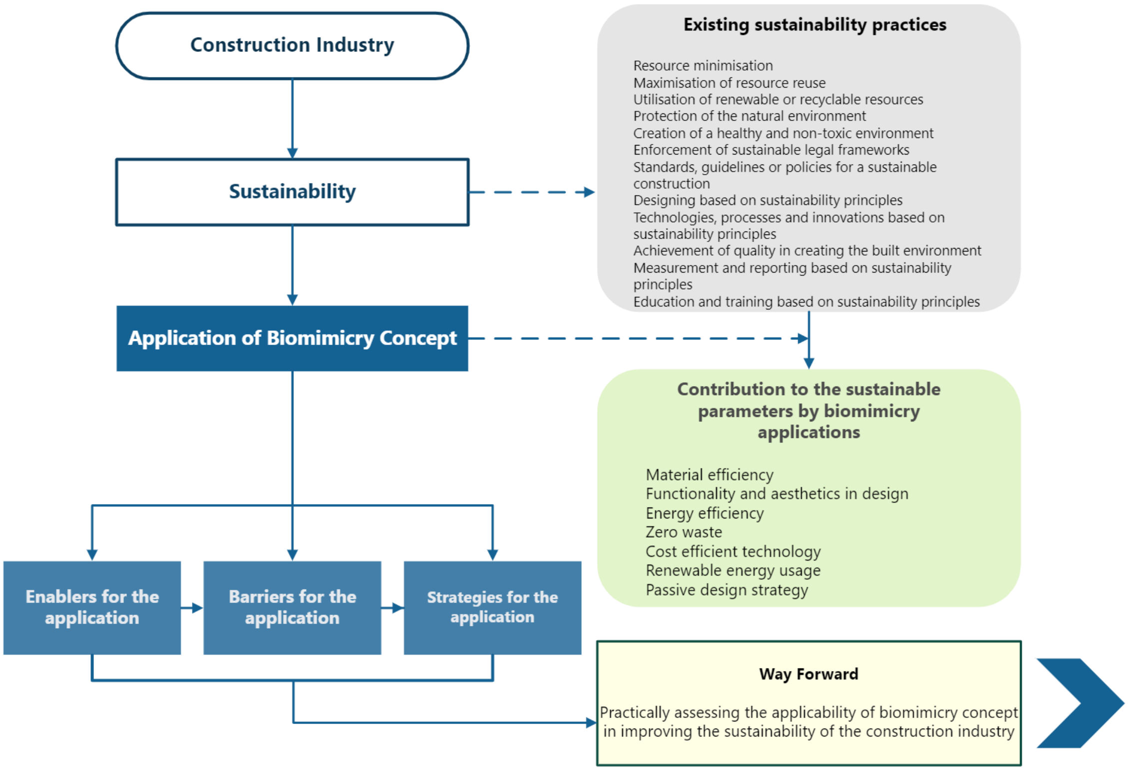


Figure 2: Conceptual framework for assessing the applicability of biomimicry applications to improve the sustainability of the construction industry

The comprehensive path to fill the research gap with the findings of the collected literature is demonstrated in Figure 2. Accordingly, the existing sustainable practices in the construction industry can be improved by biomimicry applications since they help to achieve sustainable parameters such as material efficiency, energy efficiency and cost-efficient technologies. For instance, biomimicry inspirations such as thigh bone and lotus flower will improve the material efficiency which will eventually increase the effectiveness of sustainability practices such as resource minimisation and sustainable designing (Dash, 2018). However, barriers such as limited availability of biomimetic materials, risks associated with the implementation of biomimicry and lack of awareness hinder the successful adoption of biomimicry applications, which can be overcome by strategic implementations, such as improving the affordability of biomimetic materials, providing economic incentives and increasing stakeholder awareness (Austin et al., 2020; Oguntona & Aigbavboa, 2019b; Varshabi et al., 2022). On this note, it is important for future researchers to comprehend the enablers, barriers, and strategies for biomimicry applications practically to address the research gap in employing biomimicry applications to improve the sustainability of the construction industry.

5. CONCLUSIONS AND RECOMMENDATIONS

With the excessive ecological damage caused by the construction industry, sustainability practices are considered as the key explanation to secure the environment. Nonetheless, this study reveals the need to increase the effectiveness of the existing sustainability practices, and novel concepts such as biomimicry applications can be implemented in the construction industry to increase the sustainability of projects. Accordingly, this study finds that the two approaches of the biomimicry concept, i.e., (i) the top-down approach, and (ii) bottom-up approach, have the potential to integrate the insights from nature into construction processes and eventually contribute to sustainability parameters such as energy efficiency, material efficiency and cost-efficient technology. Additionally, this study reveals that there are numerous enablers, barriers, and strategies for the implementation of biomimicry applications in the construction context, which need further exploration to successfully adapt the concept within the construction industry.

Accordingly, this study serves the theory by bringing the gap in using biomimicry applications to increase the effectiveness of sustainability practices in the construction industry. Practically, this study serves by providing insights to industry practitioners on utilising biomimicry applications for their construction projects. It is highly recommended that industry practitioners adhere to novel concepts such as biomimicry inspirations since it has a positive impact environmentally, socially and economically. While biomimicry applications offer effective solutions to certain challenges, they cannot address issues related to government support and economic barriers. Therefore, further research is needed to find appropriate solutions for these issues. Furthermore, future studies are directed at practically assessing the applicability of biomimicry applications in improving the sustainability of the construction industry. Moreover, it is highly recommended to conduct further studies on the enablers, barriers and strategies in detail for the application of the biomimicry concept in the construction industry since it is of utmost significance to ensure the conservation of the ecosphere with the progressive development of a sustainable built environment.

6. REFERENCES

Abedanzadeh, S., Nourisefat, M., & Moosavi-Movahedi, Z. (2021). Bioinspiration and biomimicry in lifestyle. In *Rationality and scientific lifestyle for health*, (pp. 93–104). Springer. https://doi.org/10.1007/978-3-030-74326-0_2

Adekunye, O. J., & Oke, A. E. (2023). Applicable areas of biomimicry principles for sustainable construction in Nigeria. *Construction Innovation*. *23*(4), 713-732. https://doi.org/10.1108/CI-12-2021-0232

Ahamed, M. K., Wang, H., & Hazell, P. J. (2022). From biology to biomimicry: Using nature to build better structures–a review. *Construction and Building Materials*, *320*, 126195. https://doi.org/10.1016/j.conbuildmat.2021.126195

Ahiabu, M. K., Emuze, F. A., & Das, D. K. (2022). A review of sustainable construction practices in Ghana. In *Climate emergency–managing, building, and delivering the sustainable development goals*, (pp. 93–104). Springer. https://doi.org/10.1007/978-3-030-79450-7_9

Ahmadi, M., Sharifi, A., Dorosti, S., Ghoushchi, S. J., & Ghanbari, N. (2020). Investigation of effective climatology parameters on COVID-19 outbreak in Iran. *Science of the Total Environment*, *729*, 138705. https://doi.org/10.1016/j.scitotenv.2020.138705

Al-Otaibi, A., Bowan, P., Daiem, M., Said, N., Ebohon, J., Alabdullatief, A., . . . Watts, G. (2022). Identifying the barriers to sustainable management of construction and demolition waste in developed and developing countries. *Sustainability, 14*(13), 7532. https://doi.org/10.3390/su14137532

Alanbari, D. H. A., Alkindi, A. P. D. S. K., & Al_Ahbabi, S. H. (2022). Biomimicry design spiral: Nature as a model. *Journal of Algebraic Statistics*, *13*(2), 2335–2345. https://www.publishoa.com/index.php/journal/article/view/428

Amer, N. (2019). Biomimetic approach in architectural education: Case study of 'biomimicry in architecture' course. *Ain Shams Engineering Journal*, *10*(3), 499–506. https://doi.org/10.1016/J.ASEJ.2018.11.005

Anwar, R., Rusman, M. S., & Kamaruzaman, M. F. (2018). The potential of biomimicry as an influence for local-inspired product design. In R. Anwar, M. Mohamood, D. Md-Zain, M. Abd-Aziz, O. Hassan, & S. Abidin (Eds.), *Proceedings of the art and design international conference (AnDIC 2016), Singapore,* (pp. 479–486). Springer. https://doi.org/10.1007/978-981-13-0487-3_53

Aramesh, M., & Shabani, B. (2020). On the integration of phase change materials with evacuated tube solar thermal collectors. *Renewable and Sustainable Energy Reviews*, *132*, 110135. https://doi.org/10.1016/j.rser.2020.110135

Athapaththu, K. I., & Karunasena, G. (2018). Framework for sustainable construction practices in Sri Lanka. *Built Environment Project and Asset Management*, *8*(1), 51–63. https://doi.org/10.1108/BEPAM-11-2016-0060

Austin, M. C., Garzola, D., Delgado, N., Jiménez, J. U., & Mora, D. (2020). Inspection of biomimicry approaches as an alternative to address climate-related energy building challenges: A framework for application in Panama. *Biomimetics*, *5*(3), 40. https://doi.org/10.3390/biomimetics5030040

Beermann, K., & Austin, C.M. (2021). An inspection of the life cycle of sustainable construction projects: Towards a biomimicry-based road map integrating circular economy. *Biomimetics*, *6*(4), 67. https://doi.org/10.3390/biomimetics6040067

Beith, D. (2021). From Biomimicry to biosophia: Ecologies of technology in benyus, oxman, fisch, and merleau-ponty. *Environmental Philosophy*, *18*(2), 259–278. doi: 10.5840/envirophil2021930112

Blanco, E., Cruz, E., Lequette, C., Raskin, K., & Clergeau, P. (2021). Biomimicry in French urban projects: Trends and perspectives from the practice. *Biomimetics*, *6*(2), 27. https://doi.org/10.3390/biomimetics6020027

Bumgardner, M. S., & Nicholls, D. L. (2020). Sustainable practices in furniture design: A literature study on customization, biomimicry, competitiveness, and product communication. *Forests*, *11*(12), 1277. https://doi.org/10.3390/f11121277

Cedeño, J. G., Williams, A., MacNaughton, P., Cao, X., Eitland, E., Spengler, J., & Allen, J. (2018). Building evidence for health: Green buildings, current science, and future challenges. *Annual Review of Public Health*, *39*(1), 291–308. https://doi.org/10.1146/annurev-publhealth-031816-044420

Chairiyah, R. (2021). CH2 inspired for air conditioning system of inpatient hospital with biomimicry approach. *Proceedings of International on Healthcare Facilities, 1(*1), 146-156. https://thejournalish.com/ojs/index.php/ichf/article/view/123

Chua, B., Yin, L., Laing, R., Leon, M., & Mabon, L. (2018). An evaluation of sustainable construction perceptions and practices in Singapore. *Sustainable cities and society, 39,* 613-620. https://doi.org/10.1016/j.scs.2018.03.024

Darko, A., Chan, A. P. C., Huo, X., & Owusu-Manu, D.-G. (2019). A scientometric analysis and visualization of global green building research. *Building and Environment*, *149,* 501–511. https://doi.org/10.1016/j.buildenv.2018.12.059

Dash, S. P. (2018). Application of biomimicry in building design. *International Journal of Civil Engineering and Technology*, *9*(2), 644–660. http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=9&IType=2?

Edwards, R., & Brannelly, T. (2017). Approaches to democratising qualitative research methods. *Qualitative Research*, 17(3), 271–277. https://doi.org/10.1177/1468794117706869

Fianko, S. K., Amoah, N., Jnr, S. A., & Dzogbewu, T. C. (2021). Green supply chain management and environmental performance: The moderating role of firm size. *International Journal of Industrial Engineering and Management*, *12*(3), 163-173. https://doi.org/10.24867/IJIEM-2021-3-285

Ghisellini, P., Ji, X., Liu, G., & Ulgiati, S. (2018). Evaluating the transition towards cleaner production in the construction and demolition sector of China: A review. *Journal of Cleaner Production*, *195,* 418–434. https://doi.org/10.1016/j.jclepro.2018.05.084

Guo, D., McTigue, E. M., Matthews, S. D., & Zimmer, W. (2020). The impact of visual displays on learning across the disciplines: A systematic review. *Educational Psychology Review*, *32*(3), 627–656.

He, B.J., Zhao, D.-X., Zhu, J., Darko, A., & Gou, Z.-H. (2018). Promoting and implementing urban sustainability in China: An integration of sustainable initiatives at different urban scales. *Habitat International*, *82*, 83–93. https://doi.org/10.1016/j.habitatint.2018.10.001

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews*, *130*, 109948. https://doi.org/10.1016/J.RSER.2020.109948

Hosseini, S. M., Mohammadi, M., Rosemann, A., Schröder, T., & Lichtenberg, J. (2019). A morphological approach for kinetic façade design process to improve visual and thermal comfort. *Building and Environment*, *153*, 186–204. https://doi.org/10.1016/j.buildenv.2019.02.040

Huo, T., Ren, H., Zhang, X., Cai, W., Feng, W., Zhou, N., & Wang, X. (2018). China's energy consumption in the building sector: A statistical yearbook-energy balance sheet based splitting method. *Journal of Cleaner Production*, *185*, 665–679. https://doi.org/10.1016/J.JCLEPRO.2018.02.283

Jalil, W. D. A., & Kahachi, H. A. H. (2019). The implementation of nano-biomimicry for sustainability in architecture. *Journal of Engineering and Sustainable Development*, *23*(3), 25-41. https://doi.org/10.31272/jeasd.23.3.3

Jamei, E., & Vrcelj, Z. (2021). Biomimicry and the built environment, learning from nature's solutions. *Applied Sciences (Switzerland)*, 11(16), 7514. https://doi.org/10.3390/app11167514

Katiyar, N. K., Goel, G., Hawi, S., & Goel, S. (2021). Nature-inspired materials: Emerging trends and prospects. *NPG Asia Materials*, *13*(56), 1–16. https://doi.org/10.1038/s41427-021-00322-y

Kazasidis, M., Pantelis, D., Caballero, F. G., Capdevila, C., Cassidy, J., Bilalis, E., & Lupoi, R. (2021). Dissimilar welding between conventional and high strength low alloy naval steels with the use of robotic metal cored arc welding. *The International Journal of Advanced Manufacturing Technology, 113,* 2895-2907. https://doi.org/10.1007/s00170-021-06819-8

Khoja, A., & Waheeb, S. (2020). Vernomimicry: Bridging the gap between nature and sustainable architecture. *Journal of Sustainable Development*, *13*(1), 33. https://doi.org/10.5539/jsd.v13n1p33

Kim, K., ElTarabishy, A., & Bae, Z. (2018). Humane entrepreneurship: How focusing on people can drive a new era of wealth and quality job creation in a sustainable world. *Journal of Small Business Management*, *56*, 10–29. https://doi.org/10.1111/jsbm.12431

Kong, L., Mayorga-Martinez, C. C., Guan, J., & Pumera, M. (2020). Photocatalytic micromotors activated by UV to visible light for environmental remediation, micropumps, reversible assembly, transportation, and biomimicry. *Small*, *16*(27), 1903179. https://doi.org/10.1002/smll.201903179

Kyngäs, H. (2020). Inductive content analysis. In H. Kyngas, K. Mikkonen, & M. Kaariainen (Eds.), *The application of content analysis in nursing science research* (pp. 13–21). Springer. http://dx.doi.org/10.1007/978-3-030-30199-6

Lin, B., & Zhu, J. (2019). Determinants of renewable energy technological innovation in China under CO2 emissions constraint. *Journal of Environmental Management*, *247*, 662–671. https://doi.org/10.1016/j.jenvman.2019.06.121

Martín, P. T., Aguilera, D., Perales-Palacios, F. J., & Vílchez-González, J. M. (2019). What are we talking about when we talk about STEM education? A review of literature. *Science Education*, *103*(4), 799–822. https://doi.org/10.1002/sce.21522

Mensah, J. (2019). Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. *Cogent Social Sciences*, *5*(1), 1653531. https://doi.org/10.1080/23311886.2019.1653531

Mikhno, I., Koval, V., Shvets, G., Garmatiuk, O., & Tamošiūnienė, R. (2021). Green economy in sustainable development and improvement of resource efficiency. *Central European Business Review (CEBR)*, *10*(1), 99–113. https://www.ceeol.com/search/article-detail?id=941002

Moshood, T. D., Nawanir, G., & Mahmud, F. (2022). Sustainability of biodegradable plastics: a review on social, economic, and environmental factors. *Critical Reviews in Biotechnology*, *42*(6), 892–912. https://doi.org/10.1080/07388551.2021.1973954

Ogunsanya, O.A., Aigbavboa, C.O., Thwala, D.W., and Edwards, D.J. (2022). "Barriers to sustainable procurement in the Nigerian construction industry: an exploratory factor analysis". *International Journal of Construction Management,* 22(5), 861-872. https://doi.org/10.1080/15623599.2019.1658697

Oguntona, O. A., & Aigbavboa, C. O. (2019a). Barriers militating against the adoption of biomimicry as a sustainable construction practice. *MATEC Web of Conferences*, *266*, 03010. https://doi.org/10.1051/matecconf/201926603010

Oguntona, O. A., & Aigbavboa, C. O. (2019b). Barriers hindering biomimicry adoption and application in the construction industry. *African Journal of Science, Technology, Innovation and Development*, *11*(3), 289–297. https://doi.org/10.1080/20421338.2018.1527968

Oguntona, O. A., & Aigbavboa, C. O. (2020). TALK capability of biomimicry for disruptive and sustainable output in the construction industry. *MATEC Web of Conferences*, *312*, 02016. https://doi.org/10.1051/matecconf/202031202016

Opoku, D. G. J., Ayarkwa, J., & Agyekum, K. (2019). Barriers to environmental sustainability of construction projects. *Smart and Sustainable Built Environment*, *8*(4), 292–306. https://doi.org/10.1108/SASBE-08-2018-0040

Othmani, N.I, Yunos, M.Y.M., Ismail, N.A., & Rahman, K.A.A.A. (2018). Review on biomimicry levels. *American Journal of Humanities and Social Sciences Research (AJHSSR)*, *2*(9), 55-58. https://www.ajhssr.com/wp-content/uploads/2018/08/H18285558.pdf

Oyebode, O. J. (2018). Green building: Imperative panacea for environmental sustainability and life cycle construction in Nigeria. *World Journal of Research and Review*, *7*(3), 15-29. https://www.wjrr.org/download_data/WJRR0703011.pdf

Pandey, P., & Pandey, M. M. (2015). *Research methodology: Tools and techniques*. Bridge Center. http://dspace.vnbrims.org:13000/jspui/bitstream/123456789/4666/1/RESEARCH%20METHODOLOGY%20TOOLS%20AND%20TECHNIQUES.pdf

Parn, E. A., & Edwards, D. (2019). Cyber threats confronting the digital built environment: Common data environment vulnerabilities and block chain deterrence. *Engineering, Construction and Architectural Management, 26*(2), 245-266. https://doi.org/10.1108/ECAM-03-2018-0101

Pathak, S. (2019). Biomimicry: Innovation inspired by nature. *International Journal of New Technology and Research*, *5*(6), 34-38. https://www.academia.edu/download/91951851/IJNTR05060017.pdf

Pautasso, M. (2019). The structure and conduct of a narrative literature review. In M. Shoja, A. Arynchyna, M. Loukas, A. Antoni, S. Buerger, M. Karl, & R. Tubbs (Eds.), *A guide to the scientific career: virtues, communication, research, and academic writing* (pp. 299-310). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118907283.ch31

Pham, H., Kim, S., & Luu, T. (2020). Managerial perceptions on barriers to sustainable construction in developing countries: Vietnam case. *Environment, Development and Sustainability*, *22*, 2979-3003. https://doi.org/10.1007/s10668-019-00331-6

Prianka, T. R., Subhan, N., Reza, H. M., Hosain, M. K., Rahman, M. A., Lee, H., & Sharker, S. M. (2018). Recent exploration of bio-mimetic nanomaterial for potential biomedical applications. *Materials Science and Engineering: C*, *93*, 1104–1115. https://doi.org/10.1016/j.msec.2018.09.012

Rai, P., Mehrotra, S., Priya, S., Gnansounou, E., & Sharma, S. K. (2021). Recent advances in the sustainable design and applications of biodegradable polymers. *Bioresource Technology*, *325*, 124739. https://doi.org/10.1016/j.biortech.2021.124739

Rajamanickam, T., Waidyasekara, K., & Pandithawatta, T. (2019). *Conceptual framework for green supply chain practices in construction industry*. University of Moratuwa. http://dl.lib.mrt.ac.lk/bitstream/handle/123/15260/WCS2019_20.pdf?sequence=1

Sá, A. A. M. de, & Viana, D. M. (2023). Design and biomimicry: A review of interconnections and creative potentials. *Biomimetics*, *8*(1), 61. https://doi.org/10.3390/biomimetics8010061

Sadegh, S. O., Haile, S. G., & Jamshidzehi, Z. (2022). Development of two-step biomimetic design and evaluation framework for performance-oriented design of multi-functional adaptable building envelopes. *Journal of Daylighting*, *9*(1), 13–27. https://dx.doi.org/10.15627/jd.2022.2

Sai, H. M., & Lakshmi, V. (2020). An analytical approach to sustainable building adaption using biomimicry. *Materials Today: Proceedings*, *33*, 514–518. https://doi.org/10.1016/j.matpr.2020.05.207

Sanchez, B., Rausch, C., Haas, C., & Saari, R. (2020). A selective disassembly multi-objective optimization approach for adaptive reuse of building components. *Resources, Conservation and Recycling*, *154*, 104605. https://doi.org/10.1016/j.resconrec.2019.104605

Seferlis, P., Varbanov, P. S., Papadopoulos, A. I., Chin, H. H., & Klemeš, J. J. (2021). Sustainable design, integration, and operation for energy high-performance process systems. *Energy*, *224*, 120158. https://doi.org/10.1016/j.energy.2021.120158

Silvestre, B. S., & Ţîrcă, D. M. (2019). Innovations for sustainable development: Moving toward a sustainable future. *Journal of Cleaner Production*, *208*, 325–332. https://doi.org/10.1016/j.jclepro.2018.09.244

Singh, C. S. (2018). Green construction: analysis on green and sustainable building techniques. *Civil Engineering Research Journal*, *4*(3), 555638. http://dx.doi.org/10.19080/CERJ.2018.04.555638

Soteriou, C., Kalli, A. C., Connell, S. D., Tyler, A. I. I., & Thorne, J. L. (2021). Advances in understanding and in multi-disciplinary methodology used to assess lipid regulation of signalling cascades from the cancer cell plasma membrane. *Progress in Lipid Research*, *81*, 101080. https://doi.org/10.1016/j.plipres.2020.101080

Stojanovic, M. (2019). Biomimicry in agriculture: Is the ecological system-design model the future agricultural paradigm?. *Journal of Agricultural and Environmental Ethics*, *32*, 789–804. https://doi.org/10.1007/s10806-017-9702-7

Syed, Y. (2021). *Biomimicry as a Strategy to Enhance Ecologically Regenerative Design*. Auckland University of Technology. https://openrepository.aut.ac.nz/handle/10292/14301

Tanwar, S., Popat, A., Bhattacharya, P., Gupta, R., & Kumar, N. (2022). A taxonomy of energy optimization techniques for smart cities: Architecture and future directions. *Expert Systems*, *39*(5), e12703. https://doi.org/10.1111/exsy.12703

van Stijn, A., & Gruis, V. (2020). Towards a circular built environment: An integral design tool for circular building components. *Smart and Sustainable Built Environment, 9*(4), 635-653. https://doi.org/10.1108/SASBE-05-2019-0063

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

Wan, O.W. N. F., & Subri, S. (2021). *Biomimicry: A Journey of "Impression de Chaos."*. Universiti Teknologi MARA (UiTM) Kedah Branch. https://ir.uitm.edu.my/id/eprint/58866/1/58866.pdf

Williams, T. S. (2022). Advancing research efforts in biomimicry to develop nature-inspired materials, processes for space exploration and more efficient aircraft. *Biomimicry for Aerospace*, 385–421. https://doi.org/10.1016/B978-0-12-821074-1.00014-1

Wuni, I. Y., Shen, G. Q. P., & Osei-Kyei, R. (2019). Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018. *Energy and Buildings*, *190*, 69–85. https://doi.org/10.1016/j.enbuild.2019.02.010

Xia, B., Olanipekun, A., Chen, Q., Xie, L., & Liu, Y. (2018). Conceptualising the state of the art of corporate social responsibility (CSR) in the construction industry and its nexus to sustainable development. *Journal of Cleaner Production*, *195*, 340–353. https://doi.org/10.1016/j.jclepro.2018.05.157

Yacubov, M., & Smith, D. (2020). *Nature does it better: Biomimicry in structural and architectural design*. Syracuse University. https://files.emailmeform.com/742180/q5kb0xUm/Thesis%20Paper%20%282%29.pdf

Yu, A. T. W., Yevu, S. K., & Nani, G. (2020). Towards an integration framework for promoting electronic procurement and sustainable procurement in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *250*, 119493.

Zari, M., & Hecht, K. (2020). Biomimicry for regenerative built environments: Mapping design strategies for producing ecosystem services. *Biomimetics*, *5*(2), 18. https://doi.org/10.3390/biomimetics5020018

Zhang, J., Huang, Y., Wang, Y., Xu, J., Huang, T., & Luo, X. (2023). Construction of biomimetic cell-sheet-engineered periosteum with a double cell sheet to repair calvarial defects of rats. *Journal of Orthopaedic Translation*, *38*, 1–11. https://doi.org/10.1016/j.jot.2022.09.005

Arachchi, K.A.C.S.K., Perera, B.A.K.S., Piyumra, R.A.D. and Jayasuriya, S., 2024. Application of circular economy principles into tropical building designs: A literature review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 200-214. DOI: https://doi.org/10.31705/WCS.2024.16. Available from: https://ciobwcs.com/papers/

APPLICATION OF CIRCULAR ECONOMY PRINCIPLES INTO TROPICAL BUILDING DESIGNS: A LITERATURE REVIEW

K.A.C.S. Kalu Arachchi[1], B.A.K.S. Perera[2], R.A. Dinithi Piyumra[3] and Sajani Jayasuriya[4]

ABSTRACT

The increasing intensity of global population growth has heightened the demand for buildings in tropical zones. Consequently, meeting this burgeoning demand poses a significant challenge to the construction sector, compounded by resource scarcity. As a result, there is mounting pressure on construction building designs to transition towards more sustainable practices. In response, Circular Economy (CE) principles are being considered for incorporation into tropical building designs to enhance sustainability. Thus, this research endeavours to assess the feasibility of integrating CE principles into building designs as a means of advancing sustainability. Adopting content analysis collected data were analysed. The study revealed that tropical building designs offer a sustainable method well-suited to address the growing demand for buildings. Furthermore, it was identified ten enabling factors, thirty-five barriers, and twenty-four strategies in relation to the application of CE principles to building designs. It was revealed that the findings of the study will drive the convergence of CE principles with tropical building designs. Consequently, this research contributes to the theory by bridging the gap in utilising CE principles within building designs to enhance sustainability in the construction industry.

Keywords: *Barriers; Circular Economy; Enablers; Strategies; Tropical Building Design.*

1. INTRODUCTION

As a cornerstone of modern development (Ferdous et al., 2019), the construction industry is attributed between 35% to 40% of global energy consumption and energy-related carbon emissions (Chen et al., 2023). Further, the authors highlighted that the production of building materials and products alone accounts for 10% of energy-related carbon emissions which are reflecting the industry's reliance on resource-intensive processes. These figures underscore the urgent need for transformative solutions to lessen the

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, kaluarachchikcs.19@uom.lk
[2] Professor in Quantity Surveying, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk
[3] Graduate in Quantity Surveying, Department of Building Economics, University of Moratuwa, Sri Lanka, 182688e@uom.lk
[4] Lecturer, School of Property, Construction and Project Management, RMIT University, Australia, sajani.jayasuriya@rmit.edu.au

negative environmental impact of construction activities (Vita et al., 2019). Moreover, the rapid growth of the world population has brought the construction sector to a more difficult phase (Avtar et al., 2019). With an estimated 8.0 billion people in 2022 and projected long-range will lie between 9.4 to 10.0 billion people by 2050, the demand for construction is set to intensify (Gu et al., 2021). The aforementioned surge will undoubtedly amplify carbon emissions and strain natural resources (Shang et al., 2022). Further, Eberhardt et al. (2020) predicted that buildings will become major temporary material stock because of the greater amount of inefficient material usage in the building sector.

According to Verma et al. (2023), there are currently 3.3 billion people living in tropical zones, and by 2050, it is predicted that this number will rise to 6.3 billion. The climate in tropical regions is hot and muggy (Al-Obaidi et al., 2014). The unique climatic context of tropical regions demands specialised design strategies that take high temperatures, humidity, and extreme weather patterns into account (Emmanuel, 2012). Hence, along with population growth, urbanisation, and material depletion, Iyer-Raniga (2019) emphasised that buildings in tropical zones need to consider regenerating energy where possible and it may include the use of energy-efficient designs.

Over the past decade, the concept of Circular Economy (CE) has gained attention due to growing environmental concerns and risks associated with resource shortages (Guerra & Leite, 2021). CE is a regenerative system that minimises resource intake and waste, emissions, and energy leaks by slowing down, closing, and tightening the cycles of materials and energy (Geissdoerfer et al., 2017). Accordingly, CE principles offer a roadmap for resource optimisation, waste reduction, and environmentally responsible construction methods, aligning with the industry's need for innovative and sustainable solutions (Guerra & Leite, 2021). Kara et al. (2022) declared that by embracing circularity, the construction field can transition towards closed-loop systems, minimising waste and promoting a more sustainable life cycle for buildings.

In the built environment, implementation of CE can mainly deal with building design and adopting CE principles in building designs can minimise resource consumption and waste production, prolong the useful life of resources to a great extent, and bring resources back into use (Rahla et al., 2021). Akhimien et al. (2021) declared that integrating CE principles into building designs in tropical regions can address these challenges by promoting sustainable material choices, energy-efficient building techniques, and adaptive strategies. In addition, the authors highlighted that the construction industry can navigate the complexities of tropical climates while contributing to more sustainable and resilient built environments by synergising circular practices with building designs.

However, the CE is relatively new for architecture, engineering, and construction (Charef et al., 2021). Although CE building design and construction strategies are increasingly being developed and implemented, the process has not yet reached a consensus or defined direction in the building sector (Eberhardt et al., 2020). Ghufran et al. (2022) have proposed a paradigm shift towards CE-based sustainability. Accordingly, Ababio and Lu (2022), Guerra and Leite (2021), Oluleye et al. (2023), have extensively discussed and studied on enablers and barriers of applying CE in the construction industry to enhance the sustainability of the buildings. On the other hand, Bulbaai and Halman (2021), Kerdan (2016), and Xianlin (2018) have primarily investigated on energy-efficient building design strategies and approaches in tropical regions to meet sustainability. Eberhardt et al., (2020) assessed which construction and design approaches are connected to the notion of CE for new buildings. Accordingly, numerous previous research focused on application of CE principles into general building designs. Nevertheless, there is a dearth of literature on application of CE principles into building designs in the tropical region to ameliorate sustainability through addressing the challenges of global population growth, material depletion and environmental impact. Hence, this research attempted to develop a conceptual framework to explore the adaptability of CE principles into building designs in tropical regions to improve sustainability through literature review. The following objectives were achieved:

1. to investigate the enablers of implementing CE principles into building designs,
2. to identify the barriers of implementing CE principles into building designs,
3. to propose suitable strategies to integrate CE principles with building designs.

Therefore, this study was undertaken to explore the potential for further study on the adaptability of CE principles into topical building designs to improve sustainability .

2. RESEARCH METHODOLOGY

Research methodology is a systematic way to solve a problem (Tan, 2022). An orderly, clear, and repeatable research process for the examination of the body of existing literature is called a literature review (Mio et al., 2020). A literature serves as the foundation for developing new conceptual frameworks or theories (Snyder, 2019). Journal articles, books, and conference proceedings with properly cited references are regarded as high-quality sources, therefore the identified literature must be of a high calibre and reliable (Xiao & Watson, 2019). Accordingly, for this study, journal papers, conference proceedings and books were referred to ensure the quality and reliability of the findings.

This study was conducted by reviewing the existing literature focusing on the integration of the concepts of Circular Economy (CE), building design, and sustainability in order to pave the road map for applying CE principles to tropical building designs. Figure 1 delineates the process adopted in conducting the literature review.

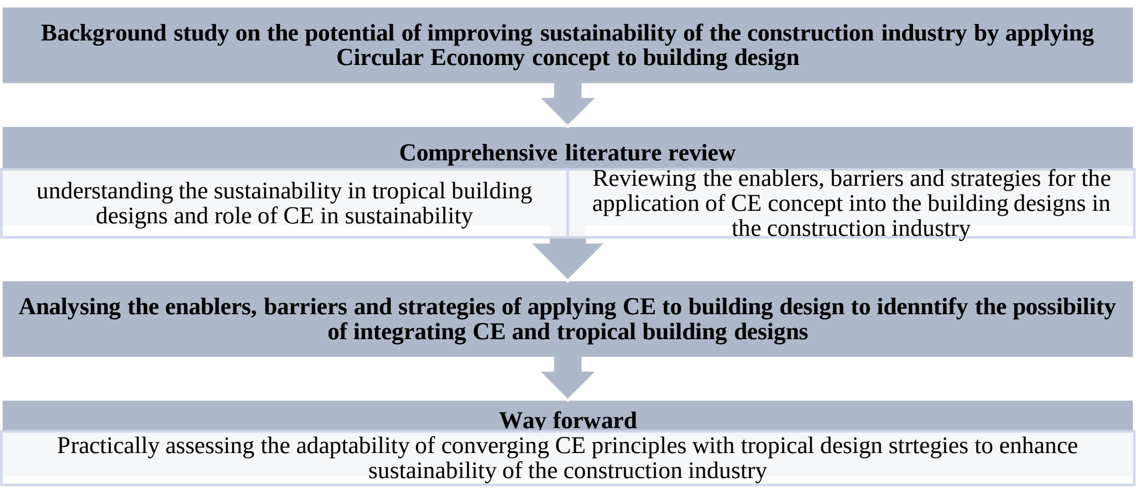


Figure 1: Research process

As shown in Figure 1, a background study was conducted followed by a literature study to understand the necessity of applying CE principles to tropical building designs to ameliorate the sustainability in the built environment. Subsequently, a comprehensive literature review was conducted on the research area by analysing and synthesising a group of related literature in developing new theories (Xiao & Watson, 2019). Content analysis is a flexible method to analyse text data (Hsieh & Shannon, 2005). Hence, adopting content analysis, gathered data through literature study was analysed. Subsequently, a conceptual framework was developed using the literature findings, as this framework will provide direction for further research on the investigated topic (Martín et al., 2019). Moreover, the aforementioned framework will guide researchers in investigating the adaptability of CE principles to tropical building designs, going beyond general building designs.

3. RESEARCH FINDINGS

3.1 SUSTAINABILITY IN DESIGN

The building industry notably impacts energy consumption and the environment through resource use and waste generation (Eberhardt et al., 2019). In order to address these obstacles, the building sector is prioritising sustainable designs, which aim to mitigate environmental impacts, promote economic viability and prioritise occupant well-being (Mirabella et al., 2018). Sustainable designs incorporate principles such as optimising insulation, using high-performance windows, and incorporating renewable energy sources like solar panels to minimise energy consumption and carbon footprint (Eberhardt et al., 2019). Eco-friendly materials that are durable and responsibly sourced reduce waste and resource depletion. Additionally, sustainable buildings enhance occupant well-being by maximising natural light, providing adequate ventilation, and using non-toxic materials (Negi, 2021). This holistic approach considers the entire lifecycle of a building, from design and construction to operation and demolition, contributing to the resilience and sustainability of communities (Fithian et al., 2017).

3.1.1 Tropical Building Design as a Sustainable Building Design Approach

Tropical design is defined as a sustainable building design approach which embraces the unique climatic and environmental conditions of tropical regions to create buildings that are not only harmonious with their surroundings but also environmentally responsible (Agbete & Frank, 2020). The key to tropical design's sustainability lies in its ability to naturally regulate temperature and minimise energy consumption. Thus, tropical design as a sustainable approach takes full advantage of the tropical climate and the available resources to create eco-friendly, energy-efficient, and culturally sensitive architectural solutions (Yusuf, 2021). By harmonising with the environment, utilising natural ventilation, and incorporating indigenous materials, tropical design offers a compelling model for sustainable architecture that not only respects the local ecosystem but also responds to the challenges of climate change and resource conservation (Seddon et al., 2021). Despite growing pressure to shift towards more sustainable practices, the building construction sector in developing countries continues to rely on a non-sustainable, linear economic model (Castell-Rüdenhausen et al., 2021). The linear approach fails to facilitate material reuse and results in obsolete buildings at the end of their lifespan (Ghufran et al., 2022). Therefore, CE building designs have been increasingly developed and implemented (Eberhardt et al., 2020).

3.2 CIRCULAR ECONOMY AND BUILDING DESIGNS

Currently, building designs have extensively made negative impacts on the environment through immense resource consumption and greater waste generation (Utrilla et al., 2018). Furthermore, CE techniques are anticipated to yield economic benefits by raising net material savings, preventing pollution and safeguarding the environment. R imperatives of CE are used to explain the strategies of the CE concept, where 9R principles are the widely used R imperatives within the construction sector (Stoiljković et al., 2023). The "9Rs" principles consist of Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover construction waste, resources and products (Ruiz et al., 2020). In order to minimise the aforementioned unresolved issues in building designs, Suárez-Eiroa et al. (2019) emphasised the necessity of applying CE principles to building designs. Nevertheless, implementing CE strategies in building design is hindered by the ambiguity surrounding the concept (Rahla et al., 2021). Hence, it is crucial to assess the enablers of implementing CE into building designs and the strategies to overcome its obstacles and improve the enablers as well (Guerra & Leite, 2021).

3.2.1 Enablers of Implementing Circular Economy Principles into Building Designs

Despite the Circular Economy's apparent simplicity, applying circular thinking to buildings may prove challenging (Rahla et al., 2021). Then, it is possible to identify the CE enablers as the drivers propelling this shift in the direction of more sustainable development (Santolin et al., 2023). Table 1 summarises enablers of implementing CE principles into building designs.

Table 1: Enablers of implementing CE principles into building designs

Enablers	Authors										
	A	B	C	D	E	F	G	H	I	J	K
Green building design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Advanced design software	✓					✓		✓	✓		
Renewable construction material	✓	✓		✓		✓		✓	✓	✓	✓
Recycled construction material	✓	✓		✓		✓	✓	✓	✓		✓
Resource efficient construction	✓	✓		✓		✓	✓			✓	
Excess material recycling (Designing out waste)	✓	✓	✓	✓				✓			✓
Energy efficient services	✓					✓	✓	✓		✓	✓
Building life extension	✓					✓	✓	✓	✓		
EOL material upcycling	✓	✓							✓	✓	✓
Foment greater maturity in quality	✓				✓		✓		✓		✓

[A] Barros et al. (2021); [B] Çetin et al. (2021); [C] Guerra & Leite (2021); [D] Antwi-Afari et al. (2022); [E] Anastasiades et al. (2021); [F] Rios et al. (2021); [G] AlJaber et al. (2023); [H] Hart et al. (2019); [I] Ababio & Lu (2022); [J] Zaman et al. (2023); [K] Oluleye et al. (2023)

As presented in Table 1, it was apparent that green building design, recycled construction materials and renewable construction materials are the most proposed enablers to encourage building designers to apply CE principles. CE is a cutting-edge approach that encourages green building design ideas within the construction sector (Rahla et al., 2021).

Moreover, applying CE principles to building design has the potential to mitigate adverse environmental effects and resource depletion by ensuring that materials are reused once the building reaches its end-of-life and by keeping resources in use (Rahla et al., 2021). On the other hand, for EOL material upcycling, there was limited literature as an enabler.

3.2.2 Barriers of Implementing Circular Economy Principles into Building Designs

Beyond the enablers of implementing CE principles into building designs, there is no review of the literature that encompasses a large range of sustainable designs in the current CE context (Charef et al., 2021). Gillott et al. (2023) also stated that the CE philosophies remain limited within the construction industry. As emphasised by Urbinati et al. (2021), despite the enormous potential and benefits of CE, application of the CE in the construction industry has been hampered by several barriers. Therefore, it is apparent that there is no exception in the case of applying CE principles to building designs. Accordingly, Table 2 indicates the potential barriers to implementing CE principles into building designs that were identified by previous studies.

Table 2: Barriers of implementing CE principles into building designs

Barriers of implementing CE principles into building designs	**Authors**												
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
Economical													
1. New approach adoption cost	✓												
2. Initial cost for principle adoption	✓						✓			✓	✓	✓	✓
3. Additional cost for design phase	✓				✓						✓		
4. Lack of client demand							✓					✓	
5. Risk of client's readiness to pay the new concept	✓							✓			✓		
6. Underdeveloped market for salvaged components						✓					✓		
Sociological													
7. Resistance to change	✓									✓	✓		✓
8. Lack of trust	✓					✓							
9. Lack of concern and awareness	✓				✓	✓		✓	✓	✓	✓	✓	✓
10. Bad image of salvaged materials	✓					✓							
11. Ignorance of long-term benefits	✓					✓		✓			✓		✓
12. Impatience to get a return on investment quickly	✓					✓					✓		
Environmental													
13. Environmental benefits of reuse are not guaranteed						✓							
14. Not all materials can be environmentally effectively recycled						✓							
15. Use of virgin stock	✓												
16. Lack of incentives on environmental assessment methods											✓		✓
17. Emissions from transport	✓										✓		
Technical													
18. Construction method adoption	✓												

Barriers of implementing CE principles into building designs	Authors												
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
19. Uncertain product composition	✓										✓	✓	
20. Lack of appropriate technology	✓										✓	✓	✓
21. Complexity of building design		✓				✓		✓					
Organisational													
22. Lack of staff	✓									✓			
23. Architect incompetence	✓									✓			
24. Lack of experienced, skilled workers	✓			✓					✓	✓	✓	✓	✓
25. Multiple stakeholders needed	✓				✓								✓
26. Lack of support from the top management team	✓			✓									
27. Complexity to implement new approaches	✓	✓											
28. Lack of certification and recertification	✓						✓						
29. Lack of recovered material standards	✓					✓						✓	
30. Lack of building standard guidance	✓										✓	✓	
Political													
31. Lack of policies and regulations	✓	✓	✓			✓	✓		✓	✓	✓	✓	✓
32. Regulation absurdity and failures	✓	✓				✓				✓			
33. Regulation complexity and strictness	✓												
34. Lack of specific constructability requirements	✓					✓							
35. Lack of fiscal incentives or support	✓			✓	✓		✓	✓	✓	✓	✓	✓	✓

[A] Charef et al. (2021); [B] Gillott et al. (2023); [C] Moscati et al. (2023); [D] Rahla et al. (2021); [E] Çimen (2021); [F] Rios et al. (2021); [G] Rizos et al. (2016); [H] Adams et al. (2017); [I] Shooshtarian et al. (2022); [J] Tambovceva & Titko (n.d.); [K] Osei-Tutu et al. (2022); [L] Springvloed (2021); [M] Kanters (2020)

As indicated in Table 2, there are six (6) main categories and subcategories of barriers to implementing CE principles into building designs. According to Charef et al. (2021) and Osei-Tutu et al. (2022), the barriers linked to the economy are mainly dealt with initial cost of principle adoption and the socioeconomic barriers are mainly related to people's behaviour and the seeking of profit first. Further, technical barriers are related to the construction materials and others to the building scale such as construction methods, project phase adoption and building lifespan. Failures of enacted rules and regulations, lack of experience and knowledge of the staff are identified as political barriers and organisational barriers respectively for implementing CE principles into building designs (Rios et al., 2021). Osei-Tutu et al. (2022) stated that complexities in building design and lack of technological advancement have become obstacles to implementing CE concept. Considering all the above, lack of fiscal support or incentives, lack of awareness and lack of policies are the barriers for which the highest literature was found.

3.2.3 Strategies to Integrate Circular Economy Principles with Building Designs

In the path of the transition to a CE, it is required a range of specific strategies for the aforementioned barriers (Dokter et al., 2021). Table 3 indicates strategies of integrating CE principles into building designs that were identified by previous studies. Following the listed below strategies enables construction designers to adopt CE principles to building designs to ensure the sustainability of the building construction.

Table 3: Strategies of implementing CE principles into building designs

Strategies to integrate CE principles with building designs	Authors												
	A	B	C	D	E	F	G	H	I	J	K	L	M
1. Exercising leadership and educating stakeholders	✓	✓		✓	✓		✓	✓	✓	✓		✓	✓
2. Integrating CE in contractual requirements for design	✓						✓	✓					
3. Assigning CE consultants to assist design	✓						✓	✓			✓		
4. Creating databases for reusable components	✓					✓					✓		✓
5. Enforcing sustainable procurement aligned with CE	✓						✓						
6. Creating tax deductions for CE design strategies	✓						✓						
7. Establishing targets for salvaged components	✓					✓	✓			✓			✓
8. Establishing targets for reducing building embodied energy	✓								✓	✓		✓	
9. Increasing demolition taxes	✓					✓							
10. Promoting carbon taxes	✓					✓							✓
11. Incorporating CE in building codes	✓					✓				✓	✓		
12. Educating designers and building owners on life cycle cost	✓			✓	✓								✓
13. Integrating client demands into architecture education	✓			✓	✓								✓
14. Integrating CE into university curricula in all sectors	✓					✓		✓					✓
15. Raising public awareness of CE through public campaigns	✓		✓										
16. Incorporating CE training into the professional license renovation requirements for architects, engineers, and contractors	✓						✓		✓	✓		✓	
17. Raising awareness of construction stakeholders about successful examples of CBMs in the sector	✓	✓	✓			✓	✓	✓			✓		
18. Allocating public funding to offer financial aid to people who want to engage in circular design and construction	✓	✓	✓		✓	✓			✓	✓	✓		✓
19. Offering subsidies, tax credits, and low-interest loans for	✓	✓	✓		✓	✓			✓	✓	✓		✓

Strategies to integrate CE principles with building designs	Authors												
	A	B	C	D	E	F	G	H	I	J	K	L	M
companies that want to engage in CE practices													
20. Developing standards and improving current methodologies for environmental assessments of CE strategies	✓						✓			✓	✓		
21. Developing and enhancing technologies to assess the quality and safety of salvaged components	✓				✓		✓						✓
22. Increasing taxes on new construction and reducing taxes for building adaptive reuse	✓						✓	✓	✓		✓		
23. Creating national and regional CE action plans	✓						✓					✓	✓
24. Integrating CE strategies to ICT	✓				✓				✓	✓			✓

[A] Rios et al. (2021); [B] Rizos et al. (2016); [C] Adams et al. (2017); [D] Shooshtarian et al. (2022); [E] Springvloed (2021); [F] Eberhardt et al. (2020); [G] Hossain et al. (2020); [H] Dokter et al. (2021); [I] Foster (2020); [J] Utrilla et al. (2018); [K] Norouzi et al. (2021); [L] Leising et al. (2018); [M] Kalmykova et al. (2018)

As per Table 3, integrating CE principles into building designs requires multifaceted strategies. In this sense, the concept of CE can advocate building designs resulting in more sustainable, efficient, and adaptable structures for the future. Empowering leadership skills of the practitioners in building designs enables professional's awareness and keen to follow CE principles (Rios et al., 2021). Allocating public funds as financial support encourages designers to study and apply CE principles (Norouzi et al., 2021). In addition to that, the government could take the initiatives to introduce new taxes and loan rates for construction organisations to facilitate the implementation of CE in the design (Hossain et al., 2020).

3.3 THE POTENTIAL FOR FURTHER STUDY ON ADAPTABILITY OF CE PRINCIPLES INTO TOPICAL BUILDING DESIGNS TO IMPROVE SUSTAINABILITY

As established in Section 3.1.1, tropical building design is a sustainable approach. Additionally, it was revealed that by creating circularity within the industry, CE fosters sustainability. It clearly indicates the potential for further enhancing sustainability in the building sector by integrating CE principles into tropical building designs. Previous studies have shown a growing demand for buildings in tropical zones, making it crucial to incorporate circularity in these designs to address resource scarcity. However, previous research has primarily focused on the general application of CE principles to building designs, identifying 10 enablers, 35 barriers, and 24 strategies. Neither in-depth research has been conducted on the specific application of each R principle of the 9R principles to building designs. Therefore, to assess the feasibility of applying CE principles to tropical buildings, it is essential to investigate the enablers, barriers, and strategies for each R principle in the 9R framework within the tropical building design approach. This will provide valuable insights to building designers and stakeholders, enhancing the sustainability of the construction sector. Hence, the findings of the study could be adopted as a baseline for investigating the enablers, barriers, and strategies in applying each R principle of 9R CE principles to tropical building designs. Furthermore, by collecting empirical data, the extent to which the findings of this research study are applicable to the tropical building design context could be further evaluated. In addition to that, further investigation could be conducted to determine which of the 9R CE principles have the most impact on achieving sustainability when applied to tropical building designs.

3.4 CONCEPTUAL FRAMEWORK

One or more formal and empirical findings from the literature are included in a conceptual framework. It serves to illustrate the connections between these concepts and how the research study relates to them (Academic Guides: Theories and Frameworks: Introduction, n.d.). The conceptual framework answers questions of "Why is this research important?" and "How does it contribute new knowledge?" (Varpio et al., 2019).

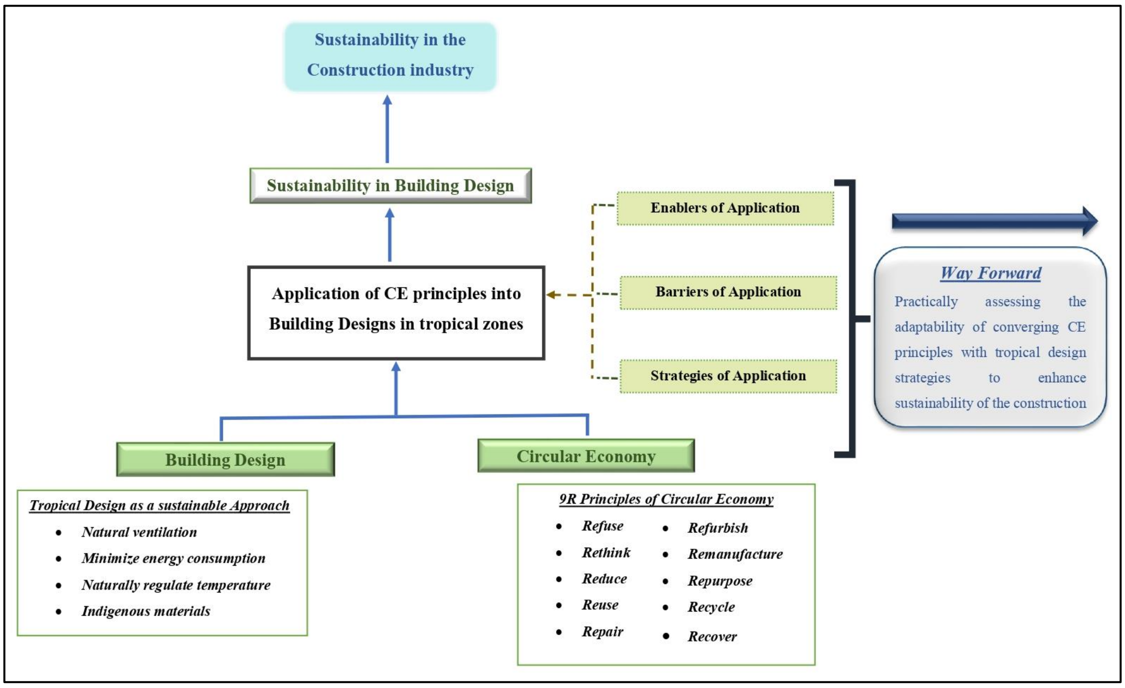


Figure 2: Conceptual framework

The conceptual framework illustrated in Figure 2 serves as a roadmap to address the identified literature gap. Sustainable strategies in tropical designs hold the potential to alleviate resource scarcity, while the 9R principles of CE steer the construction industry towards more sustainable practices. The application of CE principles in tropical building designs could accommodate the growing demand for buildings in tropical zones while enhancing sustainability practices within the construction industry. Hence, it could be further investigated the enablers, barriers, and strategies of integrating CE principles with tropical building design for each R principle of the 9R CE principles, based on the findings of this study.

4. CONCLUSIONS

Urbanisation, intensive growth of global population and material depletion have become greater concerns for the sustainability of the construction sector. Moreover, facilitating for growing population is a major difficulty faced by the building construction in tropical zones. Therefore, building design strategies should be advanced more through application of sustainable principles. Tropical designs were found as a method of sustainable building design solution and applying 9R CE principles to the tropical building designs would enhance the sustainability of the construction industry while facilitating the aforementioned surge in demand for buildings. Accordingly, it was investigated enablers, barriers and strategies for application of 9R principles to building designs. As a result, ten enablers were found, among which green buildings, renewable construction materials and recycled construction materials are the enablers for which the majority of literature was there. Moreover, under six subcategories of technological, economical, political, social, environmental and organisational, altogether 35 number of barriers were found. Subsequently, it was investigated strategies that could be adopted to manage and overcome the challenges. Establishing leadership skills, providing financial facilities, and rising awareness of the practitioners are mostly proposed strategies. It was concluded emphasising the cruciality of studying the enablers, barriers and strategies of applying CE principles to building designs for future researchers because based on the findings of this study forthcoming researchers could evaluate the integration of CE principles with tropical building designs to address the aforementioned issues. It is further recommended for building designers and architects to widen the application of CE principles into building designs and other construction practices to ensure circularity within the construction industry. Moreover, it is strongly recommended to conduct further research on the applicability of converging CE principles with energy-efficient building design strategies such as net zero energy building design strategies and tropical passive design strategies.

5. REFERENCES

Ababio, B. K., & Lu, W. (2022). Barriers and enablers of circular economy in construction: a multi-system perspective towards the development of a practical framework. *Construction Management & Economics (Print)*, *41*(1), 3–21. https://doi.org/10.1080/01446193.2022.2135750

Academic Guides: Theories and Frameworks: Introduction. (n.d.). https://academicguides.waldenu.edu/library/theory

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. In *Proceedings of the Institution of Civil Engineers. Waste and resource management/Proceedings of ICE. Waste and resource management* (Vol. 170, Issue 1, pp. 15–24). https://doi.org/10.1680/jwarm.16.00011

Agbete, M. A., & Frank, O. L. (2021). Modern vernacular architecture: An ecological approach towards energy efficiency; To reduce climate change impact in Nigeria. *IOSR Journal of Environmental Science*, *14*(3), 20–34.

Akhimien, N., Latif, E., & Hou, S. (2021). Application of circular economy principles in buildings: A systematic review. *Journal of Building Engineering, 38,* 102041. https://doi.org/10.1016/j.jobe.2020.102041

AlJaber, A., Martínez-Vázquez, P., & Baniotopoulos, C. (2023). barriers and enablers to the adoption of circular economy concept in the building sector: A systematic literature review. *Buildings*, *13*(11), 2778. https://doi.org/10.3390/buildings13112778

Al-Obaidi, K. M., Ismail, M., & Rahman, A. M. A. (2014). Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review. *Frontiers of Architectural Research*, *3*(3), 283–297. https://doi.org/10.1016/j.foar.2014.06.002

Anastasiades, K., Goffin, J., Rinke, M., Buyle, M., Audenaert, A., & Blom, J. (2021). Standardisation: An essential enabler for the circular reuse of construction components? A trajectory for a cleaner European construction industry. *Journal of Cleaner Production, 298,* 126864. https://doi.org/10.1016/j.jclepro.2021.126864

Antwi-Afari, P., Ng, S. T., & Chen, J. (2022). Developing an integrative method and design guidelines for achieving systemic circularity in the construction industry. *Journal of Cleaner Production*, *354*, 131752. https://doi.org/10.1016/j.jclepro.2022.131752

Avtar, R., Tripathi, S., Aggarwal, A. K., & Kumar, P. (2019). Population–urbanization–energy nexus: A review. *Resources*, *8*(3), 136. https://doi.org/10.3390/resources8030136

Barros, M. V., Salvador, R., Prado, G., De Francisco, A. C., & Piekarski, C. M. (2021). Circular economy as a driver to sustainable businesses. *Cleaner Environmental Systems*, *2*, 100006. https://doi.org/10.1016/j.cesys.2020.100006

Bulbaai, R., & Halman, J. I. (2021). Energy-Efficient building design for a tropical climate: A field study on the Caribbean Island Curaçao. *Sustainability*, *13*(23), 13274. https://doi.org/10.3390/su132313274

Castell-Rüdenhausen, M. Z., Wahlström, M., Astrup, T. F., Jensen, C., Oberender, A., Johansson, P., & Waerner, E. R. (2021). Policies as drivers for circular economy in the construction sector in the Nordics. *Sustainability*, *13*(16), 9350. https://doi.org/10.3390/su13169350

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular digital built environment: an emerging framework. *Sustainability*, *13*(11), 6348. https://doi.org/10.3390/su13116348

Charef, R., Morel, J., & Rakhshan, K. (2021). barriers to implementing the circular economy in the construction industry: A critical review. *Sustainability*, *13*(23), 12989. https://doi.org/10.3390/su132312989

Chen, L., Zhao, Y., Xie, R., Su, B., Liu, Y., & Renfei, X. (2023). Embodied energy intensity of global high energy consumption industries: A case study of the construction industry. *Energy*, *277*, 127628. https://doi.org/10.1016/j.energy.2023.127628

Çimen, Ö. (2021). Construction and built environment in circular economy: A comprehensive literature review. *Journal of Cleaner Production*, *305*, 127180. https://doi.org/10.1016/j.jclepro.2021.127180

Dokter, G., Thuvander, L., & Rahe, U. (2021). How circular is current design practice? Investigating perspectives across industrial design and architecture in the transition towards a circular economy. *Sustainable Production and Consumption*, *26*, 692–708. https://doi.org/10.1016/j.spc.2020.12.032

Eberhardt, L. C. M., Birkved, M., & Birgisdóttir, H. (2020). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*, *18*(2), 93–113. https://doi.org/10.1080/17452007.2020.1781588

Emmanuel, R. (2012). An urban approach to climate-sensitive design. In *Taylor & Francis eBooks*. https://doi.org/10.4324/9780203414644

Ferdous, W., Bai, Y., Ngo, T., Ferdous, W., & Mendis, P. (2019). New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review. *Engineering Structures*, *183*, 883–893. https://doi.org/10.1016/j.engstruct.2019.01.061

Fithian, L. A., Wang, N., & Siddique, Z. (2017). *Investing in Sustainable Buildings to Enhance Community Resilience*. https://doi.org/10.1061/9780784480502.086

Foster, G. J. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resources, Conservation and Recycling*, *152*, 104507. https://doi.org/10.1016/j.resconrec.2019.104507

Geissdoerfer, M., Savaget, P., Bocken, N., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghufran, M., Khan, K. I. A., Ullah, F., Nasir, A. R., Alahmadi, A. A., Alzaed, A., & Alwetaishi, M. (2022). Circular economy in the construction industry: A Step towards sustainable development. *Buildings*, *12*(7), 1004. https://doi.org/10.3390/buildings12071004

Gillott, C., Mihkelson, W., Lanau, M., Cheshire, D., & Tingley, D. D. (2023). Developing regenerate: A circular economy engagement tool for the assessment of new and existing buildings. *Journal of Industrial Ecology*, *27*(2), 423–435. https://doi.org/10.1111/jiec.13377

Guerra, B. C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resources, Conservation and Recycling*, *170*, 105617. https://doi.org/10.1016/j.resconrec.2021.105617

Hart, J., Adams, K. T., Giesekam, J., Tingley, D. D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: the case of the built environment. *Procedia CIRP*, *80*, 619–624. https://doi.org/10.1016/j.procir.2018.12.015

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable & Sustainable Energy Reviews*, *130*, 109948. https://doi.org/10.1016/j.rser.2020.109948

Hsieh, H. F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research*, *15*(9), 1277–1288. https://doi.org/10.1177/1049732305276687

Iyer-Raniga, U. (2019). Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets. *IOP Conference Series: Earth and Environmental Science*, *294*(1), 012002. https://doi.org/10.1088/1755-1315/294/1/012002

Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018). Circular economy – From review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling*, *135*, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034

Kanters, J. (2020). Circular Building Design: An analysis of barriers and drivers for a circular building sector. *Buildings (Basel)*, *10*(4), 77. https://doi.org/10.3390/buildings10040077

Kara, S., Hauschild, M. Z., Sutherland, J. W., & McAloone, T. C. (2022). Closed-loop systems to circular economy: A pathway to environmental sustainability? *CIRP Annals*, *71*(2), 505–528. https://doi.org/10.1016/j.cirp.2022.05.008

Kerdan, I. G., Raslan, R., Ruyssevelt, P., & Gálvez, D. M. (2016). An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings. Energy and Buildings, 133, 155–171. https://doi.org/10.1016/j.enbuild.2016.09.029

Leising, E., Quist, J., & Bocken, N. (2018). Circular Economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, *176*, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010

Mio, C., Panfilo, S., & Blundo, B. (2020). Sustainable development goals and the strategic role of business: A systematic literature review. *Business Strategy and the Environment*, *29*(8), 3220–3245. https://doi.org/10.1002/bse.2568

Mirabella, N., Röck, M., Saade, M. R. M., Spirinckx, C., Bosmans, M., Allacker, K., & Passer, A. (2018). Strategies to improve the energy performance of buildings: A review of their life cycle impact. *Buildings*, *8*(8), 105. https://doi.org/10.3390/buildings8080105

Moscati, A., Johansson, P., Kebede, R., Pula, A., & Törngren, A. (2023). Information exchange between construction and manufacturing industries to achieve circular economy: A literature review and interviews with swedish experts. *Buildings*, *13*(3), 633. https://doi.org/10.3390/buildings13030633

Negi, A. (2021). Green buildings: Strategies for energy-efficient and eco-friendly designs. *the Philippine Statistician (Quezon City)*, *70*(1), 683–689. https://doi.org/10.17762/msea.v70i1.2524

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering*, *44*, 102704. https://doi.org/10.1016/j.jobe.2021.102704

Oluleye, B. I., Chan, D. W., Antwi-Afari, P., & Olawumi, T. O. (2023). Modeling the principal success factors for attaining systemic circularity in the building construction industry: An international survey of circular economy experts. *Sustainable Production and Consumption*, *37*, 268–283. https://doi.org/10.1016/j.spc.2023.03.008

Osei-Tutu, S., Ayarkwa, J., Osei-Asibey, D., Nani, G., & Afful, A. E. (2022). Barriers impeding circular economy (CE) uptake in the construction industry. *Smart and Sustainable Built Environment, 12*(4), 892-918. Emerald Publishing. https://doi.org/10.1108/SASBE-03-2022-0049

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing Circular Economy Strategies in Buildings—From Theory to Practice. *Applied System Innovation*, *4*(2), 26. https://doi.org/10.3390/asi4020026

Rios, F. C., Grau, D., & Bilec, M. M. (2021). Barriers and enablers to circular building design in the US: an Empirical study. *Journal of the Construction Division and Management*, *147*(10). https://doi.org/10.1061/(asce)co.1943-7862.0002109

Rizos, V., Behrens, A., Van Der Gaast, W., Hofman, E., Ιωάννου, A., Kafyeke, T., Flamos, A., Rinaldi, R., Papadelis, S., Hirschnitz-Garbers, M., & Topi, C. (2016). Implementation of circular economy business models by small and medium-sized enterprises (SMES): Barriers and enablers. *Sustainability*, *8*(11), 1212. https://doi.org/10.3390/su8111212

Ruiz, L. a. L., Ramón, X. R., & Domingo, S. G. (2020). The circular economy in the construction and demolition waste sector – A review and an integrative model approach. *Journal of Cleaner Production*, *248*, 119238. https://doi.org/10.1016/j.jclepro.2019.119238

Santolin, R. B., Hameed, H. B., Urbinati, A., & Lazzarotti, V. (2023). Exploiting circular economy enablers for SMEs to advance towards a more sustainable development: An empirical study in the post COVID-19 era. *Resources, Conservation & Recycling Advances*, *19*, 200164. https://doi.org/10.1016/j.rcradv.2023.200164

Seddon, N., Smith, A. C., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., & Turner, B. (2021). Getting the message right on nature-based solutions to climate change. *Global Change Biology*, *27*(8), 1518–1546. https://doi.org/10.1111/gcb.15513

Shang, M., Ma, Z., Su, Y., Shaheen, F., Khan, H. U. R., Tahir, L. M., Sasmoko, Anser, M. K., & Zaman, K. (2022). Understanding the importance of sustainable ecological innovation in reducing carbon emissions: investigating the green energy demand, financial development, natural resource management, industrialisation and urbanisation channels. *Ekonomska Istrazivanja-economic Research*, *36*(2). https://doi.org/10.1080/1331677x.2022.2137823

Shooshtarian, S., Caldera, S., Maqsood, T., Ryley, T., Wong, P. S., & Zaman, A. (2022). Analysis of factors influencing the creation and stimulation of the Australian market for recycled construction and demolition waste products. *Sustainable Production and Consumption*, *34*, 163–176. https://doi.org/10.1016/j.spc.2022.09.005

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Springvloed, P. (2021). The drivers and barriers for a circular economy in the built environment of the Netherlands (Master's thesis).

Stoiljković, B., Petković, N., Krstić, H., & Petrović, V. (2023). Application of circular economy principles to Architectural design: a case study of Serbia. *Buildings*, *13*(8), 1990. https://doi.org/10.3390/buildings13081990

Suárez-Eiroa, B., Fernández, E., Martínez, G. M., & Soto-Oñate, D. (2019). Operational principles of circular economy for sustainable development: Linking theory and practice. *Journal of Cleaner Production*, *214*, 952–961. https://doi.org/10.1016/j.jclepro.2018.12.271

Tambovceva, T., & Titko, J. (2020). *Introduction to circular economy*. https://ortus0m.rtu.lv/science/en/publications/31629

Utrilla, P. N., Górecki, J., Moreno, V. M., & Corpas-Iglesias, F. A. (2018). What gets measured, gets done: Development of a circular economy measurement scale for building industry. *Sustainability (Basel)*, *10*(7), 2340. https://doi.org/10.3390/su10072340

Varpio, L., Paradis, E., Uijtdehaage, S., & Young, M. (2019). The distinctions between theory, theoretical framework, and conceptual framework. *Academic Medicine*, *95*(7), 989–994. https://doi.org/10.1097/acm.0000000000003075

Verma, A., Gupta, V., Nihar, K., Jana, A., Jain, R. K., & Deb, C. (2023). Tropical climates and the interplay between IEQ and energy consumption in buildings: A review. *Building and Environment*, *242*, 110551. https://doi.org/10.1016/j.buildenv.2023.110551

Vita, G., Lundström, J., Hertwich, E. G., Quist, J., Ivanova, D., Stadler, K., & Wood, R. (2019). The environmental impact of green consumption and sufficiency lifestyles scenarios in europe: Connecting local sustainability visions to global consequences. *Ecological Economics*, *164*, 106322. https://doi.org/10.1016/j.ecolecon.2019.05.002

Xianlin, S., Gou, Z., & Lau, S. (2018). Cost-effectiveness of active and passive design strategies for existing building retrofits in tropical climate: Case study of a zero energy building. *Journal of Cleaner Production*, *183*, 35–45. https://doi.org/10.1016/j.jclepro.2018.02.137

Xiao, Y., & Watson, M. (2019). Guidance on conducting a systematic literature review. *Journal of Planning Education and Research*, *39*(1), 93–112. https://doi.org/10.1177/0739456x17723971

Yusuf, D. H. (2021, July 11). *Integration of eco-friendly design principles in the design of mixed-use building, abuja, nigeria*. http://repository.futminna.edu.ng:8080/jspui/handle/123456789/13499

Zaman, A., Ruiz, A. M. C., Shooshtarian, S., Ryley, T., Caldera, S., & Maqsood, T. (2023). Development of the circular economy design guidelines for the australian built environment sector. *Sustainability (Basel)*, *15*(3), 2500. https://doi.org/10.3390/su15032500

Dilani, K., Mapa, M.M.I.S., Konara, G. and Samarakoon, W.K.U.R.M.K.P.K., 2024. Assessing the importance of implementing wearable technologies for construction employees in the Sri Lankan context. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 215-226. DOI: https://doi.org/10.31705/WCS.2024.17. Available from: https://ciobwcs.com/papers/

ASSESSING THE IMPORTANCE OF IMPLEMENTING WEARABLE TECHNOLOGIES FOR CONSTRUCTION EMPLOYEES IN THE SRI LANKAN CONTEXT

K. Dilani[1], M.M.I.S. Mapa[2], Gayani Konara[3], and W.K.U.R.M.K.P.K. Samarakoon[4]

ABSTRACT

Occupational Safety and Health (OSH) is important in the construction industry, as it can help ensure the physical, mental and social well-being of workers when performing work-related tasks. Wearable Safety Devices (WSDs) can proactively detect hazards and perform real-time surveillance, enabling the elimination and control of risks and improved safety outcomes. As useful as it is, there are a few things that affect adoption, such as high initial costs, lack of understanding and privacy concerns. This study identifies wearables technology applications that apply to construction. Based on the outcomes, Sri Lankan construction workers exhibited a preference for wearable technologies. Participants in the construction industry provide data via a questionnaire survey, which is then analysed and prioritised using the Relative Importance Index (RII) for wearable technology applications. The key finding from the document identifies that smart shoe for roofing work, smart glasses for dust particles and smart helmets for working at heights are the most prioritised wearable technologies in the Sri Lankan construction industry for enhancing OSH practices. In addition, this study provides insights into how essential it is to introduce wearable technology, from the point of view of overall safety and health implantation practices in the Sri Lankan construction industry and emphasises the importance of a systematic implementation approach suited to the needs and challenges of this region.

Keywords: *Construction Works; Occupational Health and Safety; Personal Protective Equipment; Sri Lanka; Wearable Technology.*

1. INTRODUCTION

OSH is a cross-disciplinary area concerned with protecting the safety, health and welfare of people engaged in work or employment (Jain et al., 2018). OSH has evolved to not

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, dilanikaneshapalan@gmail.com
[2] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, isuru.mapa@uom.lk
[3] Lecturer, Ritsumeikan University, Japan, gy_kaushi@yahoo.com
[4] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, samarakoonk@uom.lk

only prevent workplace illnesses and accidents but also to actively manage overall health and well-being in the workplace (Yilmaz & Yildiz, 2021). The construction sector may contribute significantly to economic development yet associated with a large number of fatal accidents. In particular, the construction sector is recognised as one of the most dangerous industries (Kamoli et al., 2022).

Wearable technology encompasses clothing and accessories that have sensors and electronics embedded within them, enabling real-time continuous monitoring of physiological and environmental parameters (Choi et al., 2017). The construction industry has seen technological innovations such as Wearable Safety Devices (WSD) as one of the solutions to their OSH challenges (Awolusi et al., 2018). Effectively resolving OSH concerns requires teaching and educating construction workers on the use of digital technology (Ahn et al., 2019). WSDs give employees a way to proactively check their OSH, which might help mitigate hazards.

There are many benefits to using wearable technology in construction as opposed to standard Personal Protective Equipment (PPE) (Awolusi et al., 2018). This allows them to monitor environmental and physiological data which can be a precursor of possible OSH hazards. Construction Wearables promotes improved coordination and communication between construction workers (Okpala et al., 2019). Construction work is made safer and more efficient by the smooth integration of wearable technology with PPE (Awolusi et al., 2018). Hence, to address these hazards in the best way possible and lessen them effectively, the construction industry must implement wearable technologies that aid safety procedures while making operations more productive (Al-Sahar et al., 2021).

Although WSDs have positive effects on OSH, there are drawbacks as well, including maintenance costs, operational costs, training and managerial obstacles (Didehvar et al., 2018; Young et al., 2011). The potential for technology adoption to improve OSH practices needs to be explored in Sri Lanka, where there is a lack of technological awareness (Aghimien et al., 2019). Technology is given less weight in OSH research conducted in poor nations. There is a lack of knowledge regarding the benefits of technology adoption in the construction sector of developing countries (Moshood et al., 2020).

In conclusion, the findings of this study emphasise the pressing need to address OSH issues in the construction industry, highlighting higher work-related accident rates and the importance of safety rules (Ajayi et al., 2021). It advocates an integrated approach using modern technologies such as WSDs to be effective in reducing hazards (Papazoglou & Heuvel, 2007). The extant literature, based on the construction industry of different countries, provides numerous studies that focus on the adoption and benefits of wearable technology in improving work safety. The primary aim of this study is to fill this gap in the literature by determining the types of wearable technology best suited to Sri Lankan construction workers to cater to their needs in terms of safety and considering the unique challenges faced by these workers in a contextual context.

For this reason, this study looks further into the methods of utilising wearable technologies to improve OSH for construction workers in Sri Lanka. In this context, the objectives of the study are to review existing knowledge on wearable technologies in OSH practices and their validity for use in the industry in Sri Lankan construction sector, set up a detailed implementation strategy and develop applications for using these wearables within Sri Lankan construction sites and identify strategies to overcome the constraints and support worker acceptance when integrating wearable technology devices.

2. LITERATURE REVIEW

2.1 OCCUPATIONAL SAFETY AND HEALTH ON CONSTRUCTION SITE

In the building industry, OSH ensures the physical, mental and social well-being of workers in all companies in all categories of employment at work (Patel & Jha, 2015). Cost is one of the greatest impediments to the adoption of OSH practices by small construction companies. Their financial standing often prevents them from attending to basic safety measures, such as hiring safety personnel and procuring PPE, which in other words affects the overall safety of construction activities on sites (Ying et al., 2015). A company can protect its productivity and efficiency, as well as the health of its employees, by taking care of these health threats. One of the essential OSH practices in the construction industry is the use of PPE.

2.2 PERSONAL PROTECT EQUIPMENT

PPE is fundamental in the construction industry, where technical and managerial control can be challenging to implement (Ahmad et al., 2016). The lack of PPEs has led to workers being fairly careless when it comes to OSH, in that if the workers do not wear them appropriately, the workers may be subject to multiple OSH hazards whereby all of which may have a serious impact on human health (Balkhyour et al., 2019). PPEs are highly crucial for safety purposes as they help to decrease the extent of human suffering, financial losses related to reduced productivity fines and occupational injuries and accidents (Lu et al., 2015). The construction industry now uses various technologies to address these barriers. This research aims to provide a comprehensive understanding of wearable technology usage in construction work.

2.3 WEARABLE TECHNOLOGY

In the construction sector, technology covers solutions that are adapted to address a specific challenge or to a specific device and machinery in use to meet project objectives. This set includes hand and excavation tools, as well as digital devices and space-geographic analysis systems that are used to execute the entire life cycle of a construction project from design to deconstruction. A wearable device is designed to be worn and the consumer can carry it or wear it using an accessory (Ercan & Timur, 2020). The adoption of wearable technology has grown explosively across various sectors (Seneviratne et al., 2017). As the sector faces worsening statistics in terms of OSH, more construction businesses are turning to technological advancements as a remedy (Awolusi et al., 2018). WSDs are small wearable devices designed with sensors that continuously monitor a worker's OSH. (Okpala et al., 2020). WSD can facilitate real-time monitoring and preventive practices, implying that mitigating any OSH hazard can be achievable in construction (Ahn et al., 2019). There are numerous advantages to using wearable technology in the OSH context.

2.4 WEARABLE TECHNOLOGY AN IMPLEMENTATION PLAN FOR CONSTRUCTION SITE

This represents the initial step towards implementing wearable technologies for OHS in construction through requirements assessment (Okpala et al., 2020). Based on this needs assessment, a methodology is provided to the construction industry to identify the most appropriate wearable technologies for construction sites (Aksut et al., 2024). Then, the wearable technologies that are chosen should be able to handle the hazards and obstacles that arise on construction sites (Junior et al., 2021). After selecting the appropriate wearables, it is critical to conduct pilot testing in a controlled setting or on a small-scale building site (Brandt et al., 2018). Train staff and OHS specialists in the operation of the selected wearable devices in detail (Arana-Landín et al., 2023). The next step is the implementation of wearable technologies on construction sites with a guarantee that wearable technologies are being used appropriately and efficiently, continuously monitoring their performance and utilisation (Awolusi et al., 2018). Finally, the efficacy of wearable technologies will be evaluated, and any necessary modifications or alterations will be implemented as per evaluation outcomes to maximise their impact on OHS practices.

2.5 COMMON BENEFITS OF WEARABLE SAFETY DEVICES IN CONSTRUCTION

WSDs provide several advantages to the construction sector, boosting overall job performance, monitoring worker health and promoting worker safety (Nnaji et al., 2021). Connected to wearables and smartphones, these sensors enable real-time monitoring of potentially dangerous environments, including temperature, fine dust, gas concentrations and noise (Nnaji & Awolusi, 2021). Inertial Measurement Units (IMUs) and motion sensors improve workers' awareness of their movements by identifying irregular gaits, awkward postures, and fall risks (Okpala et al., 2021). Clearing up misconceptions, WSD use in the construction industry can lead to a significant reduction in mortality, accidents and lower costs related to workplace mishaps (Mahmud et al., 2022). WSDs offer the advantage of preventive action, allowing potential risks to be recognised early and avoided (Arabshahi, 2021). WSDs provide several advantages to the construction sector, boosting overall job performance, monitoring worker health and promoting worker safety (Nnaji et al., 2021). WSDs, such as wearable Electroencephalography (EEGs), record brain wave patterns to monitor stress levels, mental fatigue and emotional states.

2.6 CHALLENGES IN THE ADOPTION AND IMPLEMENTING WEARABLE TECHNOLOGY IN CONSTRUCTION SITE

The prohibitively high initial cost is the main drawback of adopting WSDs (Alemu et al., 2020). Critical elements, including the type of organisation, its size and its past WSD experience, are necessary for the successful adoption of WSDs, such as worker education, customised WSDs and ongoing assessment strategies (Nnaji & Awolusi, 2021). Construction workers express serious worries about privacy and security confidentiality, particularly when it comes to wearable technology (Choi et al., 2017). Moreover, end-users must accept and trust IoT-based solutions in OSH deployments (Haikio et al., 2020). Some of the key technical challenges relate to how to select the appropriate sensors, overall data storage and wireless communication and connectivity protocols. Social barriers arise due to intellectual property rights, privacy and interoperability problems (Abuwarda et al., 2022).

2.7 SOLUTION TO OVERCOME CHALLENGES

Contractors prioritise technologies that have demonstrated their ability to perform, stressing the value of accurate information sharing via thorough assessments and repeatable procedures (Okpala et al., 2019). Client or owner involvement is essential for technology adoption in OSH management (Shen et al., 2015). When undertaking construction projects with fewer resources, training should encompass end-to-end processes from the start, as well as include upgrades (Tang, 2019). Management support significantly influences employees' intentions to adopt new systems. Managerial involvement at various stages of technology adoption decisions, along with interactions among managers, engineers, operational crews, and fitters, facilitates a joint decision-making process. Construction wearable promotes improved coordination and communication between construction workers (Okpala et al., 2019). It is in keeping with a philosophy that rewards contractors who have developed safety programs and adopted more expedient technologies that reduce the potential for accidents and project delays (Karakhan et al., 2018).

3. RESEARCH METHODOLOGY

Survey-eligible participants were recruited via a convenience sample that focused on construction industry professionals. A convenience sample of 40 construction industry professionals (contractors, site engineers, safety officers, technical officers and quantity surveyors) was used to ensure data quality. Surveys were conducted online through WhatsApp and Zoom platforms. Questionnaire survey questions are created based on the literature review. Before conducting the survey, information sessions were held where participants were informed about wearable technologies and their importance. A series of awareness sessions were held, leading to more thoughtful responses as attendees learned about the value and potential applications of wearable technologies in construction. To increase responses and reduce unwanted biases, they were assured of their anonymity and the confidentiality of their answers. Trained interviewers were available to help with any questions and to corroborate that the survey was answered completely and correctly. The main issue in conducting the survey was whether Sri Lankan construction workers had adequate knowledge about wearable technologies.

Questionnaires were administered to a large sample of construction workers, providing quantitative data on the application of wearable technology in construction work. When considering the structure of the questionnaire, two sections were dedicated to collecting information about the usage of wearable technologies on Sri Lankan construction sites and to obtaining respondents' perspectives on implementing wearable technologies in the Sri Lankan construction industry. There are nine questions in Section 2 categorised by categories of wearable technology, using a Likert scale to measure the suitability of wearable technology necessary for certain construction work. Five points of the Likert scale indicate that: 1=strongly disagree, 2=disagree, 3=neutral, 4=agree, and 5=strongly agree. Content analysis techniques, including code-based and manual approaches, were used to analyse data. For content that was code-based, SPSS (Statistical Package for the Social Sciences) software specifically was employed. Given the limitation of SPSS software for code-based analysis, hence was chosen to conduct simple descriptive statistic tests on base group demographics using statistical techniques. SPSS is an easy-to-use tool that can scale to large datasets with a high level of precision and reliability.

4. RESEARCH FINDINGS AND RESULTS

4.1 APPLICATION OF WEARABLE TECHNOLOGY IN CONSTRUCTION SITE

By categorising and interpreting responses from the questionnaire, content analysis provided insights into stakeholders' preferences and perceptions, identifying trends in technology adoption across different construction tasks (refer to Table 1).

Table 1: Application of wearable technology in construction site

Type	Usage of construction work
Exoskeletons	Exoskeletons can be used to support particular body parts, such as the shoulders, back or entire body (Pillai et al., 2020). Back support exoskeleton example can reduce physical strain in rebar work by supporting back muscles during activities, as well as assistive moments at the hip or lower spine (Zhang & Huang, 2018). Exoskeletons may help, but they could also create new effects and OSH risks, especially for back-supporting exoskeletons.
Smart helmet	Smart helmets can become attractive for the construction sector as they enable productivity and safety communication (Choi & Kim, 2021). The use of smart helmets with sensors allows critical vital signs to be monitored in real-time, which makes the necessary action for accident situations or health problems reliable and speedy (Singh et al., 2019). Smart helmets are fitted with accelerometers that can detect sudden movements that could be associated with a crash, for example, a fall (Wang et al., 2020).
Smart vest	Smart vests containing lots and lots of sensors are used to locate trackers, gyroscopes, accelerometers, etc. (Chan et al., 2012). While this data includes the positioning of workers, it further includes details of posture, movements and surroundings (Cheng et al., 2013). Most of the time, these smart vests can be integrated with project management systems so that they can be more effective in their respective industry (Landaluce et al., 2020). This enables real-time data to be integrated into wider project analytics and allows resource usage, efficiency and safety performance to be assessed in more detail (Ferreira et al., 2021).
Smartwatch	It is more likely for elderly people to own such gadgets as they are too small to wear (Dehghani et al., 2018). It gets complicated in the course of activities when the vibrations might interfere with prospective usability (Alpert et al., 2020). Because the information can only be displayed at a small level and requires drivers to divide their attention between the screen and their surroundings (close to multitasking), it is difficult to deal with. This limitation also makes it particularly challenging for elderly users to recognise and understand information on small screens (Kim et al., 2019).
Smart Glasses	In construction, smart glasses are supposed to offer ease of interacting with digital models and machinery in a hands-free manner using digital twins (Lombardi et al., 2019). Safety smart glasses with capabilities such as monitoring Building Information Management (BIM) data, providing the ability to see real-time onsite conditions (Sadhu et al., 2023).
Hearing Protection Devices	Workers at construction sites are subjected to high noise levels, thus they must wear appropriate hearing protection to avoid ear damage (Hong et al., 2013). It might be difficult to strike a balance between protection and awareness when using traditional options, such as earplugs, which frequently impair Auditory Situational Awareness (ASA). Earplugs and other conventional hearing

Type	Usage of construction work
	protection devices prevent ASA, which impairs response to important noises (Elelu et al., 2022).
Smart Shoes	Smart shoes are classified as measurement-oriented and passive devices that track metrics including steps walked, calories burnt and sleep efficiency (Al-Sahar et al., 2021). Without actively altering physiological states, these gadgets offer insightful data on physical activity (Steptoe et al., 2009).
Smart Hard Hats	To enable automatic identification of hard hat use and heart rate monitoring of the worker, the modification entails moving the sensor from the arm to the hard hat chin strap (Kim et al., 2021). For hard hats to be functional, headband and chin strap criteria must be followed (Fung et al., 2014).
Smart Wristband	Wristbands offer a practical solution for continuous Heart Rate (HR) monitoring without interference, making them better suited to continuous HR monitoring in situations where physical exertion is required (Sevil et al., 2020). The reading of blood flow rates is obtained through Photoplethysmography (PPG) sensors used with automatic wristband-based heart-rate monitors. The performance of ECG sensors proves their ability the monitor HR wristband-based using construction environments with accurate HR data (Anwer et al., 2021).

For quantitative data analysis, it used SPSS to calculate the RII and rank the usability of wearable technology with weighting based on cumulative response frequency. This means that SPSS was used for the necessary statistical calculations and to visualise results statistical gradients overlay these statistical factors to ensure a rigorous end-point of quantitative validation of qualitative findings. Together, these methodologies allowed for a comprehensive assessment of wearable technology implementation, integrating qualitative insights with quantitative data to inform strategies for enhancing safety and productivity in Sri Lanka's construction industry. This study aimed to examine the perspectives of these experts on the adoption priorities and the type of work roles and tasks in the construction site that are suitable for using wearable technology. Data were analysed by the responses to the questionnaire of the respondents and the final ranking of its application of wearable technology in Sri Lankan construction sites was done using the RII value.

$$\text{Relative Importance Index (RRI)} = \frac{\sum (Wn)}{AN} \qquad \textit{(Eq. 01)}$$

Where,

- W = constant expressing the weighting given to each response.
- N = frequency of responses
- A = highest weighting
- N = total number in the responses

Table 2 indicates the top 20 RII value and ranks based on wearable technology usage priority.

Table 2: RII rate of wearable technologies

Wearable Devices	Construction works	Respondent scores					Total	W	RII	Rank
		1- Stongly disagee	2- Disagree	3- Nuetral	4- Agree	5- Stongly agree				
Exoskeletons	Heavy lifting and carrying	1	2	12	7	18	40	159	0.795	4
	Demolition and excavation	4	6	11	10	9	40	134	0.670	17
Smart helmet	Fixed objects like low pipes and beams	2	3	8	10	17	40	157	0.785	6
	Work in Heights	2	4	6	8	20	40	160	0.800	3
Smart vest	Welding and construction crew	3	1	15	10	11	40	145	0.725	14
	Inspection and surveying	3	2	8	13	14	40	153	0.765	11
Smartwatch	Site inspections and surveying	3	3	11	8	15	40	149	0.745	13
	Inventory management and logistics	4	5	8	13	10	40	140	0.700	16
Smart Glasses	Dust particles	2	0	11	9	18	40	161	0.805	2
	Chemicals	2	4	7	11	16	40	155	0.775	9
	Bright or harmful light rays	2	3	7	12	15	39	152	0.779	8
Hearing Protection Devices	Demolitions	2	4	7	10	17	40	156	0.780	7
	Loud machine use	0	3	10	11	16	40	160	0.800	3
Smart Shoes	Dangling electrical wires	2	2	9	13	14	40	155	0.775	9
	Roofing Work	1	2	8	11	18	40	163	0.815	1
	Concrete Pouring	1	4	6	14	15	40	158	0.790	5
Smart Hard Hats	Electrical and plumbing work	1	3	11	11	14	40	154	0.770	10
	Work in Heights	1	2	11	11	15	40	157	0.785	6
Smart Wristband	Site inspections and surveying	3	3	9	10	15	40	151	0.755	12
	Inventory management and logistics	3	1	13	15	8	40	144	0.720	15

As a result, the majority of respondents concurred that the most usable wearable technology in the Sri Lankan construction industry is smart shoes for roofing work (RII=0.815; R=1). This is followed by smart glasses for dust particles (RII= 0.805; R=2), smart helmets for working at heights and hearing protection devices for using loud machinery (RII=0.800; R=3). However, employing exoskeletons for excavation and demolition (RII=0.670; R=17) scored lowest in the respondents' opinions. In general, the results have indicated wearable technology has the potential to enhance safety and productivity in many construction operations in Sri Lanka.

5. DISCUSSION

The study underscores the critical imperative regarding OSH issues in the construction industry and reveals the importance of protocols for individual protection and accident rate (Ajayi et al., 2021). It promotes a comprehensive approach with a combination of modern technologies to minimise hazards (Papazoglou & Van Den Heuvel, 2007). The use of WSDs is one of the most crucial construction risk mitigation strategies (Nnaji et al., 2021). Wearable technology can help enhance the awareness of workers and the real-time monitoring of construction businesses hence decrease the risks stemming from unsafe working conditions (Awolusi et al., 2018). The paper suggests strategies for addressing challenges related to initially high costs and privacy concerns by emphasising comprehensive training programs and stakeholder participation. The authors of the study should, therefore, consider their practical recommendations to work with technology providers and continue to evaluate the effectiveness of the technology as likely to be well-placed to support stakeholders in the adoption and implementation of wearable technology to support safety in Sri Lanka's construction sector. The findings highlight the positive implications of wearable devices on improving safety practices within the industry in Sri Lanka, contributing towards better worker welfare and improving construction project performance.

6. CONCLUSIONS

It is feasible to enhance OSH practices of the Sri Lankan construction sector, via integrating wearable technologies. Through an exhaustive literature review, the nine most relevant wearable technologies are identified in this study. Wearable safety devices leverage the power of real-time monitoring combined with hazard identification and prevention to protect the construction industry from accidents. A structured approach that incorporates needs assessment, pilot testing, comprehensive training and continuous evaluation should help to ensure the successful adoption of wearable technologies. Moreover, the research's empirical basis is reinforced by the methodology used in the study, which used a questionnaire survey to determine participants' preferences and wearable technology applicability in the construction industry. Through the methodical data analysis and the calculation of RII, the study offers important insight relating to the wearable technology applications required in Sri Lankan construction sites. This research assists Sri Lankan construction enterprises to assess safety concerns, improve OSH processes and provide safer workplaces for their workers by implementing wearable technology.

7. REFERENCES

Abuwarda, Z., Mostafa, K., Oetomo, A., Hegazy, T., & Morita, P. (2022). Wearable devices: Cross benefits from healthcare to construction. *Automation in Construction*, *142*, 104501. https://doi.org/10.1016/j.autcon.2022.104501

Aghimien, D., Aigbavboa, C., & Oke, A. (2019). A review of the application of data mining for sustainable construction in Nigeria. *Energy Procedia*, *158*, 3240–3245. https://doi.org/10.1016/j.egypro.2019.01.996

Ahmad, I., Sattar, A., Nawaz, A., & Professor, A. (2016). Occupational health and safety in industries in developing world. *Gomal Journal of Medical*, *14*, 4. https://gjms.com.pk/index.php/journal/article/view/694/690

Ahn, C. R., Lee, S., Sun, C., Jebelli, H., Yang, K., & Choi, B. (2019). Wearable sensing technology applications in construction safety and health. *Journal of construction engineering and management*, *145*(11). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001708

Ajayi, S. O., Adegbenro, O. O., Alaka, H. A., Oyegoke, A. S., & Manu, P. A. (2021). Addressing behavioural safety concerns on Qatari Megaprojects. *Journal of Building Engineering*, *41*, 102398. https://doi.org/10.1016/j.jobe.2021.102398

Aksüt, G., Eren, T., & Alakas, H. M. (2024). Using wearable technological devices to improve workplace health and safety: An assessment on a sector base with multi-criteria decision-making methods. *Ain Shams Engineering Journal*, *15*(2), 102423. https://doi.org/10.1016/j.asej.2023.102423

Alemu, A. A., Yitayew, M., Azazeh, A., & Kebede, S. (2020). Utilization of Personal Protective Equipment and associated factors among building construction workers in Addis Ababa, Ethiopia, 2019. *BMC Public Health*, *20*, 794. https://doi.org/10.1186/s12889-020-08889

Alpert, J. M., Manini, T., Roberts, M., Kota, N. S. P., Mendoza, T. V., Solberg, L. M., & Rashidi, P. (2020). Secondary care provider attitudes towards patient-generated health data from smartwatches. *Npj Digital Medicine*, *3*(1). https://doi.org/10.1038/s41746-020-0236-4

Al-Sahar, F., Przegalińska, A., & Krzemiński, M. (2021). Risk assessment on the construction site with the use of wearable technologies. *Ain Shams Engineering Journal*, *12*(4), 3411–3417. https://doi.org/10.1016/j.asej.2021.04.006

Anwer, S., Heng Li, P., Fordjour, M., Umer, W., & Yu Lok Wong, A. (2021). Evaluation of physiological metrics as a real-time measurement of physical 1 fatigue in construction workers: State-of-the-Art Reviews. *Journal of Construction Engineering and Management*, *147*(5), 03121001. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002038

Arabshahi, M. (2021). *Developing a governance framework to assist with the adoption of sensing technologies in construction*. [Doctoral thesis, Curtin University] Curtin Theses. http://hdl.handle.net/20.500.11937/84210

Arana-Landín, G., Laskurain-Iturbe, I., Iturrate, M., & Landeta-Manzano, B. (2023). Assessing the influence of industry 4.0 technologies on occupational health and safety. *Heliyon*, *9*(3). https://doi.org/10.1016/j.heliyon.2023.e13720

Awolusi, I., Marks, E., & Hallowell, M. (2018). Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. *Automation in Construction*, *85*, 96–106. https://doi.org/10.1016/j.autcon.2017.10.010

Balkhyour, M. A., Ahmad, I., & Rehan, M. (2019). Assessment of Personal Protective Equipment use and occupational exposures in small industries in Jeddah: Health implications for workers. *Saudi Journal of Biological Sciences*, *26*(4), 653–659. https://doi.org/10.1016/j.sjbs.2018.06.011

Brandt, M., Madeleine, P., Samani, A., Ajslev, J. Z., Jakobsen, M. D., Sundstrup, E., & Andersen, L. L. (2018). Effects of a participatory ergonomics intervention with wearable technical measurements of physical workload in the construction industry: Cluster randomized controlled trial. *Journal of medical internet research*, *20*(12), e10272. https://doi.org/10.2196/10272

dehg, M., Estève, D., Fourniols, J. Y., Escriba, C., & Campo, E. (2012). Smart wearable systems: Current status and future challenges. *Artificial Intelligence in Medicine*, *56*(3), 137–156. https://doi.org/10.1016/j.artmed.2012.09.003

Cheng, T., Migliaccio, G. C., Teizer, J., & Gatti, U. C. (2013). Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers. *Journal of computing in civil engineering*, *27*(3), 320–335. https://doi.org/10.1061/(ASCE)cp.1943-5487.0000222

Choi, B., Hwang, S., & Lee, S. H. (2017). What drives construction workers' acceptance of wearable technologies in the workplace? Indoor localization and wearable health devices for occupational safety and health. *Automation in Construction*, *84*, 31–41. https://doi.org/10.1016/j.autcon.2017.08.005

Choi, Y., & Kim, Y. (2021). Applications of the smart helmet in applied sciences: A systematic review. *Applied Sciences*, *11*, 5039. https://doi.org/10.3390/app11115039

Dehghani, M., Kim, K. J., & Dangelico, R. M. (2018). Will smartwatches last? factors contributing to the intention to keep using smart wearable technology. *Telematics and Informatics*, *35*(2), 480–490. https://doi.org/10.1016/j.tele.2018.01.007

Didehvar, N., Teymourifard, M., Mojtahedi, M., & Sepasgozar, S. (2018). An investigation on virtual information modeling acceptance based on project management knowledge areas. *Buildings*, *8*(6), 80. https://doi.org/10.3390/buildings8060080

Elelu, K., Le, T., & Le, C. (2022). Augmented hearing of auditory safety cues for construction workers: A systematic literature review. *Sensors*, *22* (23), 9135. https://doi.org/10.3390/s22239135

Ercan, I. P., & Timur, S. (2020). Changing terminology of definition and design of wearable technology products. *Online Journal of Art and Design*, *8*(3), 90-106. http://www.adjournal.net/articles/83/837.pdf

Ferreira, J. J., Fernandes, C. I., Rammal, H. G., & Veiga, P. M. (2021). Wearable technology and consumer interaction: A systematic review and research agenda, *Computers in Human Behavior*, *118*, 106710. https://doi.org/10.1016/j.chb.2021.106710

Fung, I. W. H., Lee, Y. Y., Tam, V. W. Y., & Fung, H. W. (2014). A feasibility study of introducing chin straps of safety helmets as a statutory requirement in the Hong Kong construction industry. *Safety Science*, *65*, 70–78. https://doi.org/10.1016/j.ssci.2013.12.014

Guk, K., Han, G., Lim, J., Jeong, K., Kang, T., Lim, E. K., & Jung, J. (2019). Evolution of wearable devices with real-time disease monitoring for personalized healthcare. *Nanomaterials*, *9*(6), 813. https://doi.org/10.3390/nano9060813

Haikio, J., Kallio, J., Mäkelä, S.-M., & Keränen, J. (2020). IoT-based safety monitoring from the perspective of construction site workers. *International Journal of Occupational and Environmental Safety*, *4*(1), 1–14. https://doi.org/10.24840/2184-0954_004.001_0001

Hong, O. S., Kerr, M. J., Poling, G. L., & Dhar, S. (2013). Understanding and preventing noise-induced hearing loss. *Disease-a-Month*, *59*(4), 110–118. https://doi.org/10.1016/j.disamonth.2013.01.002

Jain, A., Leka, S., & Zwetsloot, G. I. J. M. (2018). Work, health, safety and well-being: Current State of the art. In *Managing health, safety and well-being. Aligning perspectives health, safety and well-being.* (pp. 1–31). Springer, Dordrecht. https://doi.org/10.1007/978-94-024-1261-1_1

Jeferd, E., Saong, E., Babaran, A. L., Dale, G., & Balaho, A. (2021). Assessment of the awareness and safety practices in mitigating hazards of silica dust exposure among construction workers. *International Journal of Engineering Applied Sciences and Technology*, *5*(10), 60-65. https://www.ijeast.com/papers/60-65,Tesma510,IJEAST.pdf

Kamoli, A., Adul Hamid, R., & Hendra Binmahmud, Y. (2022). Roles of construction organizations in revitalizing occupational health and safety of the Nigerian construction industry. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *26*(1), 97–104. https://doi.org/10.37934/araset.26.1.97104

Karakhan, A. A., Rajendran, S., Gambatese, J., & Nnaji, C. (2018). Measuring and evaluating safety maturity of construction contractors: a multicriteria decision-making approach. *Journal of Construction Engineering and Management*, *144*(7). https://digitalcommons.cwu.edu/cotsfac

Kim, J. H., Jo, B. W., Jo, J. H., Lee, Y. S., & Kim, D. K. (2021). Autonomous detection system for non-hard-hat use at construction sites using sensor technology. *Sustainability*, *13*(3), 1–11. https://doi.org/10.3390/su13031102

Kim, J. W., Lim, J. H., Moon, S. M., & Jang, B. (2019). Collecting health lifelog data from smartwatch users in a privacy-preserving manner. *IEEE Transactions on Consumer Electronics*, *65*(3), 369–378. https://doi.org/10.1109/TCE.2019.2924466

Landaluce, H., Arjona, L., Perallos, A., Falcone, F., Angulo, I., & Muralter, F. (2020). A review of IoT sensing applications and challenges using RFID and wireless sensor networks. *Sensors*, *20*(9), 2495. https://doi.org/10.3390/s20092495

Lombardi, M., Cammarota, A., & Refoyo, J. (2019). Development, applications and benefits of the network digital twin. In *CIRED 2019, Madrid, Spain*, 3-6 June 2019. (2149). AIM. http://dx.doi.org/10.34890/974

Lu, L., Shi, L., Han, L., & Ling, L. (2015). Individual and organizational factors associated with the use of Personal Protective Equipment by Chinese migrant workers exposed to organic solvents. *Safety Science*, *76*, 168–174. https://doi.org/10.1016/j.ssci.2014.11.025

Mahmud, D., Bennett, S. T., Zhu, Z., Adamczyk, P. G., Wehner, M., Veeramani, D., & Dai, F. (2022). Identifying facilitators, barriers and potential solutions for adopting exoskeletons and exosuits in construction workplaces. *Sensors*, *22*(24). https://doi.org/10.3390/s22249987

Moshood, T. D., Nawanir, G., Sorooshian, S., Mahmud, F., & Adeleke, A. Q. (2020). Barriers and benefits of ICT adoption in the Nigerian construction industry. A comprehensive literature review. *Applied System Innovation*, *3*(4), 1–19. https://doi.org/10.3390/asi3040046

Nnaji, C., & Awolusi, I. (2021). Critical success factors influencing wearable sensing device implementation in the AEC industry. *Technology in Society*, *66*, 101636. https://doi.org/10.1016/j.techsoc.2021.101636

Nnaji, C., Awolusi, I., Park, J. W., & Albert, A. (2021). Wearable sensing devices: Towards the development of a personalized system for construction safety and health risk mitigation. *Sensors*, *21*(3), 1–25. https://doi.org/10.3390/s21030682

Okpala, I., Nnaji, C., & Awolusi, I. (2019). Emerging construction technologies: state of standard and regulation implementation. *Computing in Civil Engineering 2019: Data, Sensing and Analytics - Selected Papers from The ASCE International Conference on Computing in Civil Engineering 2019*, 153–161. https://doi.org/10.1061/9780784482438.020

Okpala, I., Nnaji, C., Awolusi, I., & Akanmu, A. (2021). Developing a success model for assessing the impact of wearable sensing devices in the construction industry. *Journal of construction engineering and management*, *147*(7). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002064

Okpala, I., Nnaji, C., & Karakhan, A. A. (2020). Utilizing emerging technologies for construction safety risk mitigation. *Practice periodical on structural design and construction*, *25*(2), 04020002. https://doi.org/10.1061/(ASCE)sc.1943-5576.0000468

Papazoglou, M. P., & Van Den Heuvel, W. J. (2007). Service-oriented architectures: Approaches, technologies and research issues. *VLDB Journal*, *16*(3), 389–415. https://doi.org/10.1007/s00778-007-0044-3

Patel, D. A., & Jha, K. N. (2015). A neural network model for the prediction of safe work behaviour in construction projects. *Journal of construction engineering and management*, *141*(1), 04014066. https://doi.org/10.1061/(ASCE)co.1943-7862.0000922

Pillai, M. V., Van Engelhoven, L., & Kazerooni, H. (2020). Evaluation of a lower leg support exoskeleton on the floor and below hip height panel work. *Human factors: The Journal of the Human Factors and Ergonomics Society*, *62*(3), 489–500. https://doi.org/10.1177/0018720820907752

Sadhu, A., Peplinski, J. E., Mohammadkhorasani, A., & Moreu, F. (2023). A review of data management and visualization techniques for structural health monitoring using BIM and virtual or augmented reality. *Journal of Structural Engineering*, *149*(1). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003498

Seneviratne, S., Hu, Y., Nguyen, T., Lan, G., Khalifa, S., Thilakarathna, K., Hassan, M., & Seneviratne, A. (2017). A survey of wearable devices and challenges. *IEEE Communications Surveys and Tutorials*, *19*(4), 2573–2620. https://doi.org/10.1109/COMST.2017.2731979

Sevil, M., Rashid, M., Askari, M. R., Maloney, Z., Hajizadeh, I., & Cinar, A. (2020). Detection and characterization of physical activity and psychological stress from wristband data. *Signals*, *1*(2), 188–208. https://doi.org/10.3390/signals1020011

Shen, Y., Koh, T. Y., Rowlinson, S., & Bridge, A. J. (2015). Empirical investigation of factors contributing to the psychological safety climate on construction sites. *Journal of construction engineering and management*, *141*(11), 04015038. https://doi.org/10.1061/(ASCE)co.1943-7862.0001021

Singh, V., Chandna, H., & Upadhyay, N. (2019). Smart PPM: An Internet of Things-based smart helmet design for potholes and air pollution monitoring. *EAI Endorsed Transactions on Internet of Things*, *5*(18), 163833. https://doi.org/10.4108/eai.13-7-2018.163833

Soares Junior, G. G., Satyro, W. C., Bonilla, S. H., Contador, J. C., Barbosa, A. P., Monken, S. F. de P., Martens, M. L., & Fragomeni, M. A. (2021). Construction 4.0: Industry 4.0 enabling technologies applied to improve workplace safety in construction. *Research, Society and Development*, *10*(12), e280101220280. https://doi.org/10.33448/rsd-v10i12.20280

Steptoe, A., Dockray, S., & Wardle, J. (2009). Positive affect and psychobiological processes relevant to health. *Journal of Personality*, *77*(6), 1747–1776. https://doi.org/10.1111/j.1467-6494.2009.00599.x

Tang, K. N. (2019). Beyond employability: Embedding soft skills in higher education. *The Turkish Online Journal of Educational Technology*, *18*(2), 1-9. https://eric.ed.gov/?id=EJ1211098

Wang, C., Kim, Y., Kim, D. G., Lee, S. H., & Min, S. D. (2020). Smart helmet and insole sensors for near fall incidence recognition during the descent of stairs. *Applied Sciences (Switzerland)*, *10*(7), 2262. https://doi.org/10.3390/app10072262

Yilmaz, M., & Yildiz, S. (2021). The importance of occupational health and safety (OHS) and OHS budgeting in terms of social sustainability in the construction sector. *Journal of Building Material Science*, *2*(1). https://doi.org/10.30564/jbms.v2i1.2591

Ying, J., Wong, Y., Gray, J., & Sadiqi, Z. (2015). Barriers to good occupational health & safety (OHS) practices by small construction firms. *Journal of Constriction Management*, *30*, 55-66. https://eprints.qut.edu.au/87062/

Young, D. A., Haas, C. T., ASCE, F., Goodrum, P., ASCE, M., Caldas, C., & ASCE, A. M. (2011). Improving construction supply network visibility by using automated materials locating and tracking technology. *Journal of Construction and Engineering Management*, *137*(11), 976-984. http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000364

Zhang, T., & Huang, H. H. (2018). A lower-back robotic exoskeleton: Industrial handling augmentation used to provide spinal support. *IEEE Robotics and Automation Magazine*, *25*(2), 95–106. https://doi.org/10.1109/MRA.2018.2815083

Dharmadasa, K.H.K., Kulatunga, U., Thayaparan, M. and Keraminiyage, K.P., 2024. Assessment of community disaster resilience in Sri Lanka: Methodological approach in developing an index. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 227-239. DOI: https://doi.org/10.31705/WCS.2024.18. Available from: https://ciobwcs.com/papers/

ASSESSMENT OF COMMUNITY DISASTER RESILIENCE IN SRI LANKA: METHODOLOGICAL APPROACH IN DEVELOPING AN INDEX

K.H.K. Dharmadasa[1], U. Kulatunga[2], M. Thayaparan[3], and K.P. Keraminiyage[4]

ABSTRACT

Disasters threaten communities, causing immense damage to life, property, and overall well-being. In recent years, the frequency and impact of disasters have increased, highlighting the urgent need for enhancing Community Disaster Resilience (CDR). CDR refers to a community's ability to effectively anticipate, respond to, and recover from disasters. This research presents the proposed methodology to develop an index to measure community resilience to disasters in Sri Lanka. Based on the previous studies on resilience, a Systematic Literature Review (SLR) was conducted to identify all possible proxy indicators of CDR across economic, social, institutional, physical, environmental, and human health dimensions. The primary data collection and analysis will be conducted using a systematic approach called Q-methodology. As the SLR results generated too many items in the first instance, a pilot study will be undertaken to reduce the number and to identify the most relevant indicators (Q-set) for measuring CDR in Sri Lanka. This Q-set data will be ranked based on how much each expert in the field of disaster management, who will be selected through the snowball technique, would agree with each identified indicator (Q-sort). Then, Q-sort data is subjected to factor analysis to determine the inter-correlation between the results of Q-sorting. The qualitative data gathered during Q-sorting is expected to be analysed using thematic analysis. Finally, the index will be constructed by deriving the weightage of each indicator based on the Q-sorting results. This paper provides an extensive illustration of the above methodology.

Keywords: *Community Disaster Resilience (CDR); Index; Indicators; Methodology.*

1. INTRODUCTION

With the increase in occurrences of high-impact disasters, the concept of resilience is widely recognised (Tanvir et al., 2022). In the disaster context, the word resilience can simply be explained as the ability of people to recover within the shortest possible time with minimal or no assistance (Malalgoda et al., 2013). Disaster resilience is further

[1] Research Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, hasangakeshan5@gmail.com
[2] Professor in Building Economics, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk
[4] Reader, School of Built Environment, University of Salford, UK, k.p.keraminiyage@salford.ac.uk

defined as the capacity to adapt existing resources and skills to new situations and operating conditions (Lee, 2020; Tanvir et al., 2022). However, natural hazard events do not always turn into natural disasters, particularly in resilient communities (Parsons et al., 2016). According to Cox and Hamlen (2015), Graveline and Germain (2022) and Tariq et al. (2022), resilience-building actions and interventions are primarily carried out at the community level because the ability of a community to survive and thrive is crucial in the face of uncertainty. Tariq et al. (2021a) define the term community as a group of people with diverse characteristics linked by social ties, sharing common perspectives, and engaging in joint action in geographical locations or settings. As Cutter et al. (2008) highlighted, key assessment factors for disaster resilience are social, economic, institutional, infrastructure, community competence (health, understanding risk, quality of life, etc.), and environmental. Further, Tariq et al. (2021a) define community resilience as a multidimensional concept that includes physical, human/health, economic, social, environmental, and governance. Those dimensions of resilience need to be transformed through a common characteristic of the community (e.g. geographic location, livelihood, etc.) to form community resilience (Norris et al., 2008; Tariq et al., 2021a)

As the Community Disaster Resilience (CDR) concept continues to evolve, researchers are increasingly focusing on developing frameworks and tools that can measure and classify community resilience (Tariq et al., 2021a). The assessment of resiliency is crucial not only for planning and decision-making yet for identifying the vulnerable population in the society that is usually most affected when a disaster strikes (Deria et al., 2020). Two main ways of measuring disaster resilience are qualitative and quantitative (Aksha & Emrich, 2020). In-depth interviews, focus group discussions, life stories, and observations are commonly used in qualitative approaches to explore community resilience in small-scale studies (Scherzer et al., 2019). Cutter (2016) stated that quantitative measures often result in indices, scorecards, models and toolkits. However, Rodriquez et al. (2022) argue that its operationalisation remains unclear despite many attempts to quantify resilience. Further, Koliou et al. (2020) emphasise that, despite the growing importance of measuring CDR, no straightforward procedure to define and measure CDR has emerged. Moreover, most existing studies focused on measuring resilience in a particular region and at a particular scale without deriving inferential rules or equations for further use (Lam et al., 2016).

Furthermore, Aksha and Emrich (2020) suggest that resilience measures have primarily been a developed world phenomenon because various methods and measures have been used to examine and estimate community disaster resilience in developed countries, while very few have been applied towards understanding disaster resilience in developing nations. Mavhura and Manyena (2018) complement that in developing countries, vulnerable populations are regularly exposed to the severity of natural hazards and disasters. Still, more focus has been paid to immediate response and coping capacities rather than resilience enhancement. When referring to the Sri Lankan context, survivors of the 2004 boxing-day tsunami relied on coping resources within their communities, such as extended supportive networks, religious faith, and cultural traditions, to manage emotional distress (Ekanayake et al., 2013). Moreover, Mendis et al. (2022) emphasised that marginalised communities in Sri Lanka are disproportionately affected by disasters highlighting the importance of their engagement in a post-disaster context. Further, Sri Lankan communities face challenges in building disaster resilience, including inadequate financial and human resource capabilities, a lack of knowledge of disaster risks and vulnerabilities, and a lack of focus on pre-disaster planning (Malalgoda et al., 2013). Therefore, assessing community resilience in Sri Lanka is vital for understanding community-specific vulnerabilities, decision-making and strengthening community resilience to disasters.

Among the different assessment methods available, only the index values make it possible to assign an overall performance rating to community resilience since they are often standardised for comparison purposes (Almutairi et al., 2020). Parsons et al. (2016) argue that many existing disaster resilience indexes lack comprehensive criteria, making it difficult to generalise the assessment process. A few indexes are empirically validated using observed disaster impacts, making it unclear which index should be preferred for decision-making (Feldmeyer et al., 2020). Singh-Peterson et al. (2014) highlighted that indicator selection for developing an index requires careful consideration, ensuring a reliable reflection of the study area characteristics. Even though different indexes to assess resilience towards disaster have been developed and relatively use the same criteria, different countries may require adjustments in sub-criteria and resilience indicators (Dyah et al., 2014). Furthermore, Beccari (2020) and Cai et al. (2018) emphasise that resilience assessments must be adjusted based on the context, as community resilience is highly context-specific. While researchers and practitioners in the hazard and disaster management field have increasingly focused on community resilience to disasters, there have been little to no empirical studies in Sri Lanka. Several disaster resilience indicators that have been developed by researchers (Cutter et al., 2008: Qasim et al., 2016: Odiase et al., 2020) can be utilised to develop a comprehensive comparative index for community disaster resilience in Sri Lanka. Even though there are several disaster resilience indexes developed by worldwide researchers there is no overarching research that provides a comprehensive and comparable index of community disaster resilience across the country in Sri Lanka. This suggests the need to conduct an extensive study on developing a community disaster resilience index for Sri Lanka. Thus, this research expects to develop a composite index to assess Community Disaster Resilience (CDR) in Sri Lanka by combining factors in different resilience domains.

Furthermore, an appropriate research methodology is critical to attaining the research objectives while providing the most out of the research. Therefore, this paper aims to design and justify the research methodology to develop a comparative community resilience index to measure the level of resilience of the community in Sri Lanka from natural disasters.

2. DEVELOPMENT OF RESEARCH METHODOLOGY

Research methodology is a general research strategy defining how research should be carried out (Mendis et al., 2023). It includes a system of beliefs and philosophical assumptions that shape the understanding of research questions and underpin the choice of research methods (Melnikovas, 2018). Figure 1 shows six layers of Research Onion i.e. (i) philosophy, (ii) approach to theory development, (iii) methodological choice, (iv) strategies, (v) time horizon, and (vi) techniques and procedures. Subsequent sections discuss each layer of the research onion and the methodology adopted on each layer.

2.1 DECIDING ON THE SUITABLE METHODOLOGY

The research design is the selection of the appropriate research philosophy, research approach, research strategy, research choice, time horizon, and techniques. The two most prominent research design models are the nested model developed by Kagioglou et al. (2000) and the research onion model developed by Saunders et al. (2019). With both systems embracing a systematic process towards researching while providing a basis to make informed decisions, research onion with further layers than the nested method is much more comprehensive (Mostafavi & Ganapati, 2021). Social science researchers widely use the research onion model to develop the theoretical framework (Mendis et al., 2023). As a result, the Saunders research onion model is followed to design this research methodology.

2.2 RESEARCH DESIGN

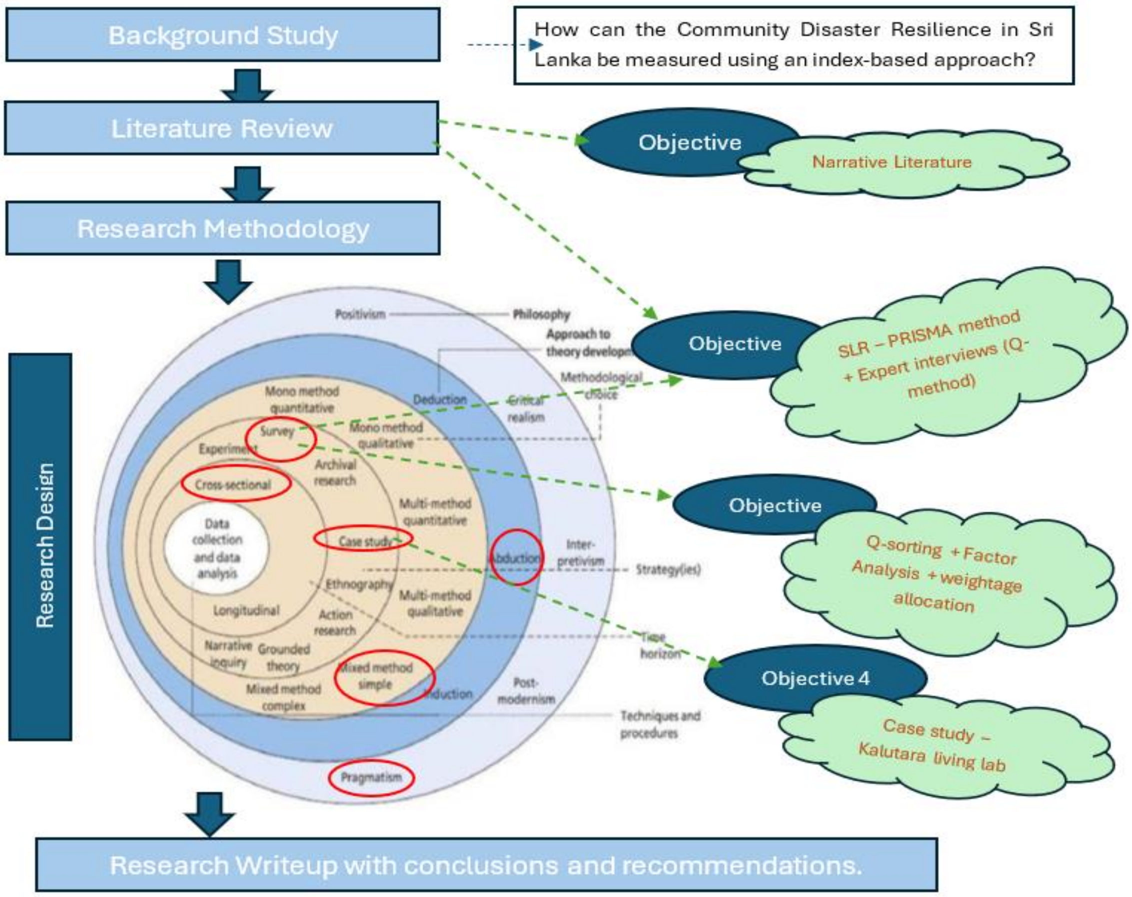


Figure 1: Research design

2.2.1 Research Philosophy

Research philosophy refers to the set of beliefs, assumptions, and principles that direct and shape a researcher's method of conducting research (Mendis et al., 2023). The Saunders research onion unpacks three perceptions (ontology, epistemology, and axiology) that underlie various research philosophies (positivism, critical realism, interpretivism, postmodernism, and pragmatism), shaping a researcher's approach to the entire research process (Saunders et al., 2019).

The **ontological** question is, "What is the form and nature of the reality?". The two leading ends of ontology can be identified as realism and idealism. As stated by Amaratunga et al. (2015), in realism, the researcher deals with the existing reality, independent of their observations. Idealism means that reality begins with ideas or thoughts based on different perspectives of people (Amaratunga et al., 2015). The **epistemological** question refers to assumptions about knowledge, what constitutes acceptable, valid and legitimate knowledge and how knowledge can be communicated to others (Burrell & Morgan, 2017). There are two extremes in the epistemology assumption. One extreme suggests that if the researcher is independent of the subject studied, the study has characteristics of positivism. The other extreme relies on knowledge based on people and their opinions, where subjectivity is encouraged (Saunders et al., 2019). The **axiological** question is directly linked to the study's value concern. A study may be either value-free or value-laden (Lewthwaite & Nind, 2016). In a value-free study, the choice of what and how to study is determined by objective criteria, while in value-laden research, the choice is based on human values and experiences (Easterby-Smith et al., 2018).

In this study, measuring community resilience to disasters using an index involves multiple indicators that should be selected as appropriate and prioritised based on the context in which they apply. Further, the background study highlighted that the inhabitants in the considered geographical location idealise indicators selected under community resilience dimensions. Conversely, idealism may not be suitable for comparing CDR in Sri Lanka across several geographical locations and taking measures to improve resilience. Therefore, this study's ontological positioning remains between realism and idealism. Moreover, the Stakeholders might have different perceptions considering the subjective nature of the research question. The subjective nature of community resilience draws the research towards interpretivism. Yet, there is a need to maintain the value-free nature of the study as much as possible since a community resilience index needs to be applicable and justifiable to the studied context regardless of the researcher's perceptions. Therefore, the knowledge for developing the resilience index is not solely constructed through the interpretation of the respondents involved in the research but rather from the context itself because the respondents were merely a sample from the context. Considering the value concern of the study, the inhabitants of a particular region clearly understand the community's level of resilience in the selected area. Therefore, the views on community resilience are laden. Nonetheless, when developing a context-specific CDR index, the researcher's values are insignificant, and the resilience index needs to be objective to the maximum degree. Hence, the research philosophy of the study is not positioned in positivism or interpretivism extremes yet in pragmatism, where it will be placed in a balanced position.

2.2.2 Approaches to Theory Development

This refers to the theory development being inductive, deductive or abductive. The inductive approach, or "bottom-up," begins with data collection to explore a phenomenon and allow a theory to emerge (Soiferman, 2010). On the other hand, the deductive approach, or "top-down," begins with a theory and then develops an empirical observation to test the theory (Saunders et al., 2019). Under the abductive approach, it generates a new theory or modifies an existing one, further validated through additional data collection (Saunders et al., 2019). This research started with existing knowledge and theories related to disaster management, community resilience, different dimensions of community resilience, indicators of measuring CDR, assessment approaches of CDR, existing resilience indices and common properties of index development. However, further investigation is required through primary data collection to gain expert opinions to contextualise and prioritise the indicators selected via a systematic literature review. Moreover, the developed index will be validated by applying it to the chosen living lab in Kalutara district, Sri Lanka. Hence, the abductive approach is the most suitable approach for this research.

2.2.3 Methodological Choice

According to Yin (2009), there are two fundamental research methods i.e. (i) quantitative, and (ii) qualitative. Further, Creswell (2016) illustrates three types of research methods i.e. (i) quantitative, (ii) qualitative, and (iii) mixed. Further, the methodological choice is the third layer of the research onion, which describes the use of qualitative, quantitative, and mixed methods (Melnikovas, 2018).

Qualitative research method

Qualitative research denotes an interpretative way of collecting and analysing data to investigate and explain a phenomenon (Cao, 2007). Qualitative research is essential to understand what is happening by looking at the whole problematic incident (Creswell, 2003). Further, qualitative research allows for a more open-ended and versatile approach to evaluation (Randall et al., 2011).

Quantitative research method

Quantitative research aims to investigate the relationship between variables, such as the dependent and independent variables (Creswell, 2016). Bryman (2004) states that quantitative work typically focuses on quantifying data collection and analysis. The core differences between these two approaches can be identified in Table 1.

Table 1: Key features of qualitative and quantitative data
Source: (Creswell, 2016)

	Qualitative	Quantitative
Purpose	To investigate the meaning of people's experiences, people's culture and how people feel about a particular issue or case	To examine the relationship between variables and to quantify the data.
Research question	Open-ended questions	Closed-ended questions
Data collection method	Unstructured (e.g., interviews, documents, observations, audio-visual materials)	Structured (e.g., performance data, attitude data, observational data and census data
Analysis technique	Non-statistical (e.g., text or image analysis)	Statistical
Nature	The researcher defines the truth	Reality is definite by the contributors

Mixed research method

There is another new approach called mixed method choice. According to Johnson and Onwuegbuzie (2004), a mixed research method combines quantitative and qualitative elements. If a researcher wishes to consider both statistical trends (quantitative data) and personal experiences (qualitative data), this method would be ideal (Creswell, 2016).

Selection of suitable research method

Based on the definitions and comparison of the above research methodologies, it was decided that the mixed research method should be chosen for this study. Mixed methods research is becoming increasingly popular given the benefit of combining quantitative and qualitative data to explore phenomena (Duncan Millar et al., 2022; Minc et al., 2022). This research aims to assess the community resilience to disasters in Sri Lanka by developing an index. Therefore, this requires an in-depth inquiry to gather information related to indicators within the context of Sri Lanka. The indicators needed to be prioritised based on the quantitative data collected during the expert interview rounds. Qualitative methods provide a closer look and richer understanding, while quantitative methods add breadth and a "big picture" approach, leading to greater breadth and depth of understanding (Boumezrag, 2023). Therefore, the mixed research method will be facilitated here to provide a deeper understanding and broader perspective regarding the research question.

2.2.4 Research Strategy

The research strategy is the fourth layer of the research onion, explaining the formal procedure for conducting the research and the method of achieving the aim and objectives (Saunders et al., 2019). According to Yin (2009), there are five different research strategies i.e. (i) survey, (ii) case study, (iii) experiment, (iv) archival analysis, and (v) history. As mentioned by Saunders et al. (2019), experiments, surveys, case studies, and archival analysis are the most commonly used research strategies in social science research.

From the perspective of having an in-depth investigation (Tellis, 1997) and examining contemporary issues in real life (Merrigan & Huston, 2004), the case study will be the perfect strategy. Further, Simmons (2017) encourages researchers to implement case studies if the phenomena related to the qualitative research question are best answered by the case study method. Moreover, qualitative case studies allow researchers to describe a phenomenon using various data sources (Baxter & Jack, 2015). The survey research strategy is the collection of information from a sample of individuals through their responses to questions (Check & Schutt, 2012). The survey research strategy mainly uses questionnaires and interviews as the data collection methods (Ponto, 2015). An experimental research strategy facilitates the researcher in reliably establishing a cause-effect relationship, and these types of studies are suitable for carried out in closed environments such as laboratories (Saunders et al., 2019). The archival analysis involves a procedure of reviewing documents and textual materials (Ventresca & Mohr, 2002).

Among these research strategies, survey and case study research strategies will be used. The study is under consideration to gain expert opinions on identifying the most appropriate indicators for measuring community disaster resilience in Sri Lanka and prioritising them to take the weighted average in developing the index. Hence, the survey strategy will be used during the preliminary phase of the study. As highlighted by Yin (2009), a case study design will be used to answer "how" and "why" questions in the research problem and when in-depth investigation is required to find answers. The study consists of a "how" nature question (How is the resilience status of the community in Sri Lanka?) Therefore, the case study strategy will be used in the final stage of the study by drawing into the living lab in Kalutara district to check the applicability of the developed index.

2.2.5 Time Horizon

A study could be designed in a longitudinal or cross-sectional time horizon (Saunders et al., 2019). A longitudinal study analyses a phenomenon over time to compare data

(Caruana et al., 2015). A cross-sectional study is a 'snapshot' study in which the phenomenon is investigated at a specific time (Setia, 2016). This study intends to measure the level of community resilience in Sri Lanka across several geographical locations at a particular time. Hence, regarding time horizons, this research is a cross-sectional study.

2.2.6 Research Techniques

Research techniques are the final peel of the research onion, which shows the different techniques available for data collection and analysis (Melnikovas, 2018). These techniques support the research in answering the research question. Research techniques consist of two strands i.e. (i) data collection, and (ii) data analysis.

Data collection techniques

As the initial step of this research, a background study was conducted to identify the research gap and formulate the research problem, aim, and objectives. Apart from the narrative literature review, a systematic literature synthesis was performed by adopting Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), mainly to explore all possible statements of the question. The primary data collection will be based on Q-methodology to gather qualitative and quantitative data to develop the index. In the final stage, the index will be validated based on the data collected through living-lab Kalutara and other census data collected from relevant authorities. Interviews will be executed in a semi-structured format. All the interviews will be recorded to enhance accuracy and minimise the risk of losing data, with the permission of the respective interviewee.

- **"Q-methodology"**

Q-methodology or Q-method approach is a participatory tool that allows for analysing individual perspectives (Tariq et al., 2022). Q-methodology combines qualitative and quantitative techniques to study the subjectivity of the research question (Millar et al., 2022). According to Duncan Miller et al. (2022), the Q methodology enables us to recognise and characterise the shared perspectives on a subject while revealing areas of consensus and disagreement across these views. Mukherjee et al. (2018) recommend the use of the Q-method in situations where conflict is high. Further, a strength of the Q-methodology is that it combines the richness of qualitative data with the rigour of statistical analysis (Dziopa & Ahern, 2009). Using Q-methods, the resilience assessment process gets a participatory approach built into its implementation, whereby key stakeholders are an inherent part of the resilience assessment process (Huggins et al., 2015). One of the benefits of using the method is that it does not require forming a prior hypothesis on perspectives in advance; the results show the patterns of opinions as they exist in the individuals in a group (Huggins et al., 2015). Tariq et al. (2021b) utilised Q-methods to understand the preferences of different stakeholder groups regarding resilience and the issues they face. Although the method works well with small, selected samples of individuals, it is not intended to be generalised to a larger population, hence its appropriateness for ranking among different stakeholder groups (Raadgever et al., 2008; Zabala & Pascual, 2016).

The Q-method approach utilises a series of statements in the domain of communicability, or the sum of topics, measures, and indicators within a particular context (Zabala, 2014). Participants sort these statements, each providing a viewpoint on what they think are the most critical statements from their perspective (Huggins et al., 2015). Moreover, according to Millar et al.(2022), there are two vital elements to any Q-study. First, participants rank a set of statements of opinion on a grid. This is followed by a factor analysis to identify clusters of shared viewpoints that can then be interpreted. Tariq et al. (2022) define a five-step approach of utilising Q-methods in their study, and those steps will be followed during this study.

Table 2: Five-step approach of the Q-method

Steps	Methods to be adopted
Collection of all possible statements about the issue at hand (the concourse)	Systematic review
Selection of the most relevant statements (the Q-set)	Internal Workshop
Selection of the respondents (the P-set)	Snowball technique
Ranking of statements by respondents according to how much they agree with each statement (Q-sorting)	In-depth interviews and focus group discussions
Analysis and interpretation	Thematic analysis, Descriptive statistics & Factor Analysis (FA)

Complex concepts such as community resilience are often defined and understood differently by the different stakeholder groups at the local levels in the community (Tariq et al., 2022). This study focuses on CDR and develops a library of indicators to measure CDR based on an SLR. The review results were used as the "Concourse" in this study, creating an initial library of 20 leading indicators and 88 sub-indicators measuring CDR. The research team then looks at these indicators in detail through an internal workshop for further refinement to form the final set of indicators (final statements). In the subsequent stages, these refined indicator sets will be used as statements in the "Q set". In Q-methodology, the participant sample is known as the P set. The p-set sample will be purposive based on the snowball technique. Data collection involves participants rank ordering the Q set statements onto spaces on a grid (Q-sorting). Once participants have completed the Q sort, they are asked, in a short interview, to explain the positioning of their statements. Once the Q sort is complete, by-person factor analysis is undertaken to identify clusters of participants who have completed their Q sorts similarly to reveal a set of shared viewpoints. As the final step, weights will be calculated using a mathematical formula to develop the index, and this index will be tested by applying it to the Living Lab at Kalutara, Sri Lanka.

Data analysis techniques

Data analysis depends on the researcher's empirical thinking and interpretation (Sridarran et al., 2018). Qualitative data collected through semi-structured interviews will be analysed using the content analysis method. Content analysis is a data analysis technique that helps organise qualitative data and achieve the research objectives (Langkos, 2014). Content analysis can be carried out either manually or using computer-aided software. This research will use manual and computer-based software for the data analysis. Further, quantitative data gathered during Q-sorting will be analysed using the factor analysis method. Factor analysis typically produces several statistically possible factor solutions to identify the inter-correlation among the Q-sort results (Millar et al., 2022). Q factor analysis is generally undertaken using specialist, free Q analysis software such as KenQ and PQ-Method.

3. CONCLUSIONS

In this paper, the authors have tried to demonstrate and justify the methodology devised to develop a comparative index to measure community disaster resilience across geographical locations in Sri Lanka. The adopted methodology helps to derive a more accurate index based on the indicators identified through the systematic literature review and expert opinions. Furthermore, this paper presents a rigorous procedure to explore the research problem with the perception of providing valuable insights to improve CDR in Sri Lanka. This research is progressing with the collection of primary data under this methodology.

4. REFERENCES

Aksha, S. K., & Emrich, C. T. (2020). Benchmarking community disaster resilience in Nepal. *International Journal of Environmental Research and Public Health, 17*(6): 1985 https://doi.org/10.3390/ijerph17061985

Almutairi, A., Mourshed, M., & Ameen, R. F. M. (2020). Coastal community resilience frameworks for disaster risk management. *Natural Hazards*, *101*(2), 595–630. https://doi.org/10.1007/s11069-020-03875-3

Amaratunga, N., Haigh, R., & Ingirige, B. (2015). Post-disaster housing reconstruction in Sri Lanka: What methodology? *Sage Open*, *5*(3). https://doi.org/10.1177/2158244015583072

Baxter, P., & Jack, S. (2015). Qualitative case study methodology: Study design and implementation for novice researchers. *The Qualitative Report*, 13(4), 544-559. https://doi.org/10.46743/2160-3715/2008.1573

Beccari, B. (2020). When do local governments reduce risk? Knowledge gaps and a research agenda. *Australian Journal of Emergency Management*, *35*(3), 20-24.

Boumezrag, M. (2023). Qualitative methods and mixed methods. *In Translational Interventional Radiology*, 233-234. https://doi.org/10.1016/B978-0-12-823026-8.15001-1

Bryman, A. (2004). *Social Research Methods* (2nd ed.). Oxford: Oxford University Press.

Burrell, G., & Morgan, G. (2017). *Sociological paradigms and organisational analysis: Elements of the sociology of corporate life.* Routledge. https://doi.org/10.4324/9781315242804

Cai, H., Lam, N. S. N., Qiang, Y., Zou, L., Correll, R. M., & Mihunov, V. (2018). A synthesis of disaster resilience measurement methods and indices. *International Journal of Disaster Risk Reduction*, *31*, 844–855. https://doi.org/10.1016/j.ijdrr.2018.07.015

Cao, G. (2007). The pattern-matching role of systems thinking in improving research trustworthiness. *Systemic Practice and Action Research*, *20*(6), 441–453. https://doi.org/10.1007/s11213-007-9069-1

Caruana, E. J., Roman, M., Hernández-Sánchez, J., & Solli, P. (2015). Longitudinal studies. *Journal of Thoracic Disease*, *7*(11), E537–E540. https://doi.org/10.3978/j.issn.2072-1439.2015.10.63

Check, J., & Schutt, R. K. (2012). *Research methods in education. In Survey Research* (pp. 159–185). CA: Sage Publications.

Cox, R. S., & Hamlen, M. (2015). Community disaster resilience and the rural resilience index. *American Behavioral Scientist*, *59*(2), 220–237. https://doi.org/10.1177/0002764214550297

Creswell, J. W. (2003). *Research design: Qualitative, quantitative and mixed methods*. Thousand Oaks: SAGE Publications.

Creswell, J. W. (2016). *Research design: Qualitative, quantitative, and mixed methods approaches* (3rd ed.). Thousand Oaks: SAGE Publications.

Cutter, S. L. (2016). The landscape of disaster resilience indicators in the USA. *Natural Hazards*, *80*(2), 741–758. https://doi.org/10.1007/s11069-015-1993-2

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environmental Change, 18*(4), 598–606. https://doi.org/10.1016/j.gloenvcha.2008.07.013

Deria, A., Ghannad, P., & Lee, Y. C. (2020). Evaluating implications of flood vulnerability factors with respect to income levels for building long-term disaster resilience of low-income communities. *International Journal of Disaster Risk Reduction*, *48,* 101608. https://doi.org/10.1016/j.ijdrr.2020.101608

Duncan Millar, J., Mason, H., & Kidd, L. (2022). What is Q methodology? *Evidence-Based Nursing*, *25*(3), 77–78. https://doi.org/10.1136/ebnurs-2022-103568

Dyah, R., Husodo, Z. A., & Suardi, L. (2014). Developing a resilience index towards natural disasters in Indonesia. *International Journal of Disaster Risk Reduction*, *10*, 327–340. https://doi.org/10.1016/j.ijdrr.2014.10.007

Dziopa, F., & Ahern, K. (2009). Three different ways mental health nurses develop quality therapeutic relationships. *Issues in Mental Health Nursing*, *30*(1), 14–22. https://doi.org/10.1080/01612840802500691

Ekanayake, S., Prince, M., Sumathipala, A., Siribaddana, S., & Morgan, C. (2013). "We lost all we had in a second": Coping with grief and loss after a natural disaster. *World Psychiatry*, *12*(1), 69–75. https://doi.org/10.1002/wps.20018

Easterby-Smith, M., Jaspersen, L. J., Thorpe, R., & Valizade, D. (2018). *Management and business research* (7th ed.). SAGE Publications.

Feldmeyer, D., Wilden, D., Jamshed, A., & Birkmann, J. (2020). Regional climate resilience index: A novel multimethod comparative approach for indicator development, empirical validation and implementation. *Ecological Indicators*, *119*, 106861. https://doi.org/10.1016/j.ecolind.2020.106861

Graveline, M. H., & Germain, D. (2022). Disaster risk resilience: Conceptual evolution, key issues, and opportunities. *International Journal of Disaster Risk Science*, *13*(3), 330–341. https://doi.org/10.1007/s13753-022-00419-0

Huggins, T. J., Peace, R., Hill, S. R., Johnston, D. M., & Muñiz, A. C. (2015). Politics of practical and academic knowledge: A Q-method analysis of gauging community disaster resilience. *Journal of Contingencies and Crisis Management*, *23*(4), 246–256. https://doi.org/10.1111/1468-5973.12092

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, *33*(7), 14–26. https://doi.org/10.3102/0013189X033007014

Kagioglou, M., Cooper, R., Aouad, G., & Sexton, M. (2000). Rethinking construction: The generic design and construction process protocol. *Engineering, Construction and Architectural Management, 7*(2), 141–153. https://doi.org/10.1108/eb021139

Koliou, M., van de Lindt, J. W., McAllister, T. P., Ellingwood, B. R., Dillard, M., & Cutler, H. (2020). State of the research in community resilience: progress and challenges. *Sustainable and Resilient Infrastructure*, *5*(3), 131–151. https://doi.org/10.1080/23789689.2017.1418547

Lam, N. S. N., Reams, M., Li, K. N., Li, C., & Mata, L. P. (2016). Measuring Community Resilience to Coastal Hazards along the Northern Gulf of Mexico. *Natural Hazards Review, 17*(1): 04015013 https://doi.org/10.1061/(ASCE)NH.1527-6996.0000193

Langkos, S. (2014). *Research methodology*. Athens as an international tourism destination: An empirical investigation to the city's imagery and the role of local DMO's*: University of Derby*. https://doi.org/10.13140/2.1.3023.1369

Lee, D. W. (2020). An exploratory assessment of infrastructure resilience to disasters. *International Journal of Disaster Resilience in the Built Environment*, *11*(4), 519–533. https://doi.org/10.1108/IJDRBE-02-2019-0006

Lewthwaite, S., & Nind, M. (2016). Teaching research methods in the social sciences: Expert perspectives on pedagogy and practice. *British Journal of Educational Studies, 64*(4), 413–430. https://doi.org/10.1080/00071005.2016.1197882

Malalgoda, C., Amaratunga, D., & Haigh, R. (2013). Creating a disaster resilient built environment in urban cities: The role of local governments in Sri Lanka. *International Journal of Disaster Resilience in the Built Environment*, *4*(1), 72–94. https://doi.org/10.1108/17595901311299017

Mavhura, E., & Manyena, B. (2018). Spatial quantification of community resilience in contexts where quantitative data are scarce: The case of Muzarabani district in Zimbabwe. *Geo-geography and Environment*, *5*(2), e00065. https://doi.org/10.1002/geo2.65

Melnikovas, A. (2018). Towards an explicit research methodology: Adapting research onion model for futures studies. *Journal of Futures Studies*, *23*(2), 29–44. https://doi.org/10.6531/JFS.201812_23(2).0003

Mendis, A.P.K.D., Disaratna, V., Thayaparan, M. and Kaluarachchi, Y., 2022. Policy-level consideration on marginalised communities in the post-disaster context: A desk study. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (eds). *Proceedings of the 10th World Construction Symposium* (pp. 668-681), 24-26 June 2022, Sri Lanka.

Mendis, A.P.K.D., Thayaparan, M. and Kaluarachchi, Y., 2023. Inclusion of marginalised communities during post-disaster context in Sri Lanka: what methodology?. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ramachandra, T. and Ranadewa, K.A.T.O. (eds). *Proceedings of the 11th World Construction Symposium* (pp. 582-594), 21-22 July 2023, Sri Lanka.

Minc, S. D., Chandanabhumma, P. P., Sedney, C. L., Haggerty, T. S., Davidov, D. M., & Pollini, R. A. (2022). Mixed methods research: A primer for the vascular surgeon. *Seminars in Vascular Surgery*, *35*(4), 447–455. https://doi.org/10.1053/j.semvascsurg.2022.09.003

Mostafavi, A., & Ganapati, N. E. (2021). Toward convergence disaster research: Building integrative theories using simulation. *Risk Analysis*, *41*(7), 1078–1086. https://doi.org/10.1111/risa.13303

Mukherjee, N., Zabala, A., Huge, J., Nyumba, T. O., Adem Esmail, B., & Sutherland, W. J. (2018). Comparison of techniques for eliciting views and judgements in decision-making. *Methods in Ecology and Evolution*, *9*(1), 54–63. https://doi.org/10.1111/2041-210X.12940

Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology*, *41*(1–2), 127–150. https://doi.org/10.1007/s10464-007-9156-6

Odiase, O., Wilkinson, S., & Neef, A. (2020). Urbanisation and disaster risk: the resilience of the Nigerian community in Auckland to natural hazards. *Environmental Hazards*, *19*(1), 90–106.

Parsons, M., Glavac, S., Hastings, P., Marshall, G., McGregor, J., McNeill, J., Morley, P., Reeve, I., & Stayner, R. (2016). Top-down assessment of disaster resilience: A conceptual framework using coping and adaptive capacities. *International Journal of Disaster Risk Reduction*, *19*, 1–11. https://doi.org/10.1016/j.ijdrr.2016.07.005

Ponto, J. (2015). Understanding and evaluating survey research. *Journal of the Advanced Practitioner in Oncology*, *6*(2), 168–171. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4601897/pdf/jadp-06-168.pdf

Qasim, S., Qasim, M., Shrestha, R. P., Khan, A. N., Tun, K., & Ashraf, M. (2016). Community resilience to flood hazards in Khyber Pukhthunkhwa province of Pakistan. *International Journal of Disaster Risk Reduction, 18*, 100–106. https://doi.org/10.1016/j.ijdrr.2016.03.009

Raadgever, G. T., Mostert, E., & Van De Giesen, N. C. (2008). Identification of stakeholder perspectives on future flood management in the Rhine basin using Q methodology. *Hydrology and Earth System Sciences*, *12*(4), 1097–1109. https://doi.org/10.5194/hess-12-1097-2008

Randall, W. S., Gravier, M. J., & Prybutok, V. R. (2011). Connection, trust, and commitment: Dimensions of co-creation? *Journal of Strategic Marketing*, *19*(1), 3–24. https://doi.org/10.1080/0965254X.2010.537760

Rodriquez, C., Mendes, J. M., & Romao, X. (2022). Identifying the importance of disaster resilience dimensions across different countries using the Delphi method. *Sustainability*, *14*(15), 9162. https://doi.org/10.3390/su14159162

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.).PearsonEducation.

Scherzer, S., Lujala, P., & Rød, J. K. (2019). A community resilience index for Norway: An adaptation of the baseline resilience indicators for communities (BRIC). *International Journal of Disaster Risk Reduction*, *36*, 101107. https://doi.org/10.1016/j.ijdrr.2019.101107

Setia, M. S. (2016). Methodology series module 3: Cross-sectional studies. *Indian Journal of Dermatology*, *61*(3), 261–264. https://doi.org/10.4103/0019-5154.182410

Simmons, N. (2017). Case study research. *The International Encyclopedia of Communication Research Methods*, 1–5. https://doi.org/10.1002/9781118901731.iecrm0020

Singh-peterson, L., Salmon, P., Goode, N., & Gallina, J. (2014). Translation and evaluation of the baseline resilience indicators for communities on the Sunshine Coast , Queensland Australia. *International Journal of Disaster Risk Reduction*, *10*, 116–126. https://doi.org/10.1016/j.ijdrr.2014.07.004

Soiferman, L. K. (2010). *Compare and contrast inductive and deductive research approaches.* https://files.eric.ed.gov/fulltext/ED542066.pdf

Sridarran, P., Keraminiyage, K., & Amaratunga, D. (2018). Enablers and barriers of adapting post-disaster resettlements. *Procedia Engineering*, *212*(2017), 125–132. https://doi.org/10.1016/j.proeng.2018.01.017

Tanvir, H., Haque, W., & Kabir, H. (2022). Resilience to natural disasters: A case study on southwestern region of coastal Bangladesh. *International Journal of Disaster Risk Management*, *4*(2), 91–105. https://doi.org/10.18485/ijdrm.2022.4.2.6

Tariq, H., Pathirage, C., & Fernando, T. (2021a). Measuring community disaster resilience at local levels: An adaptable resilience framework. *International Journal of Disaster Risk Reduction*, *62*: 102358.

Tariq, H., Pathirage, C., & Fernando, T. (2021b). Measuring community disaster resilience using Q-methods: a physical resilience perspective. *Built Environment Project and Asset Management*, *11*(4), 722–737.

Tariq, H., Pathirage, C., Fernando, T., Sulaiman, N., Nazir, U., Latib, S., & Masram, H. (2022). Measuring environmental resilience using Q-methods: A Malaysian perspective. *Sustainability*, *14*(22), 14749. https://doi.org/10.3390/su142214749

Tellis, W. (1997). Application of a case study methodology. *The Qualitative Report*, *3*(3), 1–19. https://doi.org/10.46743/2160-3715/1997.2015

Ventresca, M. J., & Mohr, J. W. (2017). *Archival research methods. In The Blackwell Companion to Organizations* (Issue January 2002, pp. 805–828). https://doi.org/10.1002/9781405164061.ch35

Yin, R. K. (2009). *Case study research: Design and methods* (4th ed.). SAGE Publications.

Zabala, A. (2014). Q method : A package to explore human perspectives using Q-methodology. *R Journal*, *6*(2), *163-173*. https://doi.org/10.32614/RJ-2014-032

Zabala, A., & Pascual, U. (2016). Bootstrapping Q methodology to improve the understanding of human perspectives. *Plos One*, *11*(2), e0148087. https://doi.org/10.1371/journal.pone.0148087

Amararathne, M.R.O.V. and Bandara, K.P.S.P.K., 2024. Assessment of effective waste recycling practices to minimise construction and demolition waste in Sri Lankan construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 240-250. DOI: https://doi.org/10.31705/WCS.2024.19. Available from: https://ciobwcs.com/papers/

ASSESSMENT OF EFFECTIVE WASTE RECYCLING PRACTICES TO MINIMISE CONSTRUCTION AND DEMOLITION WASTE IN SRI LANKAN CONSTRUCTION INDUSTRY

M.R.O.V. Amararathne[1] and K.P.S.P.K. Bandara[2]

ABSTRACT

The construction industry, a vital sector driving global development, simultaneously contributes significantly to waste generation. This research delves into the assessment of effective waste recycling practices to minimise Construction and Demolition (C&D) waste in the Sri Lankan Construction Industry. The study aims to evaluate the most applicability waste recycling practices, identify implementation barriers, and provide recommendations for overcoming these barriers. A comprehensive literature review highlights the global significance of the construction industry and its substantial contribution to waste production. Effective waste management is crucial for cost, quality, time, and environmental impact. It advocates for scientific consultation to determine appropriate waste management practices, considering extended producer responsibility, Waste-to-Energy, material recovery facilities, source separation and landfill options. C&D waste production is linked to ecological consequences, necessitating sustainable waste management practices. Recycling C&D waste emerges as a viable mitigation strategy, offering benefits such as landslide risk reduction, greenhouse gas emission reduction, and natural resource protection. The research methodology used in this study is mixed-method approach combining quantitative and qualitative methods. Major findings include appropriate waste recycling practices, implementation barriers, and recommendations for overcoming barriers. Waste management policy regulation and enforcement being the most applicable waste recycling practice according to RII analysis. The identified most significant barrier was the absence of rules and enforcement. Recommendations focus on awareness programs, incentivising through the tendering process, education and training, seeking international guidance and technology and government support programs. The study provides valuable insights for policymakers, industry stakeholders, and researchers in advancing waste recycling practices in the Sri Lankan Construction Industry.

Keywords: *Construction and Demolition Waste; Sri Lankan Construction Industry; Waste Management; Waste Recycling Practice.*

---

[1] Undergraduate, Department of Quantity Surveying, General Sir John Kotelawala Defence University, Sri Lanka, oshadaviduranga@gmail.com

[2] Lecturer, Department of Quantity Surveying, General Sir John Kotelawala Defence University, Sri Lanka, bandarakpspk@kdu.ac.lk

1. INTRODUCTION

The construction field exemplifies one of the world's most exciting and complicated industrial developments (Kabirifar et al., 2020). C&D waste refers to the materials produced from construction or demolition activities. Construction sites generate waste from raw materials with monetary value. Excessive waste can lead to financial losses and environmental damage (Wahi et al., 2016). Waste resulting from C&D encompasses a wide range of operations, such as clearing sites, excavating land, constructing buildings and other structures, carrying out demolitions, constructing roads, and renovating existing structures. The problem of C&D waste is currently a big concern in Sri Lankan construction in environmental, economic, and social, which must be addressed immediately in an effective way through waste management practices.

A number of ecological consequences, such as pollution, land depletion, environmental harm, and resource limits, are directly related to the production of C&D waste (Alsheyab, 2021). C&D waste, a significant environmental issue, is not properly managed in Sri Lanka, unlike most developed countries where effective waste management practices are established (Tissera et al., 2022). Stakeholders must implement effective waste management practices to control and prevent financial losses and environmental harm. Proper C&D waste management is critical within construction sector, with studies mostly concentrating on waste reduction and recycling (Lawson, 2020; Napier, 2023). Key objectives of this study encompass applicability of suitable waste recycling practices to Sri Lankan construction industry, barriers to implement to Sri Lankan construction industry and recommendations to overcome the barriers.

2. LITERATURE REVIEW

C&D waste is solid waste generated during constructing, repair, and demolition operations (Lu & Yuan, 2011). Nagapan and Rahman (2011) classify the causes of C&D wastes into six categories i.e., (i) design, (ii) procurement, (iii) material handling, (iv) operation, (v) residual associated, and (vi) others. Waste from C&D may be split into two major categories i.e., (i) inert waste, and (ii) non-inert waste. Large amount is made up of inert material, which is further separated into soft and hard inert materials (Yeheyis et al., 2012). Rocks and shattered concrete are examples of hard inert materials, whereas soil, earth, silt, and slurry are examples of soft inert materials. Conversely, non-inert materials include metal, plastic, wood, and packaging waste (Yuan & Shen, 2011). Due to rising C&D waste amounts, a lack of waste dumps, and the extended time negative consequences of eliminated waste from construction and demolition, the environment, and society, sustainable management of construction and demolition debris is becoming increasingly important to protect public wellness and natural ecosystems (Kourmpanis et al., 2008). Yeheyis et al. (2012) stated that C&D waste has a more clearly recognised source and a rather well-established composition. This clear classification helps in the effective management and disposal of waste from C&D (Karunasena & Rathnayake, 2014).

The management of construction and demolition waste has become a major problem across the world, particularly in developing nations where construction is a major economic activity (Yuan, 2017). There are several ways to consider in managing waste from C&D. It involves more than simply disposing of the waste but rather implementing a comprehensive plan to make the most of construction resources. The objective is to reduce waste production and discover efficient methods to use whatever waste that is generated. Although it is a widely used practice, dumping construction waste in landfill sites is not the only approach to waste management (Dania et al., 2016). The goal of managing waste from C&D is to decrease waste and properly dispose of it, which both serve to prevent negative environmental consequences and favourably influence social, economic, and economic performance (Karunasena & Rathnayake, 2014).

In Sri Lanka, waste management related to C&D must be improved, per a survey report by Nifal (2023). A study of the literature conducted by Nifal (2023) looks at the situation of C&D waste management in Sri Lanka now and highlights both potential and obstacles for better waste recycling practices. The authors contend that improved waste management policy regulation and enforcement are necessary, as well as greater public knowledge and education regarding the advantages of waste recycling ("Central Environmental Authority", 2000). According to Senarathna and Perera (2021) nonetheless, the Sri Lankan Construction Industry may find use for several C&D waste recycling practices. Extended Producer Responsibility (EPR), Waste-to-Energy (WTE), Material Recovery Facilities (MRFs), and source separation are some of these approaches (Senarathna & Perera, 2021). Robots are said to be more accurate and precise than humans at placing materials such as bricks or concrete. As a result, there may be reduced material waste from mistakes or improper positioning. By precisely measuring and cutting materials, as well as by minimising waste from overuse or cutting errors, robots can maximise material utilisation (Thompson et al., 2016). These methods are the new applicable waste recycling practices to the Sri Lankan construction industry.

Overall, the Sri Lankan construction industry might profit from certain waste recycling practises, even though there is still space for improvement in the country's C&D waste management system. The industry can lessen the quantity of waste dumped in landfills and help local economies by Vijayaragunathan and Renukappa (2017). In this study, finding most suitable applicable recycling practices according to above mentioned practices is the primary objective.

Jain (2012) outlines barriers to implement waste recycling practices that prevent waste management from being widely used. One of the barriers is the dearth of skilled workers in the sector. It has also been demonstrated that worker errors that necessitate reworking, the absence of skilled labour and subcontractors, and, particularly, worker errors that led to this, have the greatest influence on the development of C&D waste (Wahi et al., 2016). Furthermore, when duties are performed, a lack of basic competency will lead to waste that is both non-physical and physical (Jain, 2012).

Lack of knowledge is another barrier when implementing waste recycling practices. It may be challenging to adopt waste recycling practices since many stakeholders in the building sector are unaware of their advantages. Another insight is absence of rules and enforcement which is Sri Lankan waste recycling practices are not subject to any rules or enforcement mechanisms, which makes it challenging to ensure that waste management policies are being followed (Senarathna & Perera, 2021).

According to Senarathna and Perera (2021), lack of infrastructure can be challenging to gather, sort, and process waste materials due to a lack of infrastructure for waste recycling. The lack of incentives makes it challenging to justify the costs involved with waste recycling practices, as there aren't enough motivations for stakeholders in the building sector to adopt them. According to Wijewansha et al. (2021), Sri Lanka still has a long way to go before meeting the requirements of international sustainable construction. Due to the industry's lack of flexibility, the circular economy idea is still seen as unique even though it has been applied in Sri Lanka by several scholars (Bekchanov et al., 2018; Liyanage et al., 2019).

3. RESEARCH METHODOLOGY

The main aim of this research is to identify applicability waste recycling practices to the Sri Lankan Construction Industry, barriers to implement and suggestions to overcome the barriers. The Mixed Methods Research (MMR) approach used in this study's research involves combining quantitative and qualitative data collection and analysis methods.

Primary data is information gathered by researchers directly from primary sources, such as conducting semi-structured interviews and questionnaire surveys. The questionnaire was developed using the information gathered during the literature review. A Likert type scale with a maximum of five points was used in the questionnaires. This scale was used to determine how much the respondents agreed or disagreed with the factors that were presented to them.

Table 1 presents the population and sampling methods employed in data collection using questionnaire survey. Various professional disciplines were included, selected randomly from construction projects in Sri Lanka, to generate findings through content analysis.

Table 1: Population and sampling using questionnaire survey

Profession	Frequency	Sample
Project Manager	14	
Civil Engineer	23	5
Quantity Surveyor	10	
Technical Officer	3	

Table 2 presents the frequency and proportion of respondent's years of experience in the construction industry are illustrated in the following statistical format,

Table 2: Results of respondents - experience in industry

Years of Experience	Frequency	Sample
Less than 1 year	2	
1-5 years	20	50
5-10 years	18	
More than 10 years	10	

Table 3 provides a breakdown of interviewee frequencies categorised by profession.

Table 3: Breakdown of interviewee frequencies

Profession	Frequency	Sample
Project Manager	3	
Civil Engineer	3	10
Quantity Surveyor	4	

Table 4 provides a breakdown of the interviewee's years of experience in the industry.

Table 4: Breakdown of interviewee's experience

Years of Experience	Frequency	Sample
10 – 20 years	6	
More than 20 years	4	10

The Relative Importance Index (RII) method was used to analyse and present the data from the questionnaire survey in graphs, tables, and figures. Interview data was recorded, and content analysis was used to examine it.

4. ANALYSIS

For the questionnaire survey, 60 questionnaires were distributed, and 50 were returned with valid responses with a response rate of 83.3%. Out of the responses, 46% was Quantity Surveyors, 28% was Project Managers, 20% was Civil Engineers, and 6% was Technical Officers. Subsequently, ten semi-structured expertise interviews were conducted to identify barriers to implement and suggestions to overcome the identified barriers.

Seven waste recycling practices were identified through a literature survey, and their applicability to the Sri Lankan construction industry was evaluated through a questionnaire survey. The identified practices encompass Extended Producer Responsibility (EPR), Waste-to-Energy (WTE), Material Recovery Facilities (MRFs), waste management policy regulation and enforcement, source separation of waste, creating a model to forecast average waste generation, and utilising robots to measure and cut materials. These identified practices were incorporated into this study and formed the basis for a questionnaire survey to gauge the level of agreement using RII.

Table 5: RII Analysis of waste recycling practices

Practices	Total Weight	Relative Index	Rank
Extended Producer Responsibility (EPR)	190	0.7600	3
Waste-to-Energy (WTE)	172	0.6880	5
Material Recovery Facilities (MRFs)	179	0.7160	4
Waste Management Policy Regulation and Enforcement	213	0.8520	1
Source Separation of Waste	193	0.7720	2
Create a model to forecast average waste generation	171	0.6840	6
Using robots to measure and cut materials	**151**	**0.6040**	7

According to Table 5, waste management policy regulation and enforcement was ranked in the first place which means it is the most suitable waste recycling practice according to identified waste recycling practices in the literature review. Developing countries including Sri Lanka do not have much capacity to implement most initial costing waste recycling practices. The country's current economic problems and lack of financial resources are major contributors to this. Source separation of waste is the second-ranked waste recycling practice according to the above analysis. Source separation of waste practice can be implemented in Sri Lanka practically because there is no high cost. The third most applicable waste management practice is EPR. Implementing EPR practice in the construction industry motivates minimising environmental impact and promotes waste recycling. The fourth-ranked practice is material recovery facilities. In simple terms, this plant specialises in receiving, separating, and preparing recyclable materials for manufacturers to use. This is a popular waste recycling practice in developed countries. However, when implementing this to Sri Lankan construction industry barriers may arise. Because of this reason, this waste recycling practice came up in fourth place in the questionnaire. Waste to Energy is the fifth most suitable waste recycling practice to implement Sri Lankan construction industry. This waste recycling practice is another better solution to minimise waste in the construction industry. This has a high initial cost to implement. The sixth and seventh most suitable waste recycling practices are creating a model to forecast average waste generation and using robots to measure and cut materials. It is not practical to implement in Sri Lanka because of high initial cost and lack of technology. Because of these reasons these practices came up the last option from respondent.

The ten barriers to implementing waste recycling practices were identified through a literature survey, and their most significant barrier to the Sri Lankan construction field was evaluated through a questionnaire survey. These identified barriers were incorporated into this study and formed the basis for a questionnaire survey to gauge the level of agreement using RII.

Table 6: RII analysis of barriers to implementing waste recycling practices

Barriers	Total Weight	Relative Index	Rank
The dearth of Skilled workers in the sector	172	0.6880	10
The absence of subcontractors	180	0.7200	7
Worker errors	173	0.6920	9
Lack of basic competency	179	0.7160	8
Lack of Knowledge	192	0.7680	3
Absence of rules and enforcement	209	0.8360	1
Lack of infrastructure	189	0.7560	5
Lack of incentives	191	0.7640	4
Poor communication and coordination among parties involved	185	0.7400	6
Poor qualities of recycled products and their limited applications	196	0.7840	2

The five most significant barriers identified in the above table will be analysed and discussed. According to Table 6, the absence of rules and enforcement was ranked in the first place which means it is the most significant barrier to implementing waste recycling practices in SL construction field according to the identified barriers listed in the literature survey. There are statutes and regulations in SL regarding trash management and recycling practises, but they are inactive or non-efficiency. Effective implementation of recycling practices in industry requires strict penalties for non-compliance and incentives for adoption. In the absence of such measures, some companies may not prioritise recycling efforts in their waste management practices. The second most significant barrier is the poor quality of recycled products and their limited applications. In the construction industry, stakeholders have not given much attention to the use of recycled products. Many people are sceptical about the quality of recycled products. According to the above-mentioned challenges, the third most important obstacle to adopting waste recycling practises within the construction business is a lack of knowledge. Among the above-mentioned waste recycling practices implementation of robotic technology and the creation of a model to forecast average waste generation are difficult to implement in the Sri Lankan construction industry because of lack of knowledge and technology, lack of high cost, and lack of industry experts in relevant fields. Lack of incentives is the fourth significant barrier identified according to the above table. Construction projects often work within tight budgets and timelines, leading to a short-term focus on project costs. This can hinder the integration of recycling practices into project planning and execution. As economic considerations, construction companies may prioritise economic factors. Without financial incentives, the cost-effectiveness of waste recycling practices may not be immediately apparent. Investing in recycling initiatives may be discouraged by the perceived high initial costs of recycling infrastructure and processes. The fifth most significant barrier is the lack of infrastructure. In lack of infrastructure includes transportation challenges, insufficient collection systems, limited public-private partnerships, and inadequate storage facilities. Insufficient collection systems are a major barrier to lack of infrastructure.

Apart from the above-identified barriers through the literature survey, some barriers were identified through open-ended questions included in the questionnaire survey and from the semi-structured interview. A total of 28 responses out of 50 responses answered open-ended questions regarding barriers. Implementation barriers were identified as lack of cost, behaviour of the people, disagreement of skilled workers, professional to change the styles of their activities, lack of a culture in favour of waste management and economy problem.

Based on the answers provided to the open-ended questions of the questionnaire survey, the highest frequency was obtained which is lack of cost on implementation of waste recycling practices. In the prevailing situation of the construction industry, there is a lack of cost when implementing waste recycling practices. In the above-mentioned waste recycling practices using robots to measure and cut materials, Material Recovery Facilities (MRFs) and waste-to-energy (WTE) practices have high initial costs.

Numerous varied suggestions to overcome the barriers to implement waste recycling practices to industry were derived from the open-ended questions in the questionnaire survey. These recommendations, supported by insights gained from semi-structured interviews, were not only substantiated but also expanded upon. The same set of recommendations was echoed by professionals during the semi-structured interviews, where they provided additional details and perspectives. A comprehensive compilation of the recommendations to overcome implementation barriers, as identified through the questionnaire survey responses, is presented as conducting awareness programs, enforce strong rules and regulations, encourage through the tendering process, provide proper education and training, seek international guidance and technology, identify the root cause and propose alternative methods, integrated regulatory framework, government support programs.

Relying on the answers to the open-ended questions of the questionnaire survey, conducting awareness programs is the most common answer in questionnaire surveys and interviewers. Emphasise the environmental and economic benefits of waste recycling in a manner that resonates with the target audience and organise workshops and seminars to facilitate in-person interaction and engagement. The second suggestion is encouraged through the tendering process. The one interviewer stated that, "*During my time working on the HSBC project, the client asked for a certificate to ensure proper waste disposal from the site. They also requested the associated costs through a variation. However, the client did not approve the cost and mentioned that they did not have any additional funds to spend on this matter. In my opinion, if there are regulations that can be added to the tender, it would be beneficial*". The third suggestion is providing proper education and training on waste recycling practices. Conduct practical training sessions that give participants a real-world understanding of waste recycling processes. This could include on-site demonstrations and interactive exercises. The problem of these types of education and training programs is the language barrier for stakeholders. Ensure that educational materials and training sessions are accessible in multiple languages to cater to the diverse linguistic backgrounds of the construction workforce. International seek guidance and technology is the fourth suggestion. Facilitate the transfer of advanced waste recycling technologies from countries with established practices to the Sri Lankan construction industry and collaborate with technology providers to customise solutions that are suitable for local conditions and requirements are included for. The fifth suggestion is to identify the root cause and propose alternative methods. Conduct a comprehensive analysis to identify the underlying factors contributing to challenges in waste recycling practices.

5. DISCUSSION

The first objective is to identify which identify the extent to which waste recycling practices apply to the Sri Lankan construction industry. Seven waste recycling practices were identified through a literature survey, and their applicability to the Sri Lankan construction industry was evaluated through a questionnaire survey. These identified practices were incorporated into this study and formed the basis for a questionnaire survey to gauge the level of agreement. The study used the RII method to rank the identified practices. In second objective identified barriers were incorporated into this study and formed the basis for a questionnaire survey to gauge the level of agreement. In third objective fulfil from open-ended questions in the survey questionnaire and the interview that was semi-structured were used to identify recommendations.

The discussion section underscores the research's key findings on waste recycling practices in the Sri Lankan construction industry. Notably, the survey results indicate a pronounced preference for waste management policy regulation and enforcement, emphasising the industry's recognition of the importance of regulatory frameworks. Additionally, the integration of innovative technologies such as robotic assistance for material measurement reflects a forward-looking stance towards sustainable construction practices. However, identified barriers, with the absence of rules and enforcement at the forefront, present significant challenges. The study's recommendations, encompassing awareness programs, education initiatives, government support, and international collaboration, collectively aim to address these barriers, fostering a culture of environmental responsibility and propelling the industry towards effective waste recycling practices for a more sustainable future.

6. CONCLUSIONS

In conclusion, this study has provided valuable insights into the assessment of effective waste recycling practices to minimise construction and demolition waste in the Sri Lankan construction industry. The identification of key waste recycling practices, such as EPR, WTE, MRFs, and others, has been crucial in understanding the applicability of these practices in the local context. The study's major finding indicates that waste management policy regulation and enforcement emerged as the most suitable practice, emphasising the importance of regulatory frameworks in promoting effective waste recycling.

However, the study also uncovered significant barriers hindering the implementation of waste recycling practices in the Sri Lankan construction industry. The absence of rules and enforcement was identified as the most substantial barrier, highlighting the need for regulatory strengthening and enforcement mechanisms. In response to these findings, the study proposes a set of actionable recommendations, including enforce strong rules and regulations, awareness programs, encouragement through the tendering process, education and training initiatives, seeking international guidance and technology, and the development of an integrated regulatory framework with government support programs. These recommendations serve as a roadmap for overcoming the identified barriers and fostering a more sustainable and environmentally conscious construction industry in Sri Lanka.

While this study contributes significantly to the understanding of waste recycling practices in the Sri Lankan construction sector, it is essential to acknowledge its limitations, particularly its focus on building construction and exclusion of labour and plant waste. To advance the field, future research should explore technological advancements in construction and demolition waste recycling, conducting feasibility studies for implementation in the Sri Lankan context. This will provide a comprehensive understanding of emerging technologies and their potential integration into the industry, ensuring a more holistic approach to waste management in construction practices.

7. LIMITATIONS

The study focuses on present waste management practices in the construction sector, with a particular emphasis on waste recycling practices. This research is confined to building construction in Sri Lanka. This research emphasises waste from construction and demolition on the construction site, ignoring labour and plant waste.

8. REFERENCES

Alsheyab, M. A. T. (2021). Recycling of construction and demolition waste and its impact on climate change and sustainable development. *International Journal of Environmental Science and Technology*, *19*(3), 2129–2138. Retrieved from https://doi.org/10.1007/s13762-021-03217-1

Bekchanov, M., Evia, P., Hasan, M. M., Adhikari, N., & Gondhalekar, D. (2018). Institutional framework and financial arrangements for supporting the adoption of resource recovery reuse technologies in South Asia. *SSRN Electronic Journal: Zef Working Paper 176*. Retrieved from https://ssrn.com/abstract=3293535

Lawson, E. (2020, March). Best practices for construction waste management. *Recycling Magazine*. *Spring 2020*. Retrieved from https://www.recycling-magazine.com/2020/03/30/best-practices-for-construction-waste-manageme

Dania, A. A., Kehinde, J. O., & Bala, K. (2007,). A study of construction material waste management practices by construction firms in Nigeria. In C. O. Egbu & M.K.L. Tong (Eds.), *Proceedings of the 3rd Scottish conference for postgraduate researchers of the built and natural environment, Glasgow*, 20-22 November 2007 (pp. 121-129). Glasgow Caledonian University, Scotland, UK

Jain, M. (2012). Economic Aspects of Construction Waste Materials in terms of cost savings: A case of Indian construction Industry. *International Journal of Scientific and Research Publications*, *2*(10), 1-7.

Kabirifar, K., Mojtahedi, M., Wang, C., & Tam, V. W. Y. (2020). Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *Journal of Cleaner Production*, *263*, 121265.

Ranjan, H., Karunasena, G., & Rathnayake, U. (2014). Construction and demolition waste management gaps in construction industry. In J. Munasinghe (Eds.) *Proceedings of the 7th FARU international research symposium*, December (Vol. 6, No. 1, pp. 97-104).

Kourmpanis, B., Papadopoulos, A., Moustakas, K., Stylianou, M., Haralambous, K. J., & Loizidou, M. (2008). Preliminary study for the management of construction and demolition waste. *Waste Management and Research*, *26*(3), 267–275. Retrieved from https://doi.org/10.1177/0734242X07083344

Liyanage, K. L. A. K. T., Waidyasekara, K. G. A. S., Mallawaarachchi, B. H., & Pandithawatta, T. P. W. S. I. (2019, June). Origins of Construction and Demolition Waste Generation in the Sri Lankan Construction Industry. In *Proceedings of the world conference on waste management* (Vol. 1, No. 1, pp. 1-8). https://doi.org/10.17501/26510251.2019.1101

Lu, W., & Yuan, H. (2011). A framework for understanding waste management studies in construction. *Waste Management*, *31*(6), 1252–1260. Retrieved from https://doi.org/10.1016/j.wasman.2011.01.018

Nagapan, S., Rahman, I. A., & Asmi, A. (2011). A review of construction waste cause factors. In *Asian ~SE3`conference on real estate: sustainable growth managing challenges* (ACRE) (pp. 967-987).

Napier, T. (2016, October 17). *Construction Waste Management*. Whole Building Design Guide. Retrieved July 16, 2024, from https://www.wbdg.org/resources/construction-waste-management

Nifal, M., Indrakumar, P., Haleeth, M., Harees, A. & Sempotsothy, S. (2023). Construction and demolition waste management in Sri Lanka. https://www.researchgate.net/publication/374782655

Senarathna, D. R., & Perera, B. L. S. H. (2021). In Y.G. Sandanayake, S. Gunatilake, and K.G.A.S. Waidyasekara, (Eds). Proceedings of the 9th World Construction Symposium, 9-10 July 2021, Sri Lanka. (pp. 413-421) https://doi.org/10.31705/WCS.2021.36

Central Environmental Authority. (2000). *Technical Guidelines on Solid Waste Management in Sri Lanka*. Central Environmental Authority. https://www.cea.lk/web/images/pdf/Guidlines-on-solid-waste-management.pdf

Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., & Martina, F. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals - Manufacturing Technology*, *65*(2), 737–760. https://doi.org/10.1016/j.cirp.2016.05.004

Tissera, W.D.A.C., Dahanayake, R. and Edirisinghe, V., 2022. The applicability of regulations for the disposal of construction and demolition waste in Sri Lanka. In Y.G. Sandanayake, S. Gunatilake, and K.G.A.S. Waidyasekara, (Eds). *Proceedings of the 10th world construction symposium, 24-26 june 2022, Sri Lanka*. (pp. 821-832). https://doi.org/10.31705/WCS.2022.66.

Vijayaragunathan, S., & Renukappa, S. (2017). Sustainable practices in Sri Lankan construction industry. In *8th international conference on structural engineering and construction management 2017, University of Peradeniya, Sri Lanka*.

Wahi, N., Joseph, C., Tawie, R., & Ikau, R. (2016). Critical Review on Construction Waste Control Practices: Legislative and Waste Management Perspective. *Procedia - Social and Behavioral Sciences*, *224*, 276–283. Retrieved from https://doi.org/10.1016/j.sbspro.2016.05.460

Wijewansha, A. S., Tennakoon, G. A., Waidyasekara, K. G. A. S., & Ekanayake, B. J. (2021). Implementation of circular economy principles during pre-construction stage: the case of Sri Lanka. *Built Environment Project and Asset Management*, *11*(4), 750–766. Retrieved from https://doi.org/10.1108/BEPAM-04-2020-0072

Yeheyis, M., Hewage, K., Alam, S., Eskicioglu, C., & Sadiq, R. (2012). An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. *Clean Technologies and Environmental Policy, 15,* 81–91.

Yuan, H. (2017). Barriers and countermeasures for managing construction and demolition waste: A case of Shenzhen in China. *Journal of Cleaner Production*, *157*, 84–93. Retrieved from https://doi.org/10.1016/j.jclepro.2017.04.137

Yuan, H., & Shen, L. (2011). Trend of the research on construction and demolition waste management. *Waste Management*, *31*(4), 670–679. Retrieved from https://doi.org/10.1016/j.wasman.2010.10.030

Ranathunga, J.D.R., Hadiwattege, C. and Thennakoon, T.M.P.N., 2024. Augmenting performance of prefabricated MEP modular systems via BIM integration. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 251-264. DOI: https://doi.org/10.31705/WCS.2024.20. Available from: https://ciobwcs.com/papers/

AUGMENTING PERFORMANCE OF PREFABRICATED MEP MODULAR SYSTEMS VIA BIM INTEGRATION

J.D.R. Ranathunga[1], C. Hadiwattege[2] and T.M.P.N. Thennakoon[3]

ABSTRACT

Within the Architecture, Engineering, and Construction (AEC) sectors, prefabrication is an emerging technology which concerned with the construction production process and serves as a manufacturing platform to improve productivity and safety management. Whether they are located off-site or on-site, the coordination and fabrication of Mechanical, Electrical, and Plumbing (MEP) systems have consistently presented challenges. MEP designers lack the necessary expertise to create detailed models for prefabrication, but designers proposed enhancing collaboration with fabricators to develop installation-level BIM models for design coordination, construction planning, on-site delivery planning, clash detection, and fabrication planning in Modular MEP construction. Therefore, this study aims to investigate the integration of BIM in enhancing the performance for time, cost, and quality aspects of prefabricated MEP modular systems in buildings. Accordingly, a qualitative research strategy was chosen to achieve the aim, data were collected through twelve (12) semi-structured expert interviews. Experts were selected through purposive sampling followed by snowball sampling. The data analysis was conducted through manual content analysis. Findings revealed how efficiently BIM addresses the time, cost, and quality of prefabricated MEP modular systems. Finally, as a contribution to knowledge, the study revealed the importance of BIM and how it enhances the efficiency and effectiveness of the prefabricated MEP modular system.

Keywords: *Building Information Modelling (BIM); MEP Modular System; Prefabrication.*

1. INTRODUCTION

According to Baek et al. (2023), prefabrication technology involves off-site manufacturing in a controlled environment, which enhances productivity and safety by streamlining construction. This method reduces on-site material processing and waste, leading to shorter construction periods and improved efficiency. The implementation of MEP prefabrication has already taken place in some countries, such as the United

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, dileesharoshane946@gmail.com.
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, chandanieh@uom.lk.
[3] Temporary Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, piyumithnisansala146@gmail.com.

Kingdom (UK), the United States of America (USA), Australia, and China (Lavikka et al., 2021). Examples of prefabricated MEP modular solutions include technical rooms; prefabricated pipeline manifolds; corridor elements such as ductwork, pipework, and electrical cables in MEP racks; and bathroom pods that incorporate pipework, electrical cables, and ductwork. Throughout history, the coordination and fabrication of Mechanical, Electrical, and Plumbing (MEP) systems, whether situated on-site or within a factory as components of modular construction projects, have consistently posed difficulties (Korman & Lu, 2011).

MEP designers lack the necessary expertise to create detailed models for prefabrication, but one designer proposed enhancing collaboration with fabricators to develop installation-level BIM models and address this limitation (Pan et al., 2008). Specifically, BIM is acknowledged as a remedy for achieving seamless information integration between construction and manufacturing sites (Mostafa et al., 2020). BIM is ideal for design coordination, construction planning, on-site delivery planning, clash detection, and fabrication planning in Modular construction. Design, Construction, and Operation and maintenance are the three main aspects that are considered during MEP coordination (Korman & Lu, 2011).

A study by Glassman (2011), investigated whether the modelling of BIM at different levels of detail (LOD) had an impact on MEP design coordination. BIM permits the visualisation of virtual replicas of the structure or the creation of 3D models that aid in identifying issues and making improved decisions regarding materials, leading to a significant reduction in construction expenses. BIM facilitates the utilisation of prefabricated or modular construction methods, streamlining workflows to a greater extent compared to conventional construction approaches. According to Khanzode et al. (2008), the Prefabrication of plumbing and low-pressure ductwork enabled a general contractor to enhance construction site safety and efficiency, while the implementation of BIM improved MEP work productivity by 5 to 25% through streamlined work coordination

Despite the potential benefits of both BIM and prefabrication, there often exists a lack of synergy between these technologies and construction methods. In the context of construction projects involving prefabricated MEP modular systems, the full potential of BIM remains underutilised, leading to inefficiencies in project delivery and resource utilisation. The lack of seamless integration and effective implementation of BIM with prefabrication techniques hinders the industry's ability to achieve enhanced efficiency, cost-effectiveness, and sustainability in construction processes. Therefore, there is a gap in knowledge for “What are the project success factors (SF) that impact on time, cost and quality when integrating BIM for prefabricated MEP modular systems?” To achieve the knowledge, gap this study aims to examine how BIM can be leveraged to optimise prefabricated MEP modular systems, thus enhancing construction project outcomes and overall industry performance. This aim is supported by three objectives: identifying the BIM-enabled features for prefabricated MEP modular systems to enhance time, cost, and quality performance; determining the success factors of construction projects through a literature review; and evaluating how BIM integration affects the time, cost, and quality efficiency of prefabricated MEP modular systems through data collection.

2. LITERATURE REVIEW

2.1 DIGITAL TRANSFORMATION: THE INTEGRATION OF BIM AND PREFABRICATION WITH A FOCUS ON MEP SYSTEMS

In the 21st century, BIM has brought a revolutionary concept to the AEC industry, allowing construction virtually before it is built on the construction field (Raut & Valunjkar, 2017). As Hurtado (2017) explained, BIM provides a more intuitive and efficient three-dimensional (3D) visual building design. As stated by Hsu and Wu (2019), the BIM approach prioritises the whole lifetime of a building, generating connections across all building aspects through information integration. This integration leads to producing a comprehensive information model for prefabricated components, successfully addressing the construction industry's widespread challenges of inefficiency and obsolete practices (Wang, 2021). BIM has significantly improved the design process of prefabricated building components.

As stated by Haggart (2020), MEP systems constitute 25%-40% of the overall project expenditure, with the exact proportion depending on the building's nature and purpose. MEP prefabrication delivers a viable substitute for conventional approaches. By producing and assessing MEP components and modules offsite, plumbers, HVAC engineers, insulators, and electricians can collaborate simultaneously during installations. This streamlined approach accelerates trade coordination and installation timelines (John, 2018). The author further explained prefabrication MEP offers numerous advantages, i.e., enhanced safety, quality, scheduling, and cost-effectiveness. Additionally, it contributes to reducing environmental impact, dust and noise pollution, and construction debris. Quality control is improved due to controlled factory settings, optimised work sequence, and improved logistical coordination.

Advances in pre-design review technologies such as BIM, as mentioned by Baek et al. (2023), have enhanced the environment in which MEP coordination may be undertaken in advance. incorporating BIM data into working drawings and the prefabrication process has opened the road for a more efficient and streamlined building system installation procedure (Glassman, 2020).

2.2 INFLUENCE OF BIM-ENABLED PREFABRICATED MEP MODULAR SYSTEMS PROJECT PERFORMANCE

Integrating BIM into prefabricated MEP modular systems is a game changer. This is expected to substantially streamline the traditionally complex construction processes and set new benchmarks in cost optimisation, time management, and overall project quality. From the feasibility and design phase of construction to the end of construction and post-operational phase includes time, cost, and quality management which are the main body of construction project management. Despite the rapid development of technology and digitalisation in this era, construction projects still face many fundamental issues, such as project delay, cost overrun, and low efficiency and performance (Linderoth, 2010).

2.2.1 Time Efficiency: Reduction in Project Timelines

BIM is also adopted for MEP module design to minimise the redesign of services, snagging, and defects (Dogan & Polat, 2016). BIM integrates different disciplines through effective communication, analyses the project systems for constructability, and estimates the cost and time of projects at any time using quantity take-offs (Iqbal et al., 2020). As a result, prefabricated MEP modules lead to reduced project duration, improved construction quality, improved site safety, and lower labour demand and costs (Korman & Lu, 2011). Time can be measured in terms of construction time, speed of construction, and time overrun (Chan & Chan, 2004).

2.2.2 Cost Efficiency: Cost Savings and Budget Management

The clients may not receive the reduced costs of MEP prefabrication in the form of a cheaper MEP subsystem. Still, the costs of the whole project will be reduced through quicker on-site installation, lower logistics costs, less material waste, and fewer worker injuries (Lavikka et al., 2021). The measure of cost can be in the forms of unit cost, and percentage of net variation over final cost (cost overrun) (Silva et al., 2016). Heravi and Ilbeigi (2012), introduce the cost performance index (CPI) which is a measure of the cost efficiency of the project.

2.2.3 Quality Improvement: Enhanced System Performance

Some studies estimated that 10% of rework on the construction site is related to quality defects (Safa et al., 2015; Akinci et al., 2006), and the rework rate during the installation of the MEP system approaches 20% (Khanzode et al., 2008). Chan and Chan (2004) stress that quality, technical performance, and functionality are closely related and are considered important to the owner, designer, and contractor. Heravi and Ilbeigi (2012) use product quality and process quality separately. Elattar (2009) also refers to quality and technical performance as two distinctive criteria. However, the quality of a project was commonly defined as meeting technical specifications (Khosravi & Afshari, 2011).

2.3 CONSTRUCTION PROJECT SUCCESS FACTORS

According to Han et al. (2011) define success factors as those factors that influence, constitute as well as determine the success of a project. According to De Wit (1988) and Cooke-Davies (2002), success factors are those inputs to the management system that lead directly or indirectly to the success of the project. According to De Wit (1988), measuring success is complex because it depends on the stakeholders' points of view, and it is time dependent. The concept of success in a construction project, according to some researchers, corresponds to efficiency and effectiveness measures (Atkinson, 1999; Belout, 1998; Brudney & England, 1982; Crawford & Bryce, 2003; De Wit, 1988; Pinto & Slevin, 1988). Table 1 presents the factors with the most influence on a construction project's success as indicated by some previous studies.

Table 1: Project success factors

Code	Success Factors	References
SF01	Risk Management - Weather conditions	[11]
SF02	Risk Management - Government regulatory changes	[11], [15]
SF03	Risk Management - Site conditions	[27]
SF04	Project team competency - Skilled and experienced professionals	[1], [4], [7], [8], [9], [10], [20]
SF05	Stakeholder communication - Transparency	[5], [6]
SF06	Resource Management - Labour, material, and equipment	[3], [26]
SF07	Technological Integration - Construction related Software integration	[12], [13], [14], [25]

Code	Success Factors	References
SF08	Adaptability and Flexibility - Ability for modifications and customisation	[18], [20], [22]
SF09	Environmental management - Construction-related noise, dust, and other environmental impacts	[18], [19]
SF10	Logistics and Transportation planning - Logistics challenges	[20], [21], [23]
SF11	Maintenance consideration - Future maintenance and ease of access to components	[24]
SF12	Clash detection and resolution - Identify and resolve issues during the design phase	[16], [17]
SF13	Public Amenities and infrastructure improvements - Improvement of local public amenities and infrastructure	[2]
SF14	Inflation and currency risks - Risks associated with inflation and currency fluctuations	[11]
SF15	Local economic instability - Risk associated with interest rate changes, labour market changes, supply chain disruptions, and market demand fluctuations	[11]

[1] Belassi & Tukel (1996); [2] Sadeh et al. (2000); [3] Patanakul & Milosevic (2009); [4] Ihuah et al. (2014); [5] Osei-Kyei & Chan (2017); [6] Molwus et al. (2017); [7] Banihashemi et al. (2017); [8] Tripathi & Jha (2018a); [9] Tripathi & Jha (2018b); [10] Maghsoodi & Khalilzadeh (2018); [11] Gudienė et al. (2014); [12] Lam et al. (2010); [13] Hwang et al. (2017); [14] Sang & Yao (2019); [15] Unegbu et al. (2020); [16] Jiang (2021); [17] Korman & Lu (2011); [18] Gunawardena et al. (2014); [19] Schnell (2022); [20] Wuni & Shen (2020a); [21] O'Connor et al. (2014); [22] Choi et al. (2016); [23] Li et al. (2016); [24] Wuni & Shen (2020b); [25] Belay et al. (2021); [26] Esmaeili et al. (2014); [27] Salminen (2005)

Efficiency measures deal with time, budget, and specifications, whereas effectiveness measures refer to the achievement of project objectives, user satisfaction, and the use of the project (Takim & Adnan, 2009). Therefore, construction project success could be viewed as the degree of achievement of efficiency (short-term perspective) and effectiveness (long-term perspective) objectives of execution of a project (Baccarini, 1999). The construction sector still faces challenges due to time delays, excessive costs, poor quality and safety. It is important to understand a project's performance and the relationship between results and initial objectives to overcome these challenges. As a result, there is a continuing need to identify and determine the factors that influence the success of construction projects (El Touny et al., 2021).

3. RESEARCH METHODOLOGY

According to Creswell (2016), the research approach is a collection of plans and procedures for conducting research, ranging from general hypotheses to specific techniques for gathering, analysing, and interpreting data. Given the specific characteristics of the data required for this study, a qualitative approach was chosen instead of opting for quantitative or mixed approaches. Since this study required the experiences of experts and specialists and observation-based solutions to investigate how BIM enhances the efficiency of prefabricated MEP modular systems, the study followed a qualitative approach. Accordingly, in line with the qualitative research approach adopted, expert interviews with open-ended, and -semi-ended questions were deemed appropriate for gathering data in this study. The questions become more structured in successive phases to verify previous consensus, examine assumptions, and finalise decision-making frameworks (Birdsall, 2004). The semi-structured interview guide is chosen because it offers a clear set of instructions to interviewers, ensuring reliability and comparability in acquiring qualitative data (Salminen, 2005). Further, this method offers significant advantages, including the ability to gather more information, overcome resistance through interviewer skills, greater flexibility, and facilitated observation. Therefore, this data collection method can successfully achieve the third research objective by evaluating which project success factors are achieved through BIM features and how these factors contribute to improvements in cost, time, or quality efficiency of the project.

Therefore, through the expert's interviews success factors (SF) that impact on time, cost, and quality `of a construction project and the factors impacting the efficiency of prefabricated MEP modular systems when integrated with BIM were identified. Accordingly, success factors (SF) that impact on Time, Cost, and Quality were determined. Therefore, this paper addressed the research problem "What are the project success factors (SF) that impact time, cost, and quality when integrating BIM for prefabricated MEP modular systems".

Twelve semi-structured interviews which were saturated after the ninth interview, were conducted with industry professionals from diverse countries who were keenly interested in the subject matter and demonstrated curiosity about the BIM concept. These interviews were designed to produce insights aligned with the literature findings. Comprehensive interview guidelines were prepared to ensure the acquisition of relevant information. Details of the interviewees were summarised in Table 2.

Table 2: Profiles of interviewees

Code	Designation	Experiences with the construction industry (Including BIM, MEP, and prefabricated modular systems)	Country
E1	Senior Quantity Surveyor	16	Sri Lanka
E2	MEP & Infrastructure Construction Manager	25	Egypt
E3	Senior BIM Manager	17	USA
E4	Senior MEP Quantity Surveyor	10	Sri Lanka
E5	Project Manager- Modular Building Construction	21	UAE
E6	Commercial Manager	26	UAE
E7	Senior MEP Quantity Surveyor	13	Saudi Arabia
E8	MEP Prefabricator	11	UAE
E9	Senior Quantity Surveyor | Contracts Administrator	12	Qatar
E10	BIM Coordinator	18	Saudi Arabia
E11	MEP Industrialised Construction Consultant	15	Australia
E12	General Manager- Manufacturing	23	UAE

4. RESEARCH FINDINGS AND DISCUSSION

Based on the generic factors which are identified related to construction project success factors were analysed according to the opinions of the experts. Time, cost, and quality influence of that success factors when implementing BIM for prefabricated MEP projects. The collected data were analysed through manual content analysis. Consequently, findings through the conducted expert interviews have been discussed as follows.

4.1 TIME EFFICIENCY: HOW DOES BIM INTEGRATION AFFECT THE TIME EFFICIENCY OF PREFABRICATED MEP MODULAR SYSTEMS?

All the experts identified that integrating BIM within the prefabricated MEP modular systems will extensively enhance efficiency in terms of time. According to the experts analyse, most of them identified SFs have a positive impact on the time factor whereas a minority of them remained neutral considering BIM integration within the prefabricated MEP modular systems. Considering SF 03 and SF 04, all the experts agreed that integrating BIM will be time efficient. For the SF 03, most of the experts pointed out that off-site prefabrication reduces workload on-site, decreasing time spent at the construction site. Moreover, E3 and E4 insisted that BIM considerably reduces the time spent on-site to install prefabricate MEP modular systems. Considering SF 04, E7 highlighted that with BIM, the project team can collaborate more effectively, allowing MEP designers, engineers, and prefabrication specialists to work closely together.

All the experts except E1 agree that BIM can save time when integrating into Prefabricated MEP modular systems when considering SF 05. E1 conveyed that "*it only sometimes saves time, as expected. For example, coordinating stakeholders can lead to misunderstandings, causing delays in software installation".* When considering SF06 most of the experts expressed that project managers optimise resource allocation by incorporating prefabricated MEP modules into the BIM model, ensuring that labour, materials, and equipment are available at the right time and in the right quantities. This eliminates delays caused by resource shortages or overstocking, increasing time efficiency throughout construction. Considering SF 07, E4 remained neutral regarding time efficiency and E1, E7, E8, and E12 experts emphasised that digitally modelling the assembly process allows construction teams to determine the most effective order for positioning MEP modular components on-site. This optimises the construction schedule with minimal disruptions and interruptions, saving time.

Regarding the SF 11 E2, E4, E5, E7, E8, E10, and E12 experts elaborated that Engineers, designers, and fabricators can guarantee that components within prefabricated MEP systems are structured; thus, that maintenance tasks are easily accessible by incorporating future maintenance considerations into the design process utilising BIM. E2 explained the impact on time from SF 12, *"When considering prefabricated MEP modular systems, precision is key. BIM allows us to precisely coordinate these MEP modules, ensuring a flawless fit when assembled on-site. This precision saves time modifying or adjusting components due to clashes, providing faster installation".* E6 identified that SF15 positively impacts time integrating BIM whereas other experts remained neutral, elaborating that local economic instability and associated risks like interest rate changes, supply chain disruptions, labour market fluctuations, and market demand fluctuations can significantly affect construction project timelines. This helps optimise project efficiency and stability, assuring timely delivery despite economic challenges.

Discussion

MEP modular systems with BIM for improving time efficiency reveal a consensus among experts on several success factors. Experts unanimously agree that BIM integration significantly reduces on-site workload, enhances coordination, and minimises risks, thus reducing construction duration. This is attributed to real-time data exchange and seamless collaboration among stakeholders. Additionally, BIM facilitates effective communication, value engineering, regulatory compliance, resource planning, and clash detection during the design phase, all of which contribute to streamlined workflows and accelerated project timelines.

4.2 COST INFLUENCE: WHAT ARE THE COST IMPLICATIONS OF IMPLEMENTING BIM IN PREFABRICATED MEP MODULAR SYSTEMS? HOW DOES IT AFFECT SAVINGS OR OVERRUN?

The SF03, E1, and E5 mentioned that prefabrication helps mitigate on-site construction risks, such as weather delays, accidents, and material wastage, which can incur unexpected costs. E3 and E10 identified that SF 04 positively impacts cost by elaborating that a skilled professional can use BIM to facilitate the prefabrication process of MEP modules. These experts can automatically generate fabrication drawings and details directly from the model, enabling the manufacturers to understand the MEP module design and specification. Moreover, E3 clarified that SF 05 positively impacts utilising BIM and that the project team can view the same digital platform simultaneously.

For SF 06, most of the experts identified that merging BIM with prefabricated MEP modular systems positively explained their insights, while E7 stayed unbiased. E1, E3, E4, E6, and E8 clarified that prefabricated MEP modules are assembled off-site in controlled environments by skilled labourers, reducing the need for on-site labour and associated costs. Furthermore, minimises the cost with BIM, allowing for detailed planning and scheduling of labour tasks. When considering SF08 regarding the cost characteristic. E2, E7, E10, E11, and E12 Highlighted that incorporating MEP modular systems into the BIM model allows for precise coordination between off-site fabrication and on-site installation activities. As an outcome, the chance of errors and discrepancies is minimised, leading to fewer costly modifications during fabrication.

Most of the respondents insisted that integrating BIM reduces the overall transportation costs related to the project. Further, E5 specified that it reduces the need for overtime or rush deliveries, reducing labour costs and saving the project's overall cost. All experts agreed that while E1 stayed unbiased, SF11 saves costs when utilising BIM within prefabricated MEP modular systems. E12 explained that owners can make more informed decisions about system design, material selection, and maintenance strategies by modelling alternative maintenance scenarios and analysing the financial implications throughout the building's lifecycle. This proactive strategy minimises maintenance expenses while increasing system reliability and performance. Considering the SF12, all the experts highlighted that by addressing clashes early with BIM, these costly rework scenarios are avoided.

Discussion

The incorporation of BIM with prefabricated MEP modular systems is crucial for optimising cost-effectiveness in construction projects. Experts agreed that harnessing BIM incorporates several positive impacts. Automatically generating fabrication drawings and details (prefabrication model), accessibility to the project team for the same digital platform simultaneously, reducing site labour requirement due to BIM cooperated off-site work and minimising errors, and discrepancies by leading to fewer costly modifications during fabrication are the main positive impacts that extracted from experts' opinion. Additionally harnessing BIM for prefabricated MEP construction is a proactive strategy that minimises maintenance expenses while increasing system reliability and performance.

4.3 QUALITY ENHANCEMENT: IN WHAT WAYS DOES BIM CONTRIBUTE TO ENHANCING THE QUALITY OF PREFABRICATED MEP MODULAR SYSTEMS

Most of the experts identified SF 04 enhances quality when integrating BIM within the prefabricated MEP modular systems. E2 emphasised the importance of training a BIM-competent team to continuously improve and elevate quality standards. Likewise, E3, E4, E6, and E12 supported streamlined collaboration and error reduction during the fabrication and installation stages as key aspects of augmenting quality levels. For the SF 07, all the experts excluding E1 and E4 have recognised BIM enhances the Quality when integrating with the prefabricated MEP modular systems. E5, E9, and E11 explained that BIM can harmoniously integrate with modern construction techniques, such as off-site prefabrication and modular construction.

Considering SF 05, only E1, E4, and E7 remained neutral while other experts stressed that BIM integration influence positively quality in prefabricated MEP modular systems. E2, E3, and E9 stated that in organisations with a transparent culture, there is a greater emphasis on open communication and cooperation among stakeholders participating in BIM-integrated projects. For SF 08, E4 and E9 highlighted that BIM software supports parametric models, in which components are specified by their parameters and connections to other elements in the model. This parametric modelling technique allows for more freedom in design adjustments and customisations. Engineers update factors inside the BIM model, such as size, materials, or connection types, to adapt to changes without requiring extensive redesign work. Regarding SF 13, E4 and E8 explained that enhanced public amenities usually include updated building codes and regulations. Thus, incorporating BIM with local regulatory conditions ensures that prefabricated MEP systems are developed and installed in adherence with these standards, improving safety and efficiency.

Only three experts (E2, E4, and E9) expressed that incorporating BIM into prefabricated MEP modular systems positively impacted SF 03. E4 and E9 emphasised that by considering site conditions such as transportation restrictions and assembly requirements, manufacturers can reduce production workflows and ensure that the modular systems are fabricated to the highest quality standards, including implementing quality control measures to detect and rectify defects or variations before the modules are delivered to the construction site. Three experts (E2, E8, and E10) described their opinions on SF 09. E8 and E10 noted that by utilising BIM, construction teams can simulate the assembly of prefabricated MEP modules and determine the optimal sequence to minimise noise and dust generation, enhancing the quality of overall site environmental management.

Discussion

The integration of Building Information Modeling (BIM) into prefabricated modular systems has been identified as a significant factor in enhancing quality. Experts emphasise the importance of training a BIM-competent team, streamlined collaboration, and error reduction during fabrication and installation stages. BIM can harmoniously integrate with modern construction techniques, such as off-site prefabrication and modular construction. BIM integration positively influences quality in prefabricated MEP modular systems, as it allows for more freedom in design adjustments and customisations. BIM software supports parametric models, allowing for more freedom in design adjustments and customisations. By considering site conditions, manufacturers can reduce production workflows and ensure high-quality systems. BIM also allows construction teams to simulate assembly and minimise noise and dust generation, enhancing overall site environmental management.

5. CONCLUSIONS

The construction sector confronts various challenges tied to project efficiency, coordination, and resource management. One specific issue pertains to the suboptimal utilisation of BIM technology alongside prefabricated MEP modular systems. Despite the potential benefits of both BIM and prefabrication, there often exists a lack of synergy between these technologies and construction methods. This research aims to tackle this issue by examining how BIM can be leveraged to optimise prefabricated MEP modular systems, thus enhancing construction project outcomes and overall industry performance. A qualitative research strategy was chosen to achieve the aim. A multi-faceted approach to comprehensively investigate the potential of BIM in enhancing building performance within prefabricated MEP-integrated modular service systems.

The scope of this study is to identify the advantages of prefabricated MEP modular systems to traditional MEP installation within the context of BIM. Further, this research narrowed to the benefits of prefabricated MEP modular systems in terms of time, cost, and quality. The study contributed knowledge by identifying construction projects' CSFs that impact the BIM-enabled prefabricated MEP modular systems. Further, the study revealed the importance of BIM and how it enhances the efficiency and effectiveness of the prefabricated MEP modular system to achieve the time, cost, and quality efficiency of a project. Future research and exploration can further enhance the understanding, implementation, and optimisation of this integration. Future research should delve into comprehensive lifecycle analyses to understand the long-term implications of BIM-integrated prefabricated MEP systems on maintenance strategies, system performance, and sustainability.

6. REFERENCES

Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., & Park, K. (2006). A formalism for utilization of sensor systems and integrated project models for active construction quality control. *Automation in Construction, 15*(2), 124–138. https://doi.org/10.1016/j.autcon.2005.01.008

Atkinson, R. (1999). Project management: Cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. *International Journal of Project Management, 17*(6), 337–342. https://doi.org/10.1016/S0263-7863(98)00069-6

Baccarini, D. (1999). The logical framework method for defining project success. *Project Management Journal*, *30*(4), 25–32. https://doi.org/10.1177/875697289903000405

Baek, S., Won, J., & Jang, S. (2023). Economic integrated structural framing for bim-based prefabricated mechanical, electrical, and plumbing racks. *Applied Sciences, 13*(6), 3677. https://doi.org/10.3390/app13063677

Banihashemi, S., Hosseini, M. R., Golizadeh, H., & Sankaran, S. (2017). Critical success factors (CSFs) for integration of sustainability into construction project management practices in developing countries. *International Journal of Project Management*, *35*(6), 1103–1119. https://doi.org/10.1016/j.ijproman.2017.01.014

Belassi, W., & Tukel, O. I. (1996). A new framework for determining critical success/failure factors in projects. *International Journal of Project Management*, *14*(3), 141–151. https://doi.org/10.1016/0263-7863(95)00064-X

Belay, S., Goedert, J., Woldesenbet, A., & Rokooei, S. (2021). A hybrid Delphi-AHP based analysis of construction project-specific success factors in emerging markets: The case of Ethiopia. *Cogent Engineering, 8*(1). https://doi.org/10.1080/23311916.2021.1891701

Belout, A. (1998). Effects of human resource management on project effectiveness and success: Toward a new conceptual framework. *International Journal of Project Management*, *16*(1), 21-26. https://doi.org/10.1016/S0263-7863(97)00011-2

Birdsall, I. A. (2004). *It seemed like a good idea at the time: The forces affecting implementation of strategies for an information technology project in the Department of Défense* [Doctoral dissertation]. Virginia Polytechnic Institute and State University. https://www.proquest.com/openview/1a0eb701c7f2a5d504af7deb8488c2c3/1?pq-origsite=gscholar&cbl=18750&diss=y

Brudney, J. L., & England, R. E. (1982). Analyzing citizen evaluations of municipal services: A dimensional approach. *Urban Affairs Review*, *17*(3), 359–369. https://doi.org/10.1177/004208168201700306

Chan, A. P. C., & Chan, A. P. L. (2004). Key performance indicators for measuring construction success. *Benchmarking: An International Journal*, *11*(2), 203–221. https://doi.org/10.1108/14635770410532624

Choi, J. O., O'Connor, J. T., & Kim, T. W. (2016). Recipes for cost and schedule successes in industrial modular projects: Qualitative comparative analysis. *Journal of Construction Engineering and Management*, *142*(10). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001171

Cooke-Davies, T. (2002). The "real" success factors on projects. *International Journal of Project Management*, *20*(3), 185–190. https://doi.org/10.1016/S0263-7863(01)00067-9

Crawford, P., & Bryce, P. (2003). Project monitoring and evaluation: a method for enhancing the efficiency and effectiveness of aid project implementation. *International Journal of Project Management*, *21*(5), 363–373. https://doi.org/10.1016/S0263-7863(02)00060-1

Creswell, J. W. (2016). Revisiting mixed methods and advancing scientific practices. In S. N. Hesse-Biber & R. B. Johnson (Eds.), *The oxford handbook of multimethod and mixed methods research inquiry* (pp. 57–71). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199933624.013.39

De Wit, A. (1988). Measurement of project success. *International Journal of Project Management*, *6*(3), 164–170. https://doi.org/10.1016/0263-7863(88)90043-9

Dogan, E., & Polat, H. (2016). A research for efficiency of using prefabrication building components in building information modelling (BIM) process. *International Multilingual Academic Journal (IMAJ*), *3*(4). https://www.researchgate.net/publication/312626933_A_research_for_efficiency_of_using_prefabrication_building_components_in_Building_Information_Modeling_BIM_process

El Touny, A. S., Ibrahim, A. H., & Mohamed, H. H. (2021). An integrated sustainable construction project's critical success factors (ISCSFs). *Sustainability*, *13*(15), 8629. https://doi.org/10.3390/su13158629

Elattar, S. M. S. (2009). Towards developing an improved methodology for evaluating performance and achieving success in construction projects. *Scientific Research and Essay*, *4*(6), 549–554. https://academicjournals.org/journal/SRE/article-full-text-pdf/AD162CA17067/

Esmaeili, B., Pellicer, E., & Molenaar, K. R. (2016). Critical success factors for construction projects. In: J. L. A. Muñoz, J. L. Y. Blanco, S. F. Capuz-Rizo (Eds.), *Project Management and Engineering Research, 2014* (pp. 3–14). Springer, Cham. https://doi.org/10.1007/978-3-319-26459-2_1

Glassman, J. (2020). *Utilizing building information modeling in the mechanical/ plumbing prefabrication process* [Master's thesis]. University of Wisconsin-Stout. https://minds.wisconsin.edu/handle/1793/81364

Gudienė, N., Banaitis, A., Podvezko, V., & Banaitienė, N. (2014). Identification and evaluation of the critical success factors for construction projects in Lithuania: AHP approach. *Journal of Civil Engineering and Management*, *20*(3), 350–359. https://doi.org/10.3846/13923730.2014.914082

Gunawardena, T., Mendis, P., Ngo, T., Aye, L., & Alfano, J. (2014, December). Sustainable prefabricated modular buildings. *5th International conference on sustainable built environment, Kandy, Sri Lanka* (pp. 13-15). https://doi.org/10.13140/2.1.4847.3920

Haggart B. (2020, July 16). MEP interfaces – complexities of MEP design. HKA. https://www.hka.com/mep-interfaces/

Han, W. S., Yusof, A. M., Ismail, S., & Aun, N. C. (2011). Reviewing the notions of construction project success. *International Journal of Business and Management*, *7*(1), 90-101. https://doi.org/10.5539/ijbm.v7n1p90

Heravi, G., & Ilbeigi, M. (2012). Development of a comprehensive model for construction project success evaluation by contractors. *Engineering Construction & Architectural Management*, *19*(5), 526–542. https://doi.org/10.1108/09699981211259603

Hsu, H. C., & Wu, I. C. (2019). Employing simulated annealing algorithms to automatically resolve MEP clashes in building information modeling models. *2019 Proceedings of the 36th international symposium on automation and robotics in construction, Banff, Canada.* (pp. 788-795). IAARC Publications. https://doi.org/10.22260/ISARC2019/0106

Hurtado, K. A. (2017, January 9). *BIM comes of age: The new ConsensusDocs BIM addendum (2015) for life-cycle building information modeling.* ConsensusDocs. https://www.consensusdocs.org/bim-comes-of-age-the-new-consensusdocs-bim-addendum-2015-for-lifecycle-building-information-modeling/

Hwang, B. G., Zhu, L., & Ming, J. T. T. (2017). Factors affecting productivity in green building construction projects: The case of Singapore. *Journal of Management in Engineering*, *33*(3). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000499

Ihuah, P. W., Kakulu, I. I., & Eaton, D. (2014). A review of critical project management success factors (CPMSF) for sustainable social housing in Nigeria. *International Journal of Sustainable Built Environment*, *3*(1), 62–71. https://doi.org/10.1016/j.ijsbe.2014.08.001

Iqbal, S., Saad, M., Shahid, M. B., & Batool, W. (2020). An overview of the necessities, challenges & outcomes of building information modelling (BIM) framework used in project management. *Journal of Accounting and Finance in Emerging Economies*, *6*(3), 873–883. https://doi.org/10.26710/jafee.v6i3.1422

Jiang, Y. (2021). Intelligent building construction management based on BIM digital twin. *Computational Intelligence and Neuroscience*, *2021*(1). https://doi.org/10.1155/2021/4979249

John, S. (2018, October 31). *MEP prefabrication – Process and benefits manufacturing plant.* XS CAD. https://www.xscad.com/articles/mep-prefabrication-process-and-benefits-manufacturing-plant

Khanzode, A., Fischer, M., & Reed, D. (2008). Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project. *Journal of Information Technology in Construction, 13*, 324-342. https://www.itcon.org/2008/22

Khosravi, S., & Afshari, H. (2011). A success measurement model for construction projects. *International conference on financial management and economics IPEDR*. (pp.186–190). IACSIT Press, Singapore. https://www.researchgate.net/profile/Shahrzad-Khosravi-4/publication/265891053_A_Success_Measurement_Model_for_Construction_Projects/links/58ff2d730f7e9bcf65451d8f/A-Success-Measurement-Model-for-Construction-Projects.pdf

Korman, T. M., & Lu, N. (2011). Innovation and improvements of mechanical electrical and plumbing systems for modular construction using building information modelling. *AEI 2011: Building integrated solutions*. (pp. 448–455). https://doi.org/10.1061/41168(399)52

Lam, P. T. I., Chan, E. H. W., Poon, C. S., Chau, C. K., & Chun, K. P. (2010). Factors affecting the implementation of green specifications in construction. *Journal of Environmental Management*, *91*(3), 654–661. https://doi.org/10.1016/j.jenvman.2009.09.029

Lavikka, R., Chauhan, K., Peltokorpi, A., & Seppänen, O. (2021). Value creation and capture in systemic innovation implementation: Case of mechanical, electrical and plumbing prefabrication in the

Finnish construction sector. *Construction Innovation*, *21*(4), 837–856. https://doi.org/10.1108/CI-05-2020-0070

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X., & Mok, M. K. (2016). Schedule risks in prefabrication housing production in Hong Kong: A social network analysis. *Journal of Cleaner Production*, *134*, 482–494. https://doi.org/10.1016/j.jclepro.2016.02.123

Linderoth, H. C. J. (2010). Understanding adoption and use of BIM as the creation of actor networks. *Automation in Construction*, *19*(1), 66–72. https://doi.org/10.1016/j.autcon.2009.09.003

Maghsoodi, A. I., & Khalilzadeh, M. (2018). Identification and evaluation of construction projects' critical success factors employing fuzzy-TOPSIS approach. *KSCE Journal of Civil Engineering*, *22*(5), 1593–1605. https://doi.org/10.1007/s12205-017-1970-2

Molwus, J. J., Erdogan, B., & Ogunlana, S. (2017). Using structural equation modelling (SEM) to understand the relationships among critical success factors (CSFs) for stakeholder management in construction. *Engineering, Construction and Architectural Management*, *24*(3), 426–450. https://doi.org/10.1108/ECAM-10-2015-0161

Mostafa, S., Kim, K. P., Tam, V. W. Y., & Rahnamayiezekavat, P. (2020). Exploring the status, benefits, barriers and opportunities of using BIM for advancing prefabrication practice. *International Journal of Construction Management*, *20*(2), 146–156. https://doi.org/10.1080/15623599.2018.1484555

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2014). Critical success factors and enablers for optimum and maximum industrial modularization. *Journal of Construction Engineering and Management*, *140*(6). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842

Osei-Kyei, R., & Chan, A. P. C. (2017). Implementing public-private partnership (PPP) policy for public construction projects in Ghana: Critical success factors and policy implications. *International Journal of Construction Management*, *17*(2), 113–123. https://doi.org/10.1080/15623599.2016.1207865

Pan, W., Gibb, A. G. F., & Dainty, A. R. J. (2008). Leading UK housebuilders' utilization of offsite construction methods. *Building Research & Information*, *36*(1), 56–67. https://doi.org/10.1080/09613210701204013

Patanakul, P., & Milosevic, D. (2009). The effectiveness in managing a group of multiple projects: Factors of influence and measurement criteria. *International Journal of Project Management*, *27*(3), 216–233. https://doi.org/10.1016/j.ijproman.2008.03.001

Pinto, J. K., & Slevin, D. P. (1988). Project success: Definitions and measurement techniques. *Project Management Journal*, *19*(1), 67–72. https://www.researchgate.net/publication/242530015_Project_success_Definitions_and_measurement_techniques

Raut, S. P. & Valunjkar, S. S. (2017). Improve the productivity of building construction project using clash detection application in building information modelling. *International Research Journal of Engineering and Technology*, *4*(3),1784-1790. www.irjet.net

Sadeh, A., Dvir, D., & Shenhar, A. (2000). The role of contract type in the success of R&D defense projects under increasing uncertainty. *Project Management Journal*, *31*(3), 14–22. https://doi.org/10.1177/875697280003100303

Safa, M., Shahi, A., Nahangi, M., Haas, C., & Noori, H. (2015). Automating measurement process to improve quality management for piping fabrication. *Structures*, *3*, 71–80. https://doi.org/10.1016/j.istruc.2015.03.003

Salminen, J. (2005). *Measuring performance and determining success factors of construction sites* [Doctoral dissertation]. Helsinki University of Technology. https://aaltodoc.aalto.fi/server/api/core/bitstreams/0229231d-ad86-4d61-80e7-1fea95b67e05/content

Sang, P., & Yao, H. (2019). Exploring critical success factors for green housing projects: An empirical survey of urban areas in China. *Advances in Civil Engineering*, *2019*, 1–13. https://doi.org/10.1155/2019/8746836

Schnell, P. (2022, May 20). Correlation between modular construction and sustainability in the building life cycle. *10th International conference on life cycle management (LCM 2021)*. EDP Sciences. https://doi.org/10.1051/e3sconf/202234904006

Silva, G. A., Warnakulasooriya, B. N. F., & Arachchige, B. (2016, December 8). Criteria for construction project success: A literature review. *13th International conference on business management (ICBM)*. University of Sri Jayewardenepura, Sri Lanka. http://dx.doi.org/10.2139/ssrn.2910305

Takim, R., & Adnan, H. (2009). Analysis of effectiveness measures of construction project success in Malaysia. *Asian Social Science*, *4*(7), 74-91. https://doi.org/10.5539/ass.v4n7p74

Tripathi, K. K., & Jha, K. N. (2018a). Application of fuzzy preference relation for evaluating success factors of construction organisations. *Engineering, Construction and Architectural Management*, *25*(6), 758–779. https://doi.org/10.1108/ECAM-01-2017-0004

Tripathi, K. K., & Jha, K. N. (2018b). Determining success factors for a construction organization: A structural equation modeling approach. *Journal of Management in Engineering*, *34*(1), 04017050. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000569

Unegbu, H. C. O., Yawas, D. S., & Dan-asabe, B. (2020). Structural equation model of the relationship between project performance measures and the critical success factors of construction projects: A case of the Nigerian construction industry. *Jurnal Mekanikal*, *43*. 33-51. https://www.researchgate.net/publication/347569904_Structural_Equation_Model_of_the_Relationship_between_Project_Performance_Measures_and_the_Critical_Success_Factors_of_Construction_Projects_A_Case_of_the_Nigerian_Construction_Industry#fullTextFileContent

Wang, Y. P. (2021). Research on the application of feature modelling of prefabricated building components based on BIM. *IOP conference series: Earth and environmental science*, *676*(1), 1635-1646. https://doi.org/10.1088/1755-1315/676/1/012047

Wuni, I. Y., & Shen, G. Q. (2020a). Critical success factors for management of the early stages of prefabricated prefinished volumetric construction project life cycle. *Engineering, Construction and Architectural Management*, *27*(9), 2315–2333. https://doi.org/10.1108/ECAM-10-2019-0534

Wuni, I. Y., & Shen, G. Q. (2020b). Critical success factors for modular integrated construction projects: A review. *Building Research and Information*, *48*(7), 763–784. https://doi.org/10.1080/09613218.2019.1669009

Opanayake, R.L., Thayaparan, M. and Dasuni, K.A.L., 2024. Barriers for collaboration among built environment higher education: Undergraduate perspectives. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 265-278. DOI: https://doi.org/10.31705/WCS.2024.21. Available from: https://ciobwcs.com/papers/

BARRIERS FOR COLLABORATION AMONG BUILT ENVIRONMENT HIGHER EDUCATION: UNDERGRADUATE PERSPECTIVES

R.L. Opanayake[1], M. Thayaparan[2] and K.A.L. Dasuni[3]

ABSTRACT

The built environment represents a multifaceted sector characterised by its intricate nature, which demands effective stakeholder coordination and cooperation. Construction projects within this domain require the seamless collaboration of diverse disciplines, skills, and services. This collaboration is essential to navigate the fragmented and complex landscape inherent to the built environment. Recognising the evolving skill demands in the construction job market and the dynamic nature of built environment professions, higher education must update its approaches to serve as continuous education centres. Even though there are various studies explored numerous aspects of collaborations, intra-university, and inter-departmental collaborations have not been explored. Therefore, this study examines the undergraduate perspectives on the collaboration among built environment higher education by using one of the state universities in Sri Lanka as the single case study which offers all the built environment degree programmes under one roof. Primary data was collected through a questionnaire survey with 126 undergraduates of seven built environment degree programmes offered by the selected case study. The results of the study revealed that all personal, extracurricular and social collaborations are prominently existing in the context, while the existence of the academic collaboration was comparatively low. Further, the study discusses 20 barriers for collaboration in built environment higher education where rigid timetables and adherence to curriculum guidelines leaves little or no space for flexibility became the key barriers there. This paper elaborates each barrier to see how to overcome the negative consequences while enhancing the enablers to strengthen the built environment higher education collaborations.

Keywords: *Barriers; Built Environment; Collaboration; Higher Education.*

1. INTRODUCTION

Education is a fundamental human right and a prominent driver of personal, and social development (Kirya, 2019) and sustainable development. Thus, Pachauri and Yadav (2014) derived that higher education plays a pivotal role in equipping human capital with

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, raveeshaopanayaka@gmail.com
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk
[3] Temporary Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dasunikodi@gmail.com

the required skills for their respective fields contributing to the development and strength of the nation. Furthermore, the World Economic Forum (2020) highlighted, that higher education and industry are predominantly recognised as intertwined elements of economic success. Consequently, higher education is acknowledged as a significant actor in the transition to a more sustainable future (Murray, 2018). Besides, higher education is focused on the student's development in knowledge, skills and attitudes (Cockerham, 2023). University education curriculums included general education courses with the aim of disciplining and instilling students with the skills, knowledge, and strong mental state (Kleebbua & Siriparp, 2016). Hence, the pedagogical systems, being the primary source of knowledge and competencies, face the risk of developing shortcomings associated with their respective disciplines if not subject to regular transformation and updates (Makhmudov, 2020). However, there is a mismatch between the graduate's discipline specific knowledge and business requirements and soft skills due to the misalignment of curricula and market demands (Fika et al., 2021).

The concept of built environment education is emerged over the past twenty decades (Uttke, 2012), hence is not considered a novel discipline (Thurairajah & Palliyaguru, 2011). Higher education programmes in the built environment discipline play a major role in providing education and training for professionals, addressing the demand for a diverse range of professionals (Amaratunga et al., 2012). Chynoweth (2009) and Million et al. (2018) pointed out that the built environment encompasses various disciplines such as design, construction, management, economics, law, technology, architecture, environment, and arts creating a broad and interdisciplinary platform. Hartenberger et al. (2013) identified a narrow-down list of the major built environment professionals, which includes architects, designers, landscape architects, town planners, construction engineers, construction managers, project managers, specialist consultants (e.g., sustainability assessors, auditors), quantity surveyors, facility managers, construction product engineers, construction process technicians, mechanical engineers, plant, energy and waste technicians.

However, the fragmented nature of the built environment industry (Boton & Forgues, 2017; Riazi et al., 2020; Xue et al., 2005), fosters the professionals' isolation (Abadi, 2005; Nasrun et al., 2014) and failure to form effective project teams (Baiden et al., 2006). Higher education is responsible to train and produce qualified professionals for the successful execution of sustainable projects (Murray & Cotgrave, 2007). According to Wickramasinghe (2018) even after regaining independence in Sri Lanka, the state university education was predominantly influenced by the demands of colonial era public services. Consequently, Edwards et al. (2009) revealed that stereotypes are formed during the educational process as students construct their own professional identity only. Thus, it is clear that the knowledge derived from individual disciplines are insufficient to fully grasp and resolve the inherent challenges within the built environment (Yocom et al., 2012). The findings of Hyams (2008) identified that there are benefits of intra-institutional collaboration, which is important to sustain the quality of university programmes and professional services. Moreover, due to the collaborative endeavour, the built environment also demands a broad understanding of various professionals and works together in a forum of trust and collaboration (Maclaren & Birchall, 2016). The absence of professional collaboration is stemmed from higher education institutions where the major division is made (Thayaparan, 2023). This is mainly because existing higher education systems have a silo, bureaucratic approach (Harris, 2010). Moreover, Lailiyah et al. (2021) revealed the necessity to promote undergraduates' collaboration in higher education. Despite the existence of numerous research studies on university-industry collaboration, the aspect of intra-university, inter-departmental collaboration in Sri Lanka, where the initial division occurred, has not yet been properly addressed. Since the undergraduates are the key players who can facilitate inter-departmental and intra-university collaboration, this paper aims to capture their perspectives to improve collaboration in the built environment higher education.

2. LITERATURE REVIEW

Marlow-Ferguson (2002) identified education is the most prominent factor in the development of human personality. Education serves as an instrument that not only provides academic knowledge but also imparts essentials for improving the overall quality of human life (Kapur, 2023). Besides, the Organisation for Economic Cooperation and Development (OECD, 2023) demonstrated that the achievement of certain formal qualifications is essential for nationally or professionally regulated admission in many professions, in agreement with this Carnevale et al. (2010) also confirmed the higher level of formal education increase the ability to find jobs.

2.1 HIGHER EDUCATION SYSTEM

Aljohani et al. (2022) and Chettri (2022) revealed that the higher education system plays a major role in developing skilled labour into the modern post-industrial economy by ensuring the future prosperity of a nation. Thus, Tilak (2003) stated that higher education is a substantial investment in human capital. Further, Bui et al. (2023) indicated that a shared vision in the higher education sector has garnered substantial attention because it promotes cooperation, consensus, and advancement.

Oza and Japee (2020) demonstrated that one of the main responsibilities of higher education institutions is to equip students with advanced skills useful in the workplace. Therefore, instead of separate learning, integrated learning which combines various subjects provides the development of students' high-level competencies, thinking ability, multiple perspectives, and creativity (Cheng & So, 2020). Further, Annan-Diab and Molinari (2017) revealed that interdisciplinary initiatives include strategic plans, faculty collaboration, interdisciplinary research funding and teaching, and the construction of interdisciplinary buildings on universities which are identified as important aspects in higher education.

2.2 BUILT ENVIRONMENT HIGHER EDUCATION

The built environment is a complex sector, that necessitates stakeholder coordination and cooperation, with construction projects mandating the integration of diverse disciplines, skills, and services (Ebekozien & Aigbavboa, 2022). However, built environment universities' curricula are currently inadequate in preparing graduates for industry careers and therefore, the global competence of the built environment graduates is important (Aigbavboa et al., 2022). While built environment higher education involves various disciplines as mentioned in the introduction, Sampaio (2021) pointed out that the design of construction education should prioritise adaptability to address both current and future concerns. Implementation of changes in educational practices for delivering programmes in higher education across diverse disciplines within the construction industry is a major requirement (Crilly et al., 2020).

Nonetheless, as the construction team collaborates across all the aforementioned disciplines in Section 1, they are collectively responsible for the manufacturing, assembly, and construction of a building, including the logistics and contractual relationships associated with it (Royal Institute of British Architects [RIBA], 2020). Murray and Cotgrave (2007) described that the construction industry relies heavily on higher education to train and produce qualified professionals for the successful execution of sustainable projects. Therefore, it is evident that the built environment higher education should identify the responsibilities of each discipline collaboratively.

2.2.1 Collaboration in Built Environment Higher Education

Laal and Ghodsi (2012) described that collaboration embodies a philosophy of interaction and personal lifestyle wherein individuals take responsibility for their actions, including learning and respecting the abilities and contributions of their peers. Coordination and cooperation are essential aspects of collaborative activities, facilitating the shared creation of something new by aligning efforts and working harmoniously towards a common (Lee & Schottenfeld, 2014). Moreover, in the 21st century learning, to become a successful learner requires the following four skills, known as "4Cs": (1) Creativity, (2) Critical thinking, (3) Communication, and (4) Collaboration (P21, 2007). Thornhill-Miller et al. (2023) emphasised the need for the 4Cs to be central in future-oriented education, requiring institutional support in standards, assessments, curriculum, professional development, and learning environments. In the Oxford Advanced Learner's Dictionary (2015), collaboration refers to "the act of working with another person or group of people to create or produce something" (p. 290). Collaboration is widely acknowledged as advantageous since it enables the pooling of additional resources and expertise from a collective team (Zhao & Zuo, 2018). Moreover, P21 (2007) framework identified the following criteria under collaboration:

- Demonstrate ability to work effectively and respectfully with diverse teams,
- Exercise flexibility and willingness to help make necessary compromises to accomplish a common goal, and
- Assume shared responsibility for collaborative work, and value the individual contributions made by each team member.

According to Ďurišová et al. (2015), the university's external environment consists of university graduates, employers of graduates, and the accreditation commission whereas the internal environment consists of students, lecturers, heads of department, and university administration. Consequently, Kezar (2005) identified two types of collaboration in higher education as internal and external collaboration. Under external collaboration, effective collaboration between universities and industries plays a vital role in enhancing the efficiency of the national innovation system, which should be mainly addressed in developing countries (Nsanzumuhire & Groot, 2020). As an example, for internal collaboration, student collaboration and academic collaboration were identified (Kezar, 2005). Further concerning, Thayaparan (2023) reaffirmed by accenting that the higher education systems should be reformed to encourage inter-departmental and intra-university collaboration to foster collaboration within academia and industry in the long run. Intra-university collaboration identifies the collaboration within the same university whereas inter departmental collaboration occurs between members of different departments (Thompson, 2018). However, the literature review confirms that there are several barriers to formulate collaboration in the built environment higher education, that are discussed next.

2.2.2 Barriers to Formulate Collaboration in Built Environment Higher Education

This section explores the barriers that are hindering collaboration in built environment higher education. According to Gaurav (2020), since the construction sector encompasses a wide range of tasks involved in the planning, execution, and maintenance of buildings, infrastructure, and associated activities, collaborative projects meet various barriers which create difficulty in allocating resources. Table 1 reflects the barriers for collaboration in built environment higher education identified by various authors in their studies.

Table 1: Barriers to formulate collaboration in built environment higher education

Barriers	Sources
Siloed delivery education	(Kezar, 2005), (Maclaren & Birchall, 2016),
Individual resistance	(Newell & Bain, 2020)
Lack of willingness	(Hardy et al., 2021).
Non availability of shared vision and mission	(Holley, 2009),
Adherence to curriculum guidelines leaves little or no space for flexibility	(Arora et al., 2017)
Managing and monitoring project groups as the learning style, interest, and experience of the members vary	(Arora et al., 2017)
Lack of resources	(Wickramasinghe, 2018)
Lack of support from leadership	(Malik and Wickramasinghe, 2015)
Unawareness of collaborative opportunities	(Tazzyman, 2023)
Mismatched priorities of different departments	(Lailiyah et al., 2021)
Rigid timetable	(Arora et al., 2017)
Lack of research to initiate collaboration strategies	(Maclaren & Birchall, 2016)

The barriers identified in Table 1 were further contextualised to Sri Lanka by collecting specific perspectives from the undergraduates of the case study university. The next section presents the built environment higher education in Sri Lanka.

2.3 BUILT ENVIRONMENT HIGHER EDUCATION IN SRI LANKA

In Sri Lanka, the university system consists of four types; state universities under the control of the University Grants Commission (UGC); higher education institutes overseen by the Ministry of Higher Education (MOE); private non-profit education institutes, and private universities (UGC, 2023). In 2019, 98% of students who completed construction-related courses graduated from public institutes, while the remaining 2% graduated from private institutes in Sri Lanka (Tertiary and Vocational Education Commission, 2023).

According to the Sri Lankan Qualifications Framework, which is nationally consistent framework for all higher education qualifications available in Sri Lanka including both public and private higher education institutions, the qualification types are classified as (a) Undergraduate level: Diploma, Higher Diploma, Bachelors, and Bachelors Honours and (b) Postgraduate level: Postgraduate Certificate, Postgraduate Diploma, Masters, and Doctorate (Ministry of Higher Education, 2012).

2.3.1 State University System in Sri Lanka

Since 1947, the Government of Sri Lanka provide free education from grade 1 of government schools to the first-degree level at the state universities (MOE, 2020). Considering the salient features of the general education system, Sri Lanka adopts a 13-year general education system, starting at age five, and school education is divided into four levels as primary, junior secondary, senior secondary, and upper senior secondary or collegiate levels (National Education Commission [NEC], 2022). Further, NEC (2022) included that upper senior secondary education offers four streams including science and mathematics (biological/physical), art, commerce, and technology. G.C.E. Advanced Level (A/L) examination is a measure of students' achievement at the end of the school education at grade 13, and a criterion for selection of students to universities (NEC, 2022). After qualifying from the G.C.E. (A/L) examination, one becomes eligible to enter a state university.

In 1972, a district quota system was implemented for student admission to state universities, which incorporated a relatively low all-island merit component that regulates university admissions while assigning significant weight to district-based considerations (NEC, 2022). Additionally, NEC (2022) mentioned that the 'Z' score standardised marking system was introduced to rank for university admission in 2002. Generally, the one active academic year in a Sri Lankan university consists of two semesters having 15 weeks of study time and 2 to 3 weeks of examination time per semester, and 1 to 2 weeks of semester break (NEC, 2022).

3. RESEARCH METHODOLOGY

The study aims to capture the undergraduate perspectives related to the barriers in improving intra-university, and inter-departmental collaboration within the built environment higher education. The barriers, for the implementation of inter-departmental and intra-university collaboration within the built environment higher education, were further investigated by analysing perceptions captured from undergraduates. Due to the in-depth nature of the analysis required for this research, the data collection is limited to Sri Lankan State University.

This research adopted a single case study to investigate the undergraduate perspectives on the barriers for collaboration. Amongst the state universities of the country, the only university that provides several unique built environment related programmes compared to others has been selected to conduct the study. Single case study strategy can adhere extensively and in-depth into particular situations (Kothari, 2021) of improving inter-departmental and intra-university collaboration in built environment higher education. According to Noor (2008),single case study approach is suitable in the extreme or unique situations where the study documents and analyses a rare situation. As the research aims to identify the barriers in terms of inter-departmental and intra-university collaboration, a university that offers all the built environment related programmes under one roof is essentially suitable for the case study. Accordingly, there is only one state university that offers all the built environment related degree programmes under one roof. Hence that university has been selected as the single case study to undertake this research. Within the single case study selected, questionnaires were circulated to all the undergraduates of built environment education, through the Heads of the departments and student representatives. The questionnaire mainly focused on the undergraduates' opinion towards the types of existing collaborations and the barriers towards the collaborations in the built environment higher education. One hundred twenty-six (126) undergraduates who are enrolled across seven built environment degrees programmes at the case study university responded to the questionnaire and their responses were analysed using the relative importance index (RII).

4. RESULTS AND FINDINGS

4.1 DETAILS OF RESPONDENTS

The data was collected from the undergraduates of the selected degree programmes. Figure 1 represents the distribution of respondents across seven distinct undergraduate programmes (P1 to P7), each with varying student counts. The highest response rate was from the P4 degree programme, while the lowest response rates were from P2 and P7 degree programmes as shown in Figure 1.

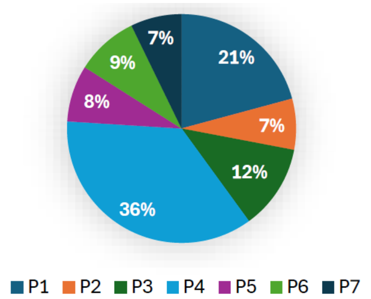


Figure 1: Responded undergraduate percentage based on the degree programme

The highest proportions, 36%, and 21% were received from the degree programmes that have the highest number of undergraduate enrolments from the selected degree programmes (P4 and P1) while the rest were from the degree programmes with the relatively low number of undergraduate enrolments. Therefore, the responses are proportionate to the student numbers enrolled to different degree programmes and reflect the opinions of the undergraduates without any bias to a specific degree programme.

Figure 2 reflects the percentages of the respondents based on their degree level while Figure 3 indicates the percentages of respondents who have completed or not completed their industrial training.

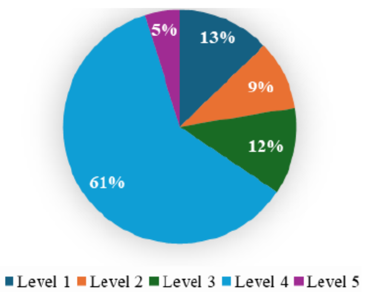


Figure 2: Respondents' undergraduate level

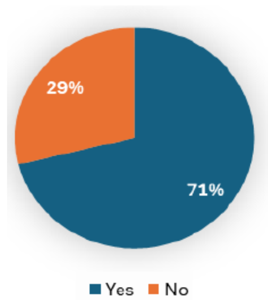


Figure 3: Respondents' status on industrial completion

The figures show that the majority of the respondents are in Level 4 and have completed their industrial training. This indicates that the respondents are in their highest level in the academic programme and have already had an exposure to the industry. This composition of this undergraduates is considered significant, as they may have already realised the significance of collaboration due to their level of knowledge in the profession and exposure in the industry.

4.2 COLLABORATION WITHIN BUILT ENVIRONMENT HIGHER EDUCATION IN SRI LANKA

Respondents were asked to rate the current level of collaboration occurring among the undergraduates from different built environment related department within the university using a Likert scale of 1-5 where 1 indicates extremely low and 5 denotes extremely high. Table 2 summarises the responses from 126 respondents regarding the collaboration within the university.

Table 2: Existing collaborations through undergraduates' perspective

Collaboration	RII	Rank
Personal collaboration	0.610	3
Academic collaboration	0.486	4
Extracurricular collaboration	0.621	1
Social collaboration	0.614	2

According to Table 2, extracurricular collaboration, social collaboration, and personal collaboration have RII values higher than 60%, indicating that their applications are at a significant level. However, academic collaboration received the lowest rating, with a 48.6 % RII value which is not at the significant level. Therefore, this result highlights a perceived deficiency in academic collaboration within the university.

4.3 BARRIERS TO FORMULATE COLLABORATIONS

The low rate of collaboration among built environment higher education in Sri Lanka is attributed to various barriers. The respondents were further asked regarding the barriers to formulate collaborations in built environment higher education in Sri Lanka. Table 3 summarises the opinion of the respondents regarding the barriers to improve collaboration among built environment higher education.

Table 3: Barriers to improve collaboration among built environment higher education in Sri Lanka

Collaboration	RII	Rank
Rigid timetable	0.759	1
Adherence to curriculum guidelines leaves little or no space for flexibility	0.703	2
Mismatched priorities of different departments	0.695	3
Lack of research- to initiate collaboration strategies	0.690	4
Individual resistance who feels that collaboration adds to their workload without sufficient benefits	0.687	5
Lack of support from leadership and authorised people	0.681	6

Collaboration	RII	Rank
Siloed delivery of education	0.676	7
Managing and monitoring project groups as the learning style, interest, and experience of the members vary	0.673	8
Non availability of shared vision and mission	0.667	9
Unawareness of collaborative opportunities	0.663	10
Lack of resources	0.643	11
Not having individual willingness (undergraduate perspective)	0.590	12

There were twelve barriers identified through the literature review for further examination. RII values of those barriers were calculated and ranked them accordingly. According to Table 3, “Rigid timetable” is identified as the most significant barrier, with an RII value of 0.759. Similarly, ranked 2nd, the “Adherence to rigid curriculum guidelines” is highlighted as a significant barrier, which hinder the collaborative initiatives. Both barriers are directly related to the current teaching conditions of the university. Stand-alone timetables of the degree programmes do not facilitate the inter-departmental collaborative work programmes. Especially, the authorities have prepared their curriculum guidelines remotely, without being flexible towards other degree programmes which do not allow them to work collaboratively between the departments. Additionally, “Not having individual willingness” is ranked lowest, with an RII value of 59% from the undergraduate perspective. However, other barriers range from 64.3% to 75.9%, reflecting that these barriers have been given importance by the undergraduates. Therefore, exploring all the identified barriers would be significant to address such barriers to improve collaborations. In addition to the aforementioned barriers identified from the literature review, undergraduates identified additional barriers based on their experience in the Sri Lankan built environment higher education system, as summarised below:

- high workload
- lack of communication
- language barriers
- decline in students' mental well-being
- lack of common hostel facilities
- silo based approach of the departments that offer built environment degree programme
- lack of policies to encourage collaboration between departments
- students individual/personal qualities who do not want to collaborate

Accordingly, these barriers further reflect the rigidity of the existing conditions of the university towards inter-departmental collaborations. Especially, the high workload students experiencing with their tight and independent schedules, goals, cultures, and priorities make them less convenient towards the collaboration. Moreover, the situation is crucial when the governing authorities do not provide either any policy requirements or incentives that are promoting collaborations between the departments. Further, most of the undergraduates tend to be with their own colleagues, specifically the students of the same degree, or same dignity where they lose the opportunity to communicate with the other related degree programme. Similarly, the undergraduates with the same ethnicity tend to be in the same group, which does not improve their language and communication capabilities while it once again hinders the collaborations among undergraduates.

5. DISCUSSION

The absence of professional collaboration within the construction industry stems from higher education institutions (Thayaparan, 2023). The findings of the questionnaire survey provide valuable insights into collaboration within the selected case study. It elaborates concerns regarding academic collaboration of undergraduates as a significant area of deficiency, with limited formal initiatives and departmental silos hindering collaborative efforts. Similarly, in the literature findings, Harris (2010) revealed that the existing higher education systems have a silo, bureaucratic approach.

There are barriers which hinder the effort for collaboration (Roper, 2021). Through the literature survey, the researcher was able to identify twelve barriers to improve collaboration among built environment higher education, which were introduced to respondents to rank during their questionnaire survey. The rigid timetable (Arora et al., 2017) and adherence to curriculum guidelines leave little or no space for flexibility and mismatched priorities of different departments (Lailiyah et al., 2021). Such barriers identified by the literature survey were also agreed by the undergraduates. Overall, all the listed barriers from the literature were validated by the undergraduates with the RII values ranging from 59% to 76%. Further, there were eight additional barriers which are more related to the Sri Lankan higher education system, identified by the respondents. Therefore, the presence of the 20 barriers identified contributes to the lack of collaboration within the built environment higher education.

The barriers to be further analysed to see how such barriers can be minimised to encourage more collaboration. The enablers of collaboration in built environment higher education, can utilise to neutralise and overcome the barriers. Collaborations emphasise the importance of continuous education centres and lifelong learning opportunities within higher education institutions. Additionally, collaboration is depicted as enhancing group work, and facilitating real-world engagement among undergraduates from different disciplines (Wilson, 2021). Assessment is intended to allow students to demonstrate proficiency through often novel forms (Marshall, 2010). Collaboration expands the opportunities for the application of theory (Gammal, 2009), and enhances the group work attending undergraduates who have knowledge in different disciplines together to engage in real-world scenarios (Arora et al., 2017). Accordingly, these enablers would be useful in the way forward to minimise the barriers and to enhance collaborations of the built environment higher education.

6. CONCLUSIONS

The built environment higher education emphasises the need for collaboration, particularly among undergraduates who eventually transition into allied professionals within the industry. Therefore, it is imperative to improve the collaboration within built environment higher education before undergraduates enter the industry as professionals. However, there is lack of collaboration in existing built environment higher education in Sri Lanka. Undergraduates are the key players in the inter-departmental collaborations. Hence, to address the research gap, this study explored the barriers to the collaborations through the perspective of undergraduates from the most prominent Sri Lankan state university that offers all the built environment related degree programmes. The study highlighted that the level of academic collaboration is comparatively low compared to other types of collaborations such as extracurricular, personal or social collaborations. This least importance given to the academic collaborations further emphasise the requirement of conducting this research.

The research explored twenty barriers that could hinder collaboration among the undergraduates across different built environment disciplines. The rigidity of the degree programmes in terms of timetable, workload, curriculum was considered as barriers to collaborations. Additionally, the silo-based approach followed by the departments discourages the collaborations across the departments. The communication and language barriers were also identified by the undergraduates. The barriers need to be minimised or eliminated to foster inter-departmental and intra-university collaborations in the built environment higher education. Developing strategies to address these identified barriers to facilitate inter-departmental and intra-university collaborations for built environment higher education is the way forward of this research.

7. REFERENCES

Abadi, M. (2005). *Issues and challenges in communication within design teams in the construction industry: Investigation into the use of virtual teams and information and communication technologies (ICTs) in the UK construction industry*. University of Manchester. ResearchGate. https://www.researchgate.net/publication/362328826

Aigbavboa, C., Aliu, J., & Ebekozien, A. (2022). Built environment academics for 21st-century world of teaching: stakeholders' perspective. *International Journal of Building Pathology and Adaptation*, *41*(6), 119–138. https://doi.org/10.1108/IJBPA-04-2022-0062

Aljohani, N. R., Aslam, M. A., Khadidos, A. O., & Hassan, S. U. (2022). A methodological framework to predict future market needs for sustainable skills management using AI and Big Data technologies. *Applied Sciences (Switzerland)*, *12*(14). https://doi.org/10.3390/app12146898

Amaratunga, P. D., Thayaparan, M., & Malalgoda, C. (2012). Bellcurve: Built environment lifelong learning challenging university responses to vocational education: Lifelong university for the built environment. *ResearchGate*. https://www.researchgate.net/publication/303676726

Arora, V. P. S., Saxena, P., & Gangwar, N. (2017). Project based learning and research-based learning. In M.S. Manna (Ed.), *Higher education faculty career orientation and advancement* (2nd ed., pp. 76-91). CEGR.

Baiden, B. K., Price, A. D. F., & Dainty, A. R. J. (2006). The extent of team integration within construction projects. *International Journal of Project Management*, *24*(1), 13–23. https://doi.org/10.1016/j.ijproman.2005.05.001

Boton, C., & Forgues, D. (2017). The need for a new systemic approach to study collaboration in the construction industry. *Procedia Engineering*, 196, 1043–1050. https://doi.org/10.1016/j.proeng.2017.08.060

Bui, H. T. M., Shoaib, S., Tran, L. T., Vu, V. H. T., & Baruch, Y. (2023). University's shared vision for research and teaching: an international comparative study. *Higher Education*. 1-24. https://doi.org/10.1007/s10734-023-01105-w

Carnevale, A. P., Smith, N., & Strohl, J. (2010). *Help wanted: Projections of job and education requirements through 2018*. Lumina Foundation. https://eric.ed.gov/?id=ED524310

Cheng, Y. C., & So, W. W. M. (2020). Managing STEM learning: A typology and four models of integration. *International Journal of Educational Management*, *34*(6), 1063–1078. https://doi.org/10.1108/IJEM-01-2020-0035

Chettri, K. B. (2022). An empirical analysis of growth and development of higher education in Sikkim. *Indian Journal of Finance and Economics*, 3(1), 1–17. https://doi.org/10.47509/ijfe.2022.v03i01.01

Chynoweth, P. (2009). The built environment interdisciplinary: A theoretical model for decision makers in research and teaching. *Structural Survey*, *27*(4), 301–310. https://doi.org/10.1108/02630800910985090

Cockerham, D. (2023). Reimagining Higher education pedagogy: Building an active understanding of the research process. In *Educational communications and technology: issues and innovations* (pp. 293–306). Springer. https://doi.org/10.1007/978-3-031-25102-3_24 Coombe, L. (2015). Models of interuniversity collaboration in higher education – How do their features act as barriers and enablers to sustainability? *Tertiary Education and Management*, *21*(4), 328–348. https://doi.org/10.1080/13583883.2015.1104379

Crilly, M., Vemury, C. M., Humphrey, R., Rodriguez, S., Crosbie, T., Johnson, K., Wilson, A., & Heidrich, O. (2020). Common language of sustainability for built environment professionals: The quintuple helix model for higher education. *Energies*, *13*(22), 5860. https://doi.org/10.3390/en13225860 .

Ďurišová, M., Kucharčíková, A., & Tokarčíková, E. (2015). Assessment of higher education teaching outcomes (Quality of higher education). *Procedia - Social and Behavioral Sciences*, *174*, 2497–2502. https://doi.org/10.1016/j.sbspro.2015.01.922

Ebekozien, A., & Aigbavboa, C. (2023). Evaluation of built environment programmes accreditation in the 21st century education system in Nigeria: stakeholders' perspective. *International Journal of Building Pathology and Adaptation*, *41*(6), 102–118. https://doi.org/10.1108/IJBPA-02-2022-0027

Edwards, M., Campkin, B., & Arbaci, S. (2009). Exploring Roles and Relationships in the Production of the Built Environment. Transactions, 6(1), 38–61. https://doi.org/10.11120/tran.2009.06010038

Fika, M., Adeniran, A. A., & Botha, B. (2021). Unemployment of the built environment graduates. *IOP Conference Series: Earth and Environmental Science*, *654*(1). https://doi.org/10.1088/1755-1315/654/1/012005

Gammal, R. S. (2009). *Laying the foundation for a New great problems seminar with an environmental focus*. https://digitalcommons.wpi.edu/iqp-all

Gaurav, J. (2020). *Skill gap analysis of civil engineering sector in India: Skills needed to succeed in job market*. Amazon. https://www.researchgate.net/publication/342131622

Hardy, J. G., Sdepanian, S., Stowell, A. F., Aljohani, A. D., Allen, M. J., Anwar, A., Barton, D., Baum, J. V., Bird, D., Blaney, A., Brewster, L., Cheneler, D., Efremova, O., Entwistle, M., Esfahani, R. N., Firlak, M., Foito, A., Forciniti, L., Geissler, S. A., … Wright, K. L. (2021). Potential for chemistry in multidisciplinary, interdisciplinary, and transdisciplinary teaching activities in higher education. *Journal of Chemical Education*, *98*(4), 1124–1145. https://doi.org/10.1021/acs.jchemed.0c01363

Harris, M. (2010). Interdisciplinary strategy and collaboration: A case study of American research universities. *Journal of Research Administration*, *22*(1).

Hartenberger, U., Lorenz, D., & Lützkendorf, T. (2013). A shared built environment professional identity through education and training. *Building Research and Information*, *41*(1), 60–76. https://doi.org/10.1080/09613218.2013.736202

Holley, K. A. (2009). Interdisciplinary strategies as transformative change in higher education. *Innovative Higher Education*, *34*(5), 331–344. https://doi.org/10.1007/s10755-009-9121-4

Hyams, A. L. (2008). *Intra-institutional collaborations: Academic and continuing intra-institutional collaborations: Academic and continuing education departments on campus*. https://doi.org/10.25669/7o7p-6tam

Kapur, R. (2023). *Understanding the meaning and significance of education*.

Kezar, A. (2005). Redesigning for collaboration within higher education institutions: An exploration into the developmental process. *Research in Higher Education*, *46*(7), 831–860. https://doi.org/10.1007/s11162-004-6227-5

Kirya, M. (2019). Education sector corruption: How to assess it and ways to address it. *U4 Anti-Corruption Resource Centre, 5(U4).* https://flic.kr/p/Dc2EQo

Kleebbua, C., & Siriparp, T. (2016). Effects of education and attitude on essential learning outcomes. *Procedia - Social and Behavioral Sciences*, *217*, 941–949. https://doi.org/10.1016/j.sbspro.2016.02.061

Kothari, C. R. (2021). *Research methodology* (2nd ed.). New Age International (P) Ltd. Publishers.

Laal, M., & Ghodsi, S. M. (2012). Benefits of collaborative learning. *Procedia - Social and Behavioral Sciences*, *31*, 486–490. https://doi.org/10.1016/j.sbspro.2011.12.091

Lailiyah, M., Setiyaningsih, L. A., Wediyantoro, P. L., & Yustisia, K. K. (2021). Assessing an effective collaboration in higher education: A study of students' experiences and challenges on group collaboration. *English Journal of Merdeka: Culture, Language, and Teaching of English*, *6*(2), 97–105. https://doi.org/10.26905/enjourme.v6i2.6971

Lee, Y. S., & Schottenfeld, M. A. (2014). Collaborative knowledge creation in the higher education academic library. *Journal of Learning Spaces*, *3*(1). https://core.ac.uk/download/pdf/234819821.pdf

Maclaren, A., & Birchall, S. (2016). Learning Together: Preparing collaborative professionals for future practice in the built environment industry. *CIBSE Technical Symposium 2016*.

Makhmudov, K. (2020). Innovative cluster of pedagogical education: Common goals and specific interests. *Academic Research in Educational Sciences, 1(2),* 182-187. doi:10.24411/2181-1385-2020-00074.

Malik, K., & Wickramasinghe, V. (2015, December 14). Initiating university-industry collaborations in developing countries. 6th Annual International Conference on Innovation and Entrepreneurship (IE 2016). https://doi.org/10.5176/2251-2039_IE15.5

Marlow-Ferguson, R. (Ed.). (2002). *World education encyclopedia - A survey of educational systems worldwide* (2nd ed.). Detroit, Mich.: Gale Group.

Marshall, S. P. (2010). Re-Imagining specialized STEM Academies: Igniting and nurturing decidedly different minds, by design. *Roeper Review*, 32(1), 48–60. https://doi.org/10.1080/02783190903386884

Ministry of Higher Education. (2012). *Sri Lanka qualifications framework (SLQF)*. http://www.ugc.ac.lk/attachments/1156_Sri_Lanka_Qualifications_Framework.pdf

Ministry of Education (MOE). (2020). *Sri Lanka: General education sector development plan (2020-2025)*. www.moe.gov.lk

Million, A., Parnell, R., & Coelen, T. (2018). Editorial: Policy, practice and research in built environment education. In *Proceedings of the Institution of Civil Engineers: Urban Design and Planning* (Vol. 171, Issue 1, pp. 1–4). ICE Publishing. https://doi.org/10.1680/jurdp.2018.171.1.1

Murray, J. (2018). Student-led action for sustainability in higher education: A literature review. *International Journal of Sustainability in Higher Education*, *19*(6), 1095–1110. https://doi.org/10.1108/IJSHE-09-2017-0164

Murray, P. E., & Cotgrave, A. J. (2007). Sustainability literacy: the future paradigm for construction education? *Structural Survey*, *25*(1), 7–23. https://doi.org/10.1108/02630800710740949

Nasrun, M. N. M., Baluch, N., & Bahauddin, A. Y. (2014). Impact of fragmentation issue in construction industry: An overview. *MATEC Web of Conferences, 15* https://doi.org/10.1051/matecconf/20141501009

National Education Commission (NEC). (2022). *National education policy framework (2020-2030)*. www.nec.gov.lk

Newell, C., & Bain, A. (2020). Academics' perceptions of collaboration in higher education course design. *Higher Education Research and Development*, *39*(4), 748–763, https://doi.org/10.1080/07294360.2019.1690431

Noor, K. M. B. (2008). Case study: A strategic research methodology. American Journal of Applied Sciences, 5(11), 1602–1604. https://doi.org/10.3844/ajassp.2008.1602.1604

Nsanzumuhire, S. U., & Groot, W. (2020). Context perspective on University-Industry Collaboration processes: A systematic review of literature. *Journal of Cleaner Production, 258*(1), 120861. https://doi.org/10.1016/j.jclepro.2020.120861

Organization for Economic Cooperation and Development (OECD). (2023). *Education at a glance 2023: OECD indicators*. OECD Publishing. https://doi.org/10.1787/e13bef63-en

Oxford. (2015). *Advanced Learner's Dictionary* (9th ed.).

Oza, P., & Japee, G. (2020). *History of higher education-From ancient to the modern*. https://doi.org/10.13140/RG.2.2.14254.46406

Pachauri, D., & Yadav, A. (2014). Importance of soft skills in teacher education programme. *International Journal of Educational Research and Technology, 5(1),* 21-25. https://soeagra.com/ijert/ijertmarch2014/5.pdf

P21. (2007). Partnership for 21st century skills - Core content integration. www.P21.orgRiazi, S., Riazi, M., Firdaus Zainuddin, M., Nasrun, M., Nawi, M., Musa, S., & Lee, A. (2020). A critical review of fragmentation issues in the construction industry. *Talent Development & Excellence*, 12(2s), 1510–1521. http://www.iratde.com

Roper, L. (2021). Encouraging interdisciplinary collaboration: A study of enablers and inhibitors across silos in higher education. *Interdisciplinary Journal of Partnership Studies*, *8*(1), 6. https://doi.org/10.24926/ijps.v8i1.3687

Royal Institute of British Architects (RIBA). (2020). *RIBA plan of work 2020 overview*. www.ribaplanofwork.com

Sampaio, A. Z. (2021). Introducing BIM in curricular programmes of civil engineering. *International Journal of Higher Education*, *11*(1), 31-42. https://doi.org/10.5430/ijhe.v11n1p31

Tazzyman, S. (2023). *The benefits of and barriers to collaborative access activity by higher education providers.*www.cfe.org.uk

Tertiary and Vocational Education Commission. (2023). *Skills Gaps Analysis of the Construction Industry Sector*. https://www.tvec.gov.lk/wp-content/uploads/2023/02/Construction_Sector_Skill_Gap_FINAL_Report.pdf

Tilak, J. B. G. (2003). Higher education and development. In *International Handbook of Educational Research in the Asia-Pacific Region* (pp. 809–826). Springer Netherlands. https://doi.org/10.1007/978-94-017-3368-7_56

Thayaparan, M. (2023, August). Focus: Quarterly E - magazine of the institute of quantity surveyors in Sri Lanka. *Achieving Sustainable Construction through Collaboration: Is Fragmentation in the Construction Industry Originates at the Higher Education Institutes*, *17*(01), 31–32.

The future of jobs report 2020. (2020). *World Economic Forum*. https://www3.weforum.org/docs/WEF_Future_of_Jobs_2020.pdf

Thompson, S. (2018). *Differences between inter-departmental & intra-departmental*. https://bizfluent.com/differences-between-interdepartmental--intradepartmental.html

Thornhill-Miller, B., Camarda, A., Mercier, M., Burkhardt, J. M., Morisseau, T., Bourgeois-Bougrine, S., Vinchon, F., El Hayek, S., Augereau-Landais, M., Mourey, F., Feybesse, C., Sundquist, D., & Lubart, T. (2023). Creativity, critical thinking, communication, and collaboration: Assessment, certification, and promotion of 21st century skills for the future of work and education. *Journal of Intelligence*, *11*(3), 54. MDPI. https://doi.org/10.3390/jintelligence11030054

Thurairajah, N., & Palliyaguru, R. (2011). Incorporating disaster management perspective into built environment undergraduate curriculum. *International Conference on Building Resilience*. https://www.researchgate.net/publication/333131988

Uttke, A. (2012). Towards the future design and development of cities with built environment education. *Procedia - Social and Behavioral Sciences*, *45*, 3–13. https://doi.org/10.1016/j.sbspro.2012.06.537

Wickramasinghe, V. (2018). Higher education in state universities in Sri Lanka: Review of higher education since colonial past through international funding for development. *International Journal of Educational Management*, *32*(3), 463–478. https://doi.org/10.1108/IJEM-01-2017-0028

Wilson, K. (2021). Exploring the challenges and enablers of implementing a STEM project-based learning programme in a diverse junior secondary context. *International Journal of Science and Mathematics Education*, *19*(5), 881–897. https://doi.org/10.1007/s10763-020-10103-8

Xue, X., Li, X., Shen, Q., & Wang, Y. (2005). An agent-based framework for supply chain coordination in construction. *Automation in Construction*, *14*(3), 413–430. https://doi.org/10.1016/j.autcon.2004.08.010

Yocom, K., Proksch, G., Born, B., & Tyman, S. K. (2012). The built environments laboratory: An interdisciplinary framework for studio education in the planning and design disciplines. *Journal for Education in the Built Environment*, *7*(2), 8–25. https://doi.org/10.11120/jebe.2012.07020008

Zhao, K., & Zuo, Z. (2018). The more multidisciplinary the better? - The prevalence and interdisciplinarity of research collaborations in multidisciplinary institutions. *Journal of Informetrics*, *12*(3), 736–756. https://doi.org/10.1016/j.joi.2018.06.006

Warakapitiya, G.Y.D., Coorey, S.B.A., Perera, N.G.R. and Giridharan, R., 2024. Behavioural adaptations and housing modification: A case study of a low-income high-rise housing estate in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 279-290. DOI: https://doi.org/10.31705/WCS.2024.22. Available from: https://ciobwcs.com/papers/

BEHAVIOURAL ADAPTATIONS AND HOUSING MODIFICATION: A CASE STUDY OF A LOW-INCOME HIGH-RISE HOUSING ESTATE IN SRI LANKA

G.Y.D. Warakapitiya[1], S.B.A. Coorey[2], N.G.R. Perera[3] and R. Giridharan[4]

ABSTRACT

Rapid urbanisation and population growth have intensified housing challenges in Sri Lanka. In response, the government initiated Urban Regeneration Projects (URPs) to create a slum-free Colombo. These projects involved constructing high-rise housing blocks for relocating low-income settlements and freeing up land for urban development. Unfortunately, several initiatives encountered failures due to inadequate services, limited employment access, substandard living conditions, poor maintenance, and unforeseen social consequences. This research delves into the adaptive behaviours of relocated low-income families in high-rise housing. It examines the challenges they face in daily life and explores the measures they take to overcome these obstacles. The study employs a case study approach, utilising interviews, surveys, and observations within a selected low-income high-rise housing block. Basic housing needs such as sufficient indoor and outdoor space, privacy, social interaction, community living, physical comfort (light & ventilation), safety, and security, are crucial for residents. To meet these needs, inhabitants adapt through behavioural changes, including multifunctional use of space, shared space, family activity organisation, and extending domestic activities into semi-public zones. Privacy emerges as the most critical requirement, often prioritised over social interaction and physical comforts. Residents primarily address these needs through behavioural adjustments rather than extensive modifications, given the challenges posed by mass housing.

Keywords: *Adaptations; Behaviours; High-rise housing; Low-income; Modifications.*

1. INTRODUCTION

Despite some economic stabilisation, Sri Lanka continues to grapple with high levels of poverty and income inequality (World Bank, 2024). The UNDP's 2023 Multidimensional Vulnerability Index highlights persistent socio-economic challenges in various districts, including Colombo, emphasising the need for targeted, evidence-based policy

[1] M.Sc. Student, Department of Architecture, University of Moratuwa, Sri Lanka, warakapitiyagyd.21@uom.lk
[2] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka, scoorey@uom.lk
[3] Professor, Department of Architecture, University of Moratuwa, Sri Lanka, nareinperera@uom.lk
[4] Reader, School of Architecture, Design and Planning, University of Kent, Canterbury, g.renganathan@kent.ac.uk

interventions to support vulnerable populations (United Nations Development Programme [UNDP], 2024).

The latest report on low-income settlements reveals that 68,000 families in Colombo's low-income settlements (LIS) cannot be classified as underserved. Approximately 98.8% of the housing in these settlements has access to water and electricity, and the structures are built using permanent materials. Unlike LIS in other parts of the world, Colombo's settlements exhibit vertical growth, forming small clusters of 10-20 houses or even larger groups of 200 houses. This incremental density and quality of housing are unique to Colombo's LIS (Centre for Policy Alternatives, 2024). Currently, the Sri Lankan government's strategic plan involves constructing 66,000 high-rise housing units within Colombo. This ambitious initiative aims to relocate inhabitants from underserved urban areas, with a projected budget of Rs 2.5 million per unit (World Bank, 2024). The Urban Regeneration Projects initiated by the Urban Development Authority in 2010 propose relocating 68,000 families residing on 9% of Colombo's land to mid-rise and high-rise apartments. However, despite these efforts, several unaddressed issues persist, resulting in deteriorated living conditions for residents ("Sri Lanka should build pandemic prevention", 2024).

While the government's focus has primarily been on enhancing tangible living spaces, Samaratunga and O'Hare (2015) identifies critical issues related to high-rise public housing. These include inadequate maintenance, frequent elevator breakdowns, cost-effective yet less durable designs, insufficient insulation to regulate extreme temperature variations, a lack of open spaces and landscaping, and social isolation due to the absence of communal areas. There is a lack of user engagement during the design phase, responsiveness to local climatic conditions, optimal orientation, privacy provisions, identity integration, adaptability, and aesthetic considerations. The prevailing design paradigms often exhibit homogeneity, reflecting a limited pool of designs (Dolapihilla, 2013). The limited space within dwelling units, typically around 400 sq. ft., comprising a living area, kitchen, two bedrooms, and a bathroom poses additional challenges (Perera, 2015).

Mass housing, particularly high-rise options, provides affordability and accessibility across income levels. However, it often clashes with traditional lifestyles and cultural contexts. Within these contexts, behavioural adaptations reveal a discord between housing design and cultural realities. This challenge is particularly pronounced for low-income communities whose lives revolve around social ties, networks, and emotional and physical interdependence. Relocation disrupts their familiar neighbourhoods, workplaces, and access to preferred education. Consequently, many residents move out and eventually return to their original settlements. To align living environments with social, economic, and environmental needs, inhabitants engage in space modifications, personalisation, and behavioural adaptations. However, space modifications and personalisation are restricted in most mass housing developments. As a result, behavioural adaptations become an essential interim solution for housing satisfaction until more substantial modifications can be implemented. Within these constraints, residents adapt through minor adjustments permitted by relevant authorities.

Given the lack of comprehensive literature and research in this field of low-income high-rise housing in Sri Lanka, increased academic inquiry and professional discourse are essential. Understanding the key factors contributing to the success or failure of low-income housing initiatives, especially those involving high-rise structures, is crucial (Dolapihilla, 2013).

1.1 BEHAVIOURAL ADAPTATIONS AND HOUSING MODIFICATIONS

Behavioural adaptations refer to modifications or changes in an organism's behaviour that enhance its survival and reproductive success within its ecological niche (Tooby & Cosmides, 1992). These adaptations are often responses to environmental changes or selective pressures. In the context of human behaviour, we observe behavioural adaptations when people react to shifts in their surroundings. For instance, in response to environmental concerns like climate change or urbanisation, individuals may adopt resource-saving practices such as water conservation or waste recycling. Additionally, behavioural adaptations occur through the lens of social norms and cultural traditions. Changes in family dynamics or social roles may arise due to economic shifts or technological advancements.

Urban contexts also witness behavioural adaptations. Daily routines and spatial use change to address urban challenges like traffic congestion, housing affordability, and access to amenities (Gärling & Steg, 2007). People may adapt to commute habits, use of public spaces, and social interactions based on infrastructure, crime rates, or socioeconomic conditions (Qi et al., 2003). Within the built environment, individuals strive to align their behaviours with the constraints and potentials of their surroundings (Archea, 1977; Proshansky et al., 1970). These adaptations, influenced by cultural, social, and economic factors, manifest in various housing modifications from spatial rearrangements to structural changes, residents personalise their living spaces to enhance comfort and well-being (Franck, 1985; Rapoport, 1969). Further, these adaptations reflect individual values and needs (Gifford, 2007; Nasar, 1983).

Research by Vega and Rubin (2010) compares residents' assessments of housing quality across three types of public housing. Their findings shed light on how these views impact inhabitants' behavioural responses to their living environments, emphasising varying degrees of satisfaction and coping strategies. Chiu (2004) delves into the socio-cultural aspects of housing sustainability, exploring how inhabitants modify their behaviours and living spaces to meet cultural and social demands. The study established a conceptual framework for understanding the relationship between housing design, community practices, and sustainability. According to Fernando and Coorey (2023), residents' satisfaction with liveability in two low-income high-rise housing complexes in Colombo was examined. The research identified critical issues related to building scale characteristics, which significantly influence tenants' overall satisfaction beyond individual dwelling units.

1.2 PERSONALISATION IN HOUSING: BRIDGING USER PREFERENCES AND DESIGN INTENTIONS

The satisfaction of housing needs encompasses both physiological and psychological dimensions, influenced by cultural, social, and economic factors (Maslow, 1943 as cited in Asad Poor Zavei & Jusan, 2012). Personalisation emerges as a critical process through which individuals express their values and aspirations within their living environments. It involves "quality homemaking" within the standards set by households themselves, promoting sustainable housing that balances quality and affordability (Jusan & Sulaiman, 2005). Grounded in basic needs theory, personalisation bridges the gap between user preferences and designer intentions, ensuring that housing environments meet diverse inhabitants' needs (Rapoport, 1969). According to Gifford (2007), this ongoing process of personalisation reflects the dynamic nature of human needs and aspirations, emphasising individuals as agents of environmental change (Gifford, 2007). Evaluating housing environments and the process of personalisation are intertwined aspects of individuals' interactions with their living spaces. A comprehensive framework integrating affective, cognitive, and behavioural dimensions, while considering cultural, social, and economic influences provides valuable insights into occupants' experiences and the dynamic nature of housing environments.

However, despite the importance of personalisation, mass housing and public housing production often lack end-user participation during design stages. These developments offer typical 2-bedroom layouts to a diverse community, disregarding variations in family sizes, social needs, emotions, and economic backgrounds. Consequently, end-users may end up in conflict with housing layouts, leading to modifications without professional consultations, resulting in suboptimal living spaces (Kularatne et al., 2019). Encouraging end-user participation, flexible design, and varied house types and layouts are essential for accommodating personalisation without compromising the purpose of creating habitable living environments.

1.2 AIM AND OBJECTIVES

The challenges of everyday life vs the built environment have implications on the behaviours and adaptive measures in housing. This research aims to explore the challenges to everyday life; adaptive measures and housing modifications to overcome such challenges. The objectives are to:

1. Examine the basic needs and challenges to everyday life of "low-income dwellers" when living in high-rise resettlements.
2. Examine the behavioural adaptation and housing modifications in high-rise resettlements in response to the basic needs and challenges of everyday life.

2. METHODOLOGY

2.1 INTRODUCTION TO THE CASE STUDY

This research employs a case study approach to investigate a typical model of high-rise low-income housing. The selected case is shown in Figure 1.

Figure 1: Case study 1 - unit layout, floor layout, and the photograph of the housing development
Source – UDA & by author

The selected case is a 14-story low-income housing complex comprising 200-250 dwelling units per block. The residents have lived in their units for 4-5 years, with construction spanning from 2015 to 2019. Housing units are approximately 500.55 sq. ft with a living room, two bedrooms, a kitchen, and a toilet which is consistent across low-income high-rise housing. Notably, these buildings feature a natural ventilation system facilitated by windows, ventilation grills, and light wells, allowing residents to regulate airflow according to their preferences.

2.2 DATA COLLECTION

Sample: Respondents for this study were identified through a pilot survey interview involving 150 individuals, of whom 57 agreed to participate in further interviews. The selection criteria encompassed various factors influencing household dynamics, including family size, the gender and age of children, the family life cycle, and housing design.

Interviews: Interviews served as the primary method of data collection. A standardised set of questions guided the interviews, ensuring consistency across. The interview structure encompassed several sections namely 1. Demographic information such as occupation, family size, length of stay, and Building occupation details; 2. Building conditions and facilities; 3. Residents' satisfaction and rating on comfort, neighbourhood, and amenities in and outside the houses; 4. Community's diversity, infrastructure, and personal customisation of the housing units; 5. Problems that residents encounter and suggestions for future modifications and 6. Overall housing satisfaction of the living environment.

Observations: observations supplemented the interview data, with photographs and sketches used to document physical changes within the housing units. However, access to the internal spaces of respondents' homes for photography was limited.

3. FINDINGS AND DISCUSSIONS

3.1 CONTENT ANALYSIS OF INTERVIEW DATA

Content analysis was employed for analysing interview data. This approach facilitated the identification of recurrent patterns within the recorded communication, enabling the exploration of meaning units, codes, categories, and underlying themes. The overarching objective of this process is the systematic transformation of voluminous textual data into a meticulously organised and brief summary of paramount findings.

3.1.1 Housing Needs and Challenges

Table 1 illustrates transcribed interview data explored as meaning units, codes, categories, and the formation of thematic elements. This iterative method involved gradually shifting from overt and explicit content to researching latent meanings buried in the dataset. According to Table 1, the major challenges to everyday life are lack of space for a variety of indoor and outdoor functions, privacy, security & safety, and maintenance, which are directly related to the design characteristics of the housing. The analysis also shows concerns related to mental health, social interactions, and other social problems that can be considered as the social conditions of the housing. Physical comfort such as light, ventilation, and thermal comfort that relates to the environmental conditions of the housing were also identified as important basic needs affecting the everyday life of the inhabitants.

Table 1: Overall summary of organisation of related coded meaning units into codes, categories, and themes based on housing needs and challenges to everyday life.

Meaning units condensations	Codes	Categories	Themes
Two bedrooms are insufficient.	Lack of bedroom space	Space requirement	Housing Need
No space for a kitchen yard, and storage	No space for storage		
No space for a garden, and balcony as such	Lack of Garden & Balcony		
Lack of place for the garbage disposal	No space for Garbage		
Lack of space for Dry clothes	Lack of laundry area		
Lack of parking space, no individual parking slots being provided	Lack of parking space		
Lack of community hall or a gathering space	Lack of internal and external spaces for community interactions.	Space for Social Activities	
Lack of play area, or playground for children	Lack of play space		
Lack of connection between the community	Community interactions		
No such space as a funeral hall or a space to hold a funeral	Lack of community hall		
Bedroom windows opened to the corridor	Lack of privacy	Privacy	
Lack of clear division of the spaces inside the house	Space Constraints		
A breakable door is a main door	Lack of safety	Security & Safety	
No grills are fixed to the windows	Lack of safety		
The front window starts low on the wall, providing easy access to the living area when opened	Lack of security		
Bedrooms are dark and no proper ventilation	Inadequate Light & Ventilation	Poor Housing Quality	Housing Challenges
Housing units inside the environment are really hot	Thermal dissatisfaction	Physical Comfort	
Plumbing and Electrical problems	Poor Construction	Maintenance Issues	
Regular Lift breakdowns	Lack of Maintenance		
Lack of maintenance of the overall building	Lack of Maintenance		
Small to large-scale robberies happen all the time	Theft	Social problems	
New drugs and drug dealers	Drugs & Alcohol		
Prostitution	Illegal businesses		

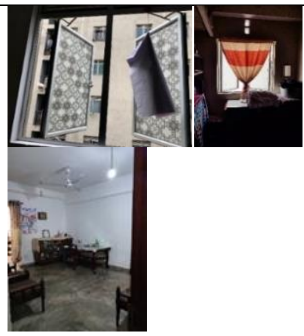
Meaning units condensations	Codes	Categories	Themes
Increased crime rates including violence			
Lack of Grama Niladari services	Lack of Social Services		
Loss of memory due to being forcibly displaced from previous home	Amnesia		
Sudden change in daily life routines	Unable to bounce back to normal	Displacement	
Vastly different new environment	Disorientation		
No experience with high-rise living always lived on the ground level	Lack of coping and control		
Moving away from familiar environments and feeling lonely	Mental Health Issues		
Missing the previous home environment	PTSD	Gentrification	
Losing the previous home and the familiar neighbourhood	Lack of confidence		

3.1.2 Behavioural Adaptations and Modifications

The below section explores the behavioural adaptations and spatial modifications in response to basic needs and challenges to the everyday life of resettled communities in high-rise housing. Both interview data and observational data are analysed in Table 2.

Table 2: Summary of behavioural adaptations or modifications in response to the basic needs and challenges of everyday life based on interview data and observations

Basic needs and challenges to everyday life in high-rises	Behaviour Adaptation or modifications	Photographs
Lack of Space		
• Lack of laundry areas and places for drying clothes. • Two bedrooms are insufficient due to large family size and extended family. • Lack of shared spaces for communal interactions - internal & external • Lack of storage space • Lack of green spaces and balconies/outdoors • Lack of space in pantry/kitchens	• Use of corridors and corner spaces. • Use mattresses on the floor to sleep. • Bedrooms used as a multifunctional space • Corridors used for communal space • Storage inside bedrooms and service duct spaces used for kitchen yard/equipment • Common corridors used for fish tanks, and plants. • Extension of kitchen using appliances	

Basic needs and challenges to everyday life in high-rises	Behaviour Adaptation or modifications	Photographs
Privacy		
• Lack of divisions and demarcation of spaces in living/dining • Positions of windows/ doors across units & proximity of housing towers affect privacy	• Use of curtains, and tinted windows. • Use of temporary boards to block views • Closing doors and windows at all times • Overcome heat and light issues by using fans and lights during the day	
Light & Ventilation		
• Lack of light or ventilation in the bedrooms - especially rooms facing the corridor	• Closing windows due to privacy and using fans and lights for light & ventilation	
Safety & Security		
• Lack of security	• Additional grill gates for doors and windows. • Grill gates at roof slab levels • Grill gates at every floor level	

4. SUMMARY OF FINDINGS

Privacy: The research underscores the critical role of behavioural adaptations in maintaining privacy across different activity systems. Notably, these modifications are essential for achieving visual seclusion, limiting unwanted social interactions, ensuring smooth daily routines, preserving parental intimacy, securing privacy for adolescents, demarcating sleeping areas, and maintaining privacy during guest visits within domestic environments. The need for such adaptations is particularly pronounced in households with adolescent daughters and sons, where spatial segregation accommodates their distinct daily routines.

Multifunctional Use of Space & Shared Spaces: Living and dining areas in high-rise housing serve a multitude of functions, including dining, relaxation, sleeping, study, and even clothes drying. Family members share this space for various activities. The research highlights a common practice of bedroom sharing. Unlike the concept of individualised rooms, which did not emerge, children grew accustomed to communal privacy during their early years. However, privacy becomes more critical during adolescence. Notably, Islamic households tend to establish separate sleeping spaces for parents, daughters, and sons to ensure privacy. This aligns with the concept of spatial appropriation discussed by Giuliani et al. (1990). Spatial constraints within housing units lead to behavioural adaptations that occasionally diverge from cultural norms. For example, entertaining male guests may be relocated from interior spaces to the living area, challenging expectations of family privacy. Respondents also acknowledged that spatial limitations prevent accommodating overnight relatives, conflicting with cultural norms of hospitable treatment, especially among Muslim and Hindu families. Achieving privacy for family members in the presence of guests proves challenging due to the open layout. The interchangeable functionality of dining and living zones occasionally leads to conflicts in use.

Privacy and Social Interactions: A significant number of participants emphasised the importance of behavioural adjustments to maintain privacy, limit unwanted social interactions, and enhance security. Regular practices included securing entrances, keeping windows closed, and shutting doors, all aimed at regulating these aspects. However, these measures sometimes had a negative impact on neighbourly interactions. Respondents primarily focused on intra-family dynamics, with interactions among neighbours being rare. The close proximity of the towers and window placement encroached upon the privacy of families residing across from each other. While these adaptations ensured privacy, they also led to visual constraints, reduced ventilation, and fewer interactions among neighbours.

Privacy, Family Organisations, and Arrangements: The proximity of neighbouring and common areas in high-rise housing can compromise familial privacy. Corridors indirectly serve as spaces that balance interaction and privacy, especially during the presence of male guests. The reorganisation of bedrooms results in functional sleeping quarters tailored to the privacy and activities of adolescent children. Consequently, parents and small children often use the living area to sleep at night. During family functions or when guests arrive, the living area accommodates males, while females use the bedrooms. However, this arrangement often compromises the comfort and quality of sleeping spaces.

Privacy and Physical Comfort: In high-rise housing, residents often face a trade-off between light, ventilation, and privacy. Windows and openings oriented toward corridors and common areas compromise natural light and airflow in exchange for security and privacy. Tinted glass windows, layered curtains in bedrooms, and bamboo blinds for pantry windows are used to regulate visual privacy. Additionally, strategic placement of grill gates and other privacy-enhancing measures is observed. The reorganisation of interior spaces, coupled with intentional modifications to windows and doors, exemplifies the dynamic interplay between architectural adaptations and the essential need for privacy, security, comfort, and versatility within domestic environments. This finding aligns with a study by Wong and Yap (2003), emphasising the significance of home privacy in densely populated living spaces like Hong Kong. Prioritising privacy often leads to limitations on interactions, causing individuals to retreat within their confined boundaries. Other behavioural adaptations include noise control within personal residences and refraining from peering into adjacent units, especially when units directly face each other.

Extension of Domestic Space: In low-income high-rise housing, residents often reorganise and extend their living spaces. This process involves the living area, kitchen, lobby, and bedrooms. By doing so, they indirectly redefine spatial boundaries, blurring the lines between public and private realms. Simultaneously, corridors shift into a semi-private domain. The lack of space provisions for day-to-day needs drives this extension of activities into public and semi-public areas, a strategy reminiscent of former informal settlements. Residents optimise spatial utilisation for daily activities and interactions. Service ducts serve as kitchen backyards or storage spaces, while corridors double as areas for drying clothes. Corridors, which resemble extended verandas, offer better ventilation and become spaces for relaxation. In a way, they represent “borrowed space.” However, authorities often regulate these personalised extensions, limiting residents’ ability to meet their human needs.

Lack of Domestic Space: In contrast to addressing other basic needs, residents in high-rise housing face limitations when it comes to modifying their living spaces. Unlike in previous low-income informal settlements, where vertical incremental growth was common, residents cannot expand their units or increase square footage to accommodate extended families, family growth, or multigenerational living. Instead, they adapt behaviourally by sharing spaces, using multifunctional areas, and extending domestic activities (such as relaxation, religious practices, and storage) into public and semi-public spaces like corridors and lobbies. However, encroachment or any form of personalisation of these common areas is restricted and regulated by authorities. Unfortunately, the mass housing model typically provides a uniform 2-bedroom unit for all residents, regardless of family size or life cycle, making it impossible to allocate sufficient space for multiple families and restricting comfortable living.

Community Living: Corridors became a part of the house and the corner area of the towers was converted into shrines for religious activities common to all. The lack of playgrounds and lack of secured play areas within close proximity is a challenge. Residents adapt by using corridors, stairwells, and ground floor central courts. Corridors and stairway lobbies facilitate better surveillance of younger children within close proximity to their homes and parents' views.

5. CONCLUSIONS

The study highlights the crucial role of behavioural adaptation, personalisation, and housing modifications among low-income families residing in high-rise buildings. These adaptations are essential due to limitations in environmental comfort, functionality, space allocation, and socio-cultural requirements. Residents adapt their behaviour to enhance daily comfort, family privacy, and social interactions, harmonising domestic life within the constraints of high-rise housing. Interestingly, some behavioural adaptations occasionally diverge from cultural and religious norms, revealing a complex interplay between architectural modifications and deeply rooted beliefs. However, the opportunity for personalisation and modification based on residents’ needs is often restricted, compromising comfort and well-being. The research underscores the dynamic relationship between behavioural adaptation, housing modifications, and cultural considerations in low-income high-rise housing. To create an optimised and harmonious domestic environment, architectural interventions should balance physical requirements with socio-cultural needs, values, and lifestyle patterns.

6. ACKNOWLEDGEMENTS

This work was supported by the SRC Long Terms Grant No: SRC/LT/2020/05 by the University of Moratuwa Senate Research Committee (SRC).

7. REFERENCES

Archea, J. (1977). The place of architectural factors in behavioural theories of privacy. *Journal of Social Issues, 33*(3), 116-137. https://doi.org/10.1111/j.1540-4560.1977.tb01886.x

Zavei, S. J. A. P, & Jusan, M. M. (2012). Exploring housing attributes selection based on Maslow's hierarchy of needs. *Procedia - Social and Behavioural Sciences, 42,* 311–319. https://doi.org/10.1016/j.sbspro.2012.04.195

Centre for Policy Alternatives. (2024). *Colombo settlement survey 2023.* https://www.csf-asia.org/wp-content/uploads/2024/03/CSS-Survey-2023-report_Final.pdf

Chiu, R. L. H. (2004). Socio-cultural sustainability of housing: A conceptual exploration. *Housing, Theory and Society, 21*(2), 65-76. https://doi.org/10.1080/14036090410014999

Dolapihilla, P. (2013). *Public sector housing development in Sri Lanka with special reference to urban informal resettlements in colombo*. https://www.hdm.lth.se/fileadmin/hdm/alumni/papers/ad2000/ad2000-15.pdf

Sri Lanka should build pandemic prevention into urban plans: IPS. (2024, January 15). Retrieved from https://economynext.com/sri-lanka-should-build-pandemic-prevention-in-to-urban-plans-ips-75370/

Fernando, M. R. S. M., & Coorey, S. B. A. (2023). Assessment of residents' satisfaction of 'Liveability' in low-income high-rise housing in Colombo. *Built-Environment Sri Lanka*, *13*(2), https://doi.org/10.4038/besl.v13i2.7681

Gärling, T., & Steg, L. (2007). *Threats from car traffic to the quality of urban life: Problems, causes, and solutions*. (1st ed.) Elsevier.

Gifford, R. (2007). *Environmental psychology: Principles and practice* (4th ed.). Optimal Books.

Giuliani, M. V., Rullo, G., & Bove, G. (1990). Socializing and Privacy Spaces Inside Homes. An Empirical Study. In *Proceedings 11th International Conference of International Association of People Built Environment Study IAPS* (pp. 129-138).

Jusan, M. M., & Sulaiman, A. B. (2005). *Personalization As a Sustainable Approach To Mass Housing*. Conference on Sustainable Building South, (April), 11–13. Retrieved from https://core.ac.uk/download/pdf/11795821.pdf

Kularatne, K., Coorey, S., & Perera, R. (2019). Space modification and personalization in public housing: Case of walk-up apartments in sri lanka. *Proceedings of the annual international conference on architecture and civil Engineering*. https://www.researchgate.net/publication/337315466_Space_Modification_and_Personalization_in_Public_Housing_Case_of_Walk-Up_Apartments_in_Sri_Lanka

Maslow, A. H. (1943). A theory of human motivation. *Psychological Review, 50*(4), 370-396. https://doi.org/10.1037/h0054346

Nasar, J. L. (1983). Adult viewers' preferences in residential scenes: A study of the relationship of environmental attributes to preference. *Environment and Behaviour, 15*(5), 589–614. https://doi.org/10.1177/0013916583155003

Perera, I. (2015). *Forced evictions in Colombo: High-rise living*. Centre for Policy Alternatives. https://www.cpalanka.org/wp-content/uploads/2015/05/High-rise-living_report-FINAL.pdf

Proshansky, H. M., Ittelson, W. H., & Rivlin, L. G. (1970). *Environmental psychology: Man and his physical setting.* Holt, Rinehart, and Winston.

Qi, J., Mazumdar, S., & Vasconcelos, A. C. (2023). Understanding the relationship between urban public space and social cohesion: A systematic review. *International Journal of Community Well-Being*. http://dx.doi.org/10.1007/s42413-024-00204-5

Rapoport, A. (1969). *House form and culture*. Prentice-Hall.

Samaratunga, T. C., & O'Hare, D. (2015). Sahaspura: The first high-rise housing project for low-income people in Colombo, Sri Lanka. *Australian* Planner, 51(3), 223-231. https://doi.org/10.1080/07293682.2013.820204

Tooby, J., & Cosmides, L. (1992). The psychological foundations of culture. In J. H. Barkow, L. Cosmides, & J. Tooby (Eds.), *The adapted mind: Evolutionary psychology and the generation of culture* (pp. 19-136). Oxford University Press.

United Nations Development Programme. (2024, March 4). *District profiles of the socio-economic context and multidimensional poverty and vulnerability in Sri Lanka launched*. United Nations Development Programme. Retrieved from https://www.undp.org/srilanka/press-releases/district-profiles-socio-economic-context-and-multidimensional-poverty-and-vulnerability-sri-lanka-launched

Vega, M., & Rubin, A. (2010). Perceptions of housing quality among residents living in three forms of public housing. Journal of Urban Affairs, 32(3), 335-354. https://doi.org/10.1111/j.1467 9906.2010.00507.x

World Bank. (2024, April 2). *Sri Lanka development update 2024.* The World Bank.

Wong, T. C., & Yap, A. (2003). From universal public housing to meeting the increasing aspiration for private housing in Singapore. *Habitat International*, *27*(3), 361–380.

Sood, R., Sharma, N. and Laishram, B., 2024. BIM and blockchain integrated construction management: A review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 291-305. DOI: https://doi.org/10.31705/WCS.2024.23. Available from: https://ciobwcs.com/papers/

BIM AND BLOCKCHAIN INTEGRATED CONSTRUCTION MANAGEMENT: A REVIEW

Rhijul Sood[1], Nandini Sharma[2], and Boeing Laishram[3]

ABSTRACT

The Architectural, Engineering, Construction, and Operations (AECO) industry has implemented Building Information Modelling (BIM) for a significant time, and its applications are widely recognised. Nevertheless, numerous studies have emphasised that BIM in isolation is unable to tackle the difficulties encountered by construction stakeholders and needs integration with other technologies to augment its practicality. In the last few years, there has been an increasing curiosity and utilisation of Blockchain Technology (BCT) within the construction industry. Limited research has been conducted on the amalgamation of BIM and BCT across many domains of application. To undertake a thorough analysis of the integration between BIM and BCT, this study employed a Systematic Literature Review (SLR) methodology utilising the Scopus database. The research employed a combination of quantitative and qualitative content analysis techniques to examine the selected articles. The study has identified five distinct domains of integration between BIM and BCT. These domains encompass data management, contract management, facility/asset management, sustainability/waste management, and supply chain management. Furthermore, certain obstacles were identified that impact the incorporation of BIM-BCT in the industry. In general, this study can provide stakeholders with insights into the capabilities of BIM-BCT within the construction industry, enabling them to develop a strategic plan for improving the integration of these technologies.

Keywords: *Architectural, Engineering, Construction, and Operations (AECO); Blockchain Technology (BCT); Building Information Modelling (BIM); Systematic Literature Review (SLR).*

1. INTRODUCTION

The AECO industry is characterised by cost and time overruns resulting in low profit margins coupled with low stakeholder satisfaction (Selvanesan & Satanarachchi, 2023). In the intricate and dynamic operating environment of the construction sector, the utilisation of technology advancements is important to optimise its efficacy within the business. Among various innovations in the construction sector, BIM is one such technology that helps in developing n-dimensional models with multiple Levels of Development (LOD), further resulting in higher maturity levels (Sood & Laishram, 2022). Additionally, BIM was majorly employed for the designing and construction

[1] Research Scholar, Department of Civil Engineering, IIT Guwahati, India, rsood@iitg.ac.in
[2] Research Scholar, Department of Civil Engineering, IIT Guwahati, India, nandini.sharma@iitg.ac.in
[3] Professor, Department of Civil Engineering, IIT Guwahati, India, boeing@iitg.ac.in

applications (Becerik-Gerber & Kensek, 2010), however, in the last few years, the applications of BIM can be seen during post-construction phases (such as the O&M phase, and demolition phase) as well (Motawa & Almarshad, 2013; Yung & Wang, 2014; Edirisinghe et al., 2017; Gerrish et al., 2017; Tsay et al., 2022), resulting in effective management of entire project lifecycle (Eastman et al., 2011). BIM enhances project delivery efficiency, fosters stakeholder engagement, minimises design errors and modifications, clash detections, facilitates sustainable material selection at the planning stage, and several other benefits (Azhar, 2011; Farghaly et al., 2019; Deng et al., 2019; Deng et al., 2020). However, various issues exist during the isolated use of BIM technology, resulting in lower operational value to stakeholders (Nawari & Ravindran, 2019b; Espinoza-Zambrano et al., 2023). A few of these issues include transparency and reliability of information that is exchanged between multiple parties resulting in contractual claims and disputes (Eadie et al., 2015; Zhong et al., 2020), and lack of security of the BIM model resulting in information leak, loss, or corruption/piracy (Nawari & Ravindran, 2019a; Das et al., 2021). The potential solution to these issues can be achieved by combining BIM and Blockchain (Chung et al., 2022) and the present study is focused on comprehending the applications and consequences of this integration. The operational weaknesses of BIM could be compensated by the unique properties of BCT, including very high safety, benefits for data sharing and reliability, and the capacity to design smart contracts that encourage conformity (Selvanesan & Satanarachchi, 2023). Nevertheless, despite the prevailing popularity of BCT in several sectors, its use within the construction industry remains rather limited (Kiu et al., 2024).

1.1 BLOCKCHAIN TECHNOLOGY (BCT)

BCT also known as Distributed Ledger Technology (DLT), is a decentralised and transparent system that aims to enable secure transactions in a thrustless way using a distributed directory (Wood, 2014). The preliminary review of BCT indicates that it possesses various suitable attributes and benefits, including enhanced transparency and security, the facilitation of trust, and reduced instances of non-compliance with contractual obligations (Zheng et al., 2018; Clohessy et al., 2020). To ensure transparency of activity, security enhancement, synchronisation, and recording of data in distributed environments, many technologies are employed, including encrypted data structures, peer-to-peer networking and consensus algorithms (Nawari & Ravindran, 2019a; Das et al., 2021). In the BCT network, transactions are recorded in blocks that are interconnected in a chain-like manner and arranged in a logical order (Huang et al., 2022), hence, avoiding a single-point failure without requiring any trusted third party.

The BCT had significant growth in recent years, evolved from the initial decentralised cryptocurrency Bitcoin (Nakamoto, 2008), known as BCT 1.0, to Ethereum, which incorporates smart contracts, referred to as BCT 2.0 (Buterin, 2014) and its subsequent development involves the emergence of permission-editable blockchains, such as Hyperledger Fabric, which operates on the 'Proof of Stake' (PoS) mechanism known as BCT 3.0 (Cachin, 2016; Nawari & Ravindran, 2019b). BCT 2.0 generates digital records that possess the property of being unalterable and can be transferred to another user by a trusted third party, such as a financial institution (Geipel, 2017). Whereas BCT 3.0 seeks to enhance the functionalities of BCT 2.0 by focusing on transaction speed, expansion, and deployment simplicity through the utilisation of decentralised tools (Raval, 2016).

Given its decentralised nature, BCT has successfully infiltrated various domains that are intricately interconnected with our everyday existence. These domains encompass cryptocurrencies, commercial applications, smart cities, Internet of Things (IoT) applications, government services, and almost every existing industry (Huang et al., 2022). Furthermore, there are few studies about the utilisation, impact, and possibilities of BCT in the construction sector (Penzes, 2018; Nawari & Ravindran, 2019b; Dakhli et al., 2019; Li et al., 2019; Perera et al., 2020; Prakash & Ambekar, 2021; H. Liu, 2023; Z. Liu et al., 2023; Kiu et al., 2024). The application areas in these studies include data traceability (Turk & Klinc, 2017; Amaludin et al., 2018), measuring construction productivity (Heiskanen, 2017), contract management (Wang et al., 2017), automated project bank accounts and other regulations and compliances (Li et al., 2019). Despite the numerous applications and benefits of BCT in the construction industry, its adoption remains significantly limited (Selvanesan & Satanarachchi, 2023) as compared to other manufacturing, finance, or service sectors (Nawari & Ravindran, 2019b).

1.2 RESEARCH PROBLEM

The utilisation of BCT in the context of Industry 4.0 has been the subject of extensive theoretical investigation, although there is a scarcity of practical applications that effectively demonstrate its capabilities (Dounas et al., 2021), whereas if we look at its integration with BIM, the studies are even less. The studies related to BIM-BCT have picked up pace in the last two or three years, with still ongoing research as well as few implementation gaps. Even though the value of combining BCT and BIM has long been acknowledged, there is a dearth of scholarly work demonstrating this integration's viability. Few studies have been conducted to explore diverse applications of this integration, which will be elaborated upon in the subsequent sections of this paper. Additionally, a few literature-based studies have tried to investigate the integration of BIM and BCT for different construction operations. However, such studies shed light on the individual applications of this integration and were limited to data management (Nawari & Ravindran, 2019b; Das et al., 2021), contract management (Chung et al., 2022), and supply chain management (Selvanesan & Satanarachchi, 2023). Hence, through a Systematic Literature Review (SLR) approach, the current study looks from the perspective of all the other application areas (such as sustainability, waste management, digital twin, facility management, etc.) that are possible with BIM-BCT integration but have not been included in other similar studies.

2. RESEARCH METHODOLOGY

To conduct a thorough and in-depth examination of the incorporation of BIM and BCT technologies in the construction industry, a SLR was carried out (refer to Figure 1). This review followed a three-stage strategy as suggested by Tranfield et al. (2003).

The first stage involves the selection of databases and the identification of the keywords based on our research problem. The study selected the Scopus database as it is widely recognised as a reputable database engine for academic data (Khan et al., 2021). Additionally, Scopus has indexed a greater number of journals compared to other databases such as PubMed, WOS, and Google Scholar (Chadegani et al., 2013; Fetters et al., 2013). Similarly, the keywords and their synonyms that were selected based on the building blocks include: “BIM” and “BCT” and were connected using Boolean operators “AND” and “OR” as shown in the syntax below:

[Title-Abs-Key ("BIM" OR "Building Information Model*") AND ("Blockchain" OR "Blockchain Technology" OR "BCT")]

This initial research resulted in 245 articles. The subsequent step involves screening and filtering of articles based on various options available in the Scopus database. Hence, the 245 articles were screened based on language and type of articles. The articles written in the English language and formed part of journal publications were only considered. It was found that two articles were in the non-English language whereas 165 articles were part of either conferences or book chapters due to their typically less rigorous peer-review process and less detailed content compared to journal articles, hence, not considered in a further step. This resulted in a list of 80 articles which were then further filtered based on their relevance to BIM and BCT integration by analysing their titles, abstracts, and conclusions. It was found that 22 articles were either from non-construction areas or were not relevant to our research, leaving us with a set of 58 articles.

The last stage involves analysis and reporting the review findings. The analysis of shortlisted articles was conducted in two forms i.e. (i) quantitative, and (ii) qualitative analysis. The quantitative analysis involves understanding the trend of publication of articles and for that, a data extraction form in MS Excel was developed. The information in the form included the title, author, year of publication, journal, and country. Additionally, the shortlisted articles were further analysed based on research type and application areas. Similarly, the qualitative analysis of these articles involves the description of the various BIM-BCT integrated applications in construction management and the barriers that are hindering BIM and BCT integration. The results of quantitative and qualitative analysis will be shown utilising various visualisation tools such as charts, graphs, and tables along with descriptive statistics.

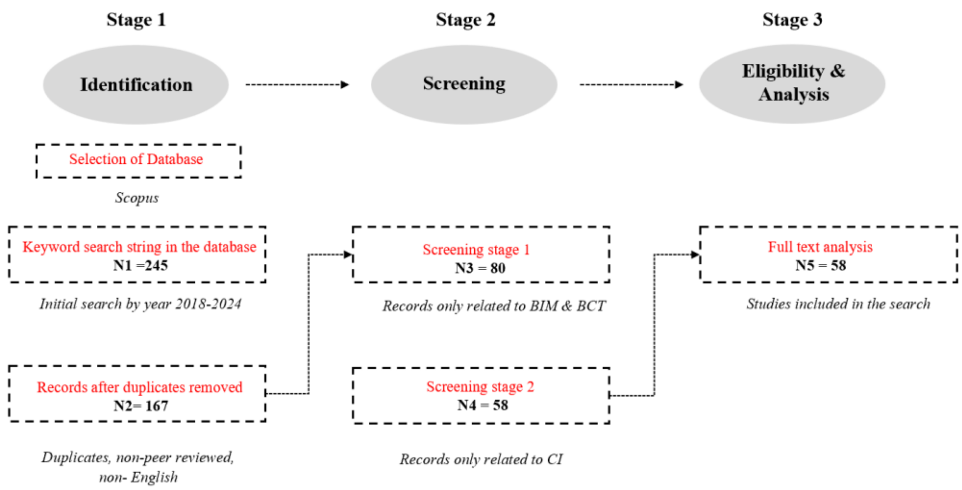
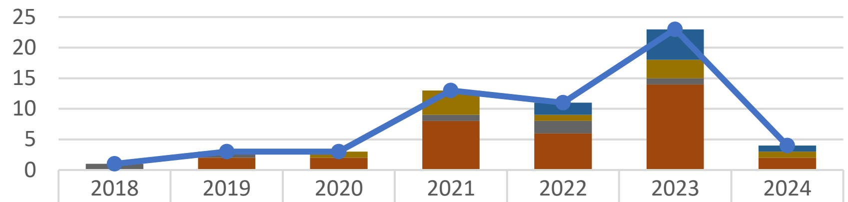


Figure 1: Research methodology

3. ANALYSIS

3.1 QUANTITATIVE ANALYSIS

It involves a chronological understanding of publications to identify the temporal distribution of articles. This aids in comprehending the progression of research interest in a specific field throughout time. Figure 2 shows the distribution of papers from the year 2018 to 2024 with publications increasing from 1 to 23 in the years 2018 and 2023 respectively.



	2018	2019	2020	2021	2022	2023	2024
Survey	0	0	0	0	2	5	1
Case Study	0	0	1	4	1	3	1
Literature Review	1	1	0	1	2	1	0
Conceptual	0	2	2	8	6	14	2
Total	1	3	3	13	11	23	4

Figure 2: Yearly publications

The initial year of 2018 shows that the research in this domain is very new and is still in the initial phase of implementation in the construction industry. Furthermore, the articles were categorised according to the study methodology employed by the authors of the shortlisted articles. It was found that 34 papers (59%) were conceptual, six papers (10%) were based on literature review, ten papers (17%) adopted a case study approach whereas the remaining eight papers (14%) involved survey-based methodology.

Similarly, the articles were also distributed based on their geographical location of studies. The 58 shortlisted articles belonged to 20 different countries. Among these, the top five countries with the highest number of publications include China (eleven papers), Hong Kong (eight papers), Australia (six papers), UK (ix papers), USA (four papers), Indonesia (four papers) and Spain (three papers). Additionally, the articles were also classified into five different application areas of BIM-BCT integration. These include data management (21 papers), contract management (ten papers), sustainability/waste management (twelve papers), supply chain management (eight papers), and facility/asset management (seven papers). Moreover, the shortlisted articles were also published in ten top-tier peer-reviewed construction journals, among which the top three include Automation in Construction (eleven papers), Buildings (eight papers), Journal of Information Technology in Construction and Computers in Industry (four papers each).

3.2 QUALITATIVE ANALYSIS

3.2.1 BIM-Blockchain Integration

Based on the analysis of shortlisted papers, it was found that the integration of BIM and BCT had been utilised in various applications of construction management. These are categorised into five areas i.e. (i) Data Management (DM), (ii) contract management, (iii) sustainability/waste management, (iv) facility/asset management, and (v) Supply Chain Management (SCM) which are briefly described below:

Data Management (DM)

The construction sector deals with a substantial volume of data that requires management, security, and exchange among multiple stakeholders. Therefore, construction firms must possess the ability to effectively manage and safeguard their data. Various research has explored the integration of BIM and BCT to effectively manage, exchange, and enhance the security of shared data. In terms of managing data, (Kiu et al., 2024) highlighted the role of BCT-based Electronic Data Management (EDM) in BIM models for BIM projects. Similarly, various other studies have developed BIM-BCT integrated frameworks for reducing data redundancy (Xue & Lu, 2020) and effective design data management (Tao et al., 2023b) in mega complex infrastructure projects (Sarkar & Dhaneshwar, 2023), offsite manufacturing (Brand & Abrishami, 2021), and even for Martian buildings (Javaherikhah et al., 2023a, 2023b). Similarly, BIM data exchange through BCT technology has been noted in various studies. The studies involve a BIM-BCT integrated platform for the automatic sharing of information in emergency construction projects (Tao et al., 2023a), among the group of related participants and stakeholders (Suliyanti & Sari, 2021, 2023), heritage structures (Kao et al., 2023) further resulting in reduces costs, and improves risk contingencies in construction projects (Celik et al., 2023). Furthermore, the aspect of data security, particularly in terms of data management and data exchange, is of utmost importance. Therefore, some studies have combined BIM and BCT to ensure the security of the data that is being stored or shared (Das et al., 2021). These include developing a double-fingerprint identity for the Industry Foundation Classes (IFC) (Darabseh & Martins, 2023), BCT-Based Parametric Model Library (BBPML) to protect from data tampering and copyright disputes (Hsu et al., 2023), protect the copyright interests of designers (Wang et al., 2022), protect sensitive data and enhance design collaboration (Tao et al., 2022), preventing data corruption and enhancing data privacy, data integrity and data longevity (Sai et al., 2021), eliminating BIM related digital safety vulnerabilities associated with misuse and blocking of permission to design data (Tao et al., 2021) and tackle information security in mobile cloud architectures (Zheng et al., 2019).

Contract Management (CM)

The construction projects involve a contractual agreement between multiple parties, which includes various clauses and conditions about milestones, automated payments, and deliverables, among others. Several researchers have attempted to employ BCT and combine it with BIM to enhance the administration of contracts more efficiently and intelligently. The studies involve the development of BIM-BCT integrated framework for administrating dispute resolution process (Faraji et al., 2024), performance-based smart contract (Hunhevicz et al., 2022), automated, transparent, and traceable payment in construction projects , metaverse/virtual construction applications and smart contracts (Huang et al., 2022), effective governance, trust and incentivisation for architectural design (Amaludin et al., 2018; Dounas et al., 2021), and improving the efficiency and quality of project management (Li et al., 2021).

Sustainability/Waste Management (WM)

The construction sector is commonly linked to unsustainable practices with a tendency to prioritize short-term and large amounts of resource use that possess high embodied and operational energy, hence rendering it a prominent contributor to carbon emissions. In addition, it encounters numerous other sustainability obstacles, including the generation of construction waste, the emission of construction noise, the presence of motor traffic near building sites, the release of dust and other air and water pollutants, and the assurance of safety and well-being for construction workers (Wong & Loo, 2022). Therefore, numerous researchers have attempted to combine BIM with BCT to improve sustainability and minimise waste by implementing the principles of the circular economy (CE). There have been studies based on BIM-BCT integration-based frameworks for implementing CE principles (Elghaish et al., 2023; Teisserenc & Sepasgozar, 2021a; Teisserenc & Sepasgozar, 2021b) in both organisational and inter-organisational contexts (Zandee, 2024), designing and cost improvement through sustainable/green buildings (Husin et al., 2023; Husin & Priyawan, 2023; Liu et al., 2019), reducing carbon emissions and enhance safety, the well-being of construction workers as well as future occupants (Loo & Wong, 2023), assist in making design choices and advancing health, while achieving the goal of creating a health metaverse within the framework of sustainable development (Liu et al., 2022b), for resource reduction and sustainability enhancement in Prefabricated housing construction (PHC) (Zhengdao et al., 2021), construction waste information management (Liu et al., 2022a) and WM strategies by adopting environmentally sustainable practices (Pellegrini et al., 2020).

Facility Management (FM)/Asset Management (AM)

FM is an essential component of construction management. It entails the coordination of several operations to guarantee a secure and operational facility that fulfils the requirements of its users (Demirdöğen et al., 2023). Similarly, AM evaluates the remaining useful life and performance capability of assets. This assessment provides crucial information for decision-making regarding asset maintenance, renewal, or replacement (Dejaco et al., 2017). The traditional FM is transitioning into asset life cycle management, since an effective O&M relies on the efficient management of the asset in all relevant strategic and operational elements throughout its life cycle (Wijekoon et al., 2020). For this purpose, DT is one of the most effective ways it offers asset managers the ability to access up-to-date, reliable, and unalterable documents on any asset or infrastructure (Macchi et al., 2018). Hence, various studies have developed an integrated BIM/DT-BCT framework (Gotz et al., 2020; Teisserenc & Sepasgozar, 2022) for effective designing, scheduling and procurement, construction and whole life cycle management (Ni et al., 2021), effective operations, maintenance, and renovations (Espinoza-Zambrano et al., 2023), improving the management of buildings and urban assets (Lawal & Nawari, 2023), and improving the asset monitoring and diagnostics in terms of financial, physical, functional and sustainability aspects (Ye et al., 2023).

Supply Chain Management (SCM)

SCM encompasses the oversight of establishments involved in the acquisition of raw materials, their conversion into intermediate commodities and final products, and the subsequent delivery of these products to customers via the channels of distribution (Lee & Billington, 1995). However, SCM in the construction industry is frequently characterised by its intricate nature and differs from the manufacturing industry in a significant way (Vrijhoef & Koskela, 2000). Hence, to optimise the efficiency and transparency of SCM operations in the construction industry few studies have tried to integrate BIM and BCT. These include improvement in SCM for offsite construction projects (Brandín & Abrishami, 2024), and exploration of potential benefits that can address significant inherent challenges which include hesitancy to share knowledge and trust, worries regarding sustainability, and safety (Selvanesan & Satanarachchi, 2023). A prototype was constructed in a study to assess the technological feasibility of combining BCT and BIM using a single source of truth (BIMSSoT) data model (Hijazi et al., 2023a, 2023b). This integration aims to facilitate the transfer of supply chain data for handover purposes. Similarly, an IoT-BIM platform that utilises BCT technology (BIBP) to enhance SCM and off-site production management in the context of modular construction has also been proposed (Li et al., 2022; Wu & Lu, 2022).

Even though the study identified five different application areas of BIM-BCT integration, however, the adoption of such integration remains significantly limited in the construction sector due to various hurdles. Hence, a few studies have also tried to find out different the critical barriers as well as provide strategies that affect this integration (Ebekozien et al., 2023; Selvanesan & Satanarachchi, 2023; Ye et al., 2023). As per Kiu *et al.* (2024), before utilising BIM-BCT-based data management the stakeholders need to focus on and overcome various challenges related to BCT scalability, industry knowledge, and culture. Similarly, high costs (Kiu et al., 2024; Wu & Lu, 2022), information redundancies (Wu & Lu, 2022; Xue & Lu, 2020), lack of pilot case studies (X. Li et al., 2022; Wu & Lu, 2022; Xue & Lu, 2020) low server capacities (Zhengdao et al., 2021), lack of stakeholder proficiency in using novel technologies (Zhengdao et al., 2021), lack of smart contracts (Li et al., 2022; Xue & Lu, 2020) and limited available technical infrastructure for all conditions (Li et al., 2022; Xue & Lu, 2020; Zhengdao et al., 2021) were highlighted as the most critical barriers. In another study, Singh and Kumar (2023) revealed challenges related to adopting BIM-BCT for the FM sector of the Indian construction industry. The most critical barriers include limited cooperation and interaction among stakeholders, regulatory limitations and challenges in establishing trust and governance models.

4. PRACTICAL IMPLICATIONS

The integration of BIM has significant practical implications for the construction industry, enhancing efficiency and transparency across various domains. Within data management, BCT enhances data integrity and security, reducing tampering risks, and optimising data handling processes. This leads to better coordination and reduced redundancies in large projects. BCT also benefits contract management through smart contracts, automating payments, streamlining dispute resolutions, fostering trust, and reducing delays. Moreover, sustainability practices are bolstered by BIM-BCT frameworks that facilitate the implementation of circular economy principles, leading to efficient resource management, reduced construction waste, and lower carbon emissions. In a similar vein, facility and asset management are improved by integrated lifecycle management, enhancing operational efficiency and extending asset longevity. In SCM, BIM-BCT integration ensures transparency and efficiency, addressing knowledge-sharing challenges and fostering collaboration. However, to fully realise these benefits, the industry must overcome barriers such as scalability, cost, technical infrastructure, stakeholder proficiency, and regulatory frameworks.

5. CONCLUSIONS

The paper has provided a comprehensive analysis of the integration of BIM and BCT, employing a systematic literature review methodology using the Scopus database. The study identified 58 articles suitable for conducting quantitative and qualitative content analysis. The quantitative analysis involved classifying articles based on year of publication, research methodology employed by authors, geographical location, journals, and application areas. However, in qualitative analysis, a comprehensive investigation was carried out to examine BIM and BCT integration. The study revealed the potential synergistic effects of these two technologies in improving the efficiency, transparency, and security of construction projects. Our investigation has shed light on the numerous benefits that are possible through BIM-BCT integration. These include streamlined data management, contract management, facility/asset management, sustainability/waste management, and supply chain management. Furthermore, we have highlighted the role of integrated applications in mitigating common challenges encountered in the construction industry, such as data inconsistency, lack of trust, and contractual disputes.

However, despite the promising opportunities presented by the integration of BIM and BCT, our analysis has also identified several barriers that hinder widespread adoption. These barriers include technological complexity, lack of knowledge among stakeholders, high cost of resources, regulatory concerns, and the need for industry-wide standardisation. Addressing these challenges will require collaborative efforts from stakeholders across the construction ecosystem, including policymakers, industry practitioners, technology developers, and researchers. Moving forward, future research endeavours should focus on developing practical solutions to tackle these hurdles and help in the seamless integration of BIM and BCT in construction projects. Moreover, continued exploration of emerging technologies and innovative applications will be essential in unlocking the full potential of this integration, ultimately driving greater efficiency, accountability, and circular economy within the construction industry.

6. REFERENCES

Amaludin, A. E., Radzif, M., Taharin, B., & Programme, C. E. (2018). Prospect of blockchain technology for construction project management in malaysia. *ASM Science Journal*, *11*(3), 199–205. http://eprints.ums.edu.my/24265/

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the aec industry. *Leadership and Management in Engineering*, *11*(3), 241–252. https://doi.org/10.1061/(asce)lm.1943-5630.0000127

Becerik-Gerber, B., & Kensek, K. (2010). Building information modeling in architecture, engineering, and construction: Emerging research directions and trends. *Journal of Professional Issues in Engineering Education and Practice*, *136*(3), 139–147. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000023

Brandin, R., & Abrishami, S. (2021). Information traceability platforms for asset data lifecycle : blockchain- based technologies. *Smart and Sustainable Built Environment*, *10*`(3), 364–386. https://doi.org/10.1108/SASBE-03-2021-0042

Brandín, R., & Abrishami, S. (2024). IoT-BIM and blockchain integration for enhanced data traceability in offsite manufacturing. *Automation in Construction*, *159*. https://doi.org/10.1016/j.autcon.2024.105266

Buterin, V. (2014). A next-generation smart contract and decentralized application platform. *White paper*, *3*(37), 2-1.

Cachin, C. (2016, July). *Architecture of the hyperledger blockchain fabric.* Workshop Distrib. Cryptocurrencies Consensus Ledgers, Switzerland.

Celik, Y., Petri, I., & Barati, M. (2023). Blockchain supported bim data provenance for construction projects. *Computers in Industry*, *144*. https://doi.org/10.1016/j.compind.2022.103768

Chadegani, A. A., Salehi, H., Yunus, M. M., Farhadi, H., Fooladi, M., Farhadi, M., & Ebrahim, N. A. (2013). A comparison between two main academic literature collections: Web of science and scopus databases. *Asian Social Science*, *9*(5), 18–26. https://doi.org/10.5539/ass.v9n5p18

Chung, I. B., Caldas, C., & Leite, F. (2022). An analysis of blockchain technology and smart contracts for building information modeling. *Journal of Information Technology in Construction*, *27*, 972–990. https://doi.org/10.36680/j.itcon.2022.047

Clohessy, T., Treiblmaier, H., Acton, T., & Rogers, N. (2020). Antecedents of blockchain adoption: An integrative framework. *Strategic Change*, *29*(5), 501–515. https://doi.org/10.1002/jsc.2360

Dakhli, Z., Lafhaj, Z., & Mossman, A. (2019). The potential of blockchain in building construction. *Buildings*, *9*(4), 77. https://doi.org/10.3390/buildings9040077

Darabseh, M., & Martins, J. P. (2023). Protecting the intellectual property of built environment designs using blockchain technology. *Organization, Technology and Management in Construction*, *15*(1), 157–168. https://doi.org/10.2478/otmcj-2023-0011

Das, M., Tao, X., & Cheng, J. C. P. (2021). BIM security : A critical review and recommendations using encryption strategy and blockchain. *Automation in Construction*, *126*. https://doi.org/10.1016/j.autcon.2021.103682

Dejaco, M. C., Re Cecconi, F., & Maltese, S. (2017). Key performance indicators for building condition assessment. *Journal of Building Engineering*, *9*, 17–28. https://doi.org/10.1016/j.jobe.2016.11.004

Demirdöğen, G., Işık, Z., & Arayici, Y. (2023). Bim-based big data analytic system for healthcare facility management. *Journal of Building Engineering*, *64*. https://doi.org/10.1016/j.jobe.2022.105713

Deng, Y., Gan, V. J. L., Das, M., Cheng, J. C. P., & Anumba, C. (2019). Integrating 4d bim and gis for construction supply chain management. *Journal of Construction Engineering and Management*, *145*(4), 1–14. https://doi.org/10.1061/(asce)co.1943-7862.0001633

Deng, Y., Li, J., Wu, Q., Pei, S., & Xu, N. (2020). Using network theory to explore bim application barriers for bim sustainable development in china. *Sustainability*, *12*(8). https://doi.org/10.3390/su12083190

Dounas, T., Lombardi, D., & Jabi, W. (2021). Framework for decentralised architectural design bim and blockchain integration. *International Journal of Architectural Computing*, *19*(2), 157 –173. https://doi.org/10.1177/1478077120963376

Eadie, R., McLernon, T., & Patton, A. (2015, July 08). *An investigation into the legal issues relating to building information modelling (bim).* Rics Cobra Aubea, Australia.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors*. John Wiley & Sons.

Ebekozien, A., Aigbavboa, C., & Samsurijan, M. S. (2023). An appraisal of blockchain technology relevance in the 21st century nigerian construction industry : Perspective from the built environment professionals. *Journal of Global Operations and Strategic Sourcing*, *16*(1), 142–160. https://doi.org/10.1108/JGOSS-01-2022-0005

Edirisinghe, R., London, K. A., & Aranda-mena, G. (2017). Building information modelling for facility management : Are we there yet ? *Engineering, Construction and Architectural Management*, *24*(6), 1119–1154. https://doi.org/10.1108/ECAM-06-2016-0139

Elghaish, F., Hosseini, M. R., Kocaturk, T., & Arashpour, M. (2023). Digitalised circular construction supply chain : An integrated bim-blockchain solution. *Automation in Construction*, *148*. https://doi.org/10.1016/j.autcon.2023.104746

Espinoza-Zambrano, P., Marmolejo-Duarte, C., & García-Hooghuis, A. (2023). Libro del edificio electrónico (lde-e): Advancing towards a comprehensive tool for the management and renovation of multifamily buildings in spain. *Sustainability*, *15*(4). https://doi.org/10.3390/su15042957

Faraji, A., Rashidi, M., Perera, S., & Tam, V. (2024). A conceptual framework of decentralized blockchain integrated system based on building information modeling to steering digital administration of disputes in the ipd contracts. *Construction Innovation*, *24*(1), 384–406. https://doi.org/10.1108/CI-01-2023-0008

Farghaly, K., Abanda, F. H., Vidalakis, C., & Wood, G. (2019). BIM-linked data integration for asset management. *Built Environment Project and Asset Management*, *9*(4), 489–502. https://doi.org/10.1108/BEPAM-11-2018-0136

Fetters, M. D., Curry, L. A., & Creswell, J. W. (2013). Achieving integration in mixed methods designs: Principles and practices. *Health Services Research*, *48*, 2134–2156. https://doi.org/10.1111/1475-6773.12117

Geipel, M. (2017, July 07). *Blockchains will change construction.* Future of construction. https://www.futureofconstruction.org/blog/blockchains-will-change-construction/

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., Phillip, M., & Lowry, C. (2017). Bim application to building energy performance visualisation and management: Challenges and potential. *Energy and Buildings*, *144*, 218–228. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.03.032

Gotz, C. S., Karlsson, P., & Yitmen, I. (2020). Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management. *Smart and Sustainable Built Environment*, *11*(3), 532–558. https://doi.org/10.1108/SASBE-08-2020-0115

Hamledari, H., & Fischer, M. (2021). Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. *Automation in Construction*, *132*. https://doi.org/10.1016/j.autcon.2021.103926.

Heiskanen, A. (2017). The technology of trust: How the internet of things and blockchain could usher in a new era of construction productivity. *Construction Research and Innovation*, *8*(2), 66–70. https://doi.org/10.1080/20450249.2017.1337349

Hijazi, A. A., Perera, S., & Alashwal, A. M. (2023a). Developing a bim single source of truth prototype using blockchain technology. *Buildings*, *13*(1). https://doi.org/10.3390/buildings13010091

Hijazi, A. A., Perera, S., Calheiros, R. N., & Alashwal, A. (2023b). A data model for integrating bim and blockchain to enable a single source of truth for the construction supply chain data delivery. *Engineering, Construction and Architectural Management*, *30*(10), 4645–4664. https://doi.org/10.1108/ECAM-03-2022-0209

Hsu, C., Wang, J., & Hou, H. (2023). A blockchain-based parametric model library for knowledge sharing in building information modeling collaboration. *Journal of Construction Engineering and Management*, *149*(11), 1–17. https://doi.org/10.1061/JCEMD4.COENG-13060

Huang, H., Zeng, X., Zhao, L., Qiu, C., Wu, H., & Fan, L. (2022). Fusion of building information modeling and blockchain for metaverse : A survey. *IEEE Open Journal of the Computer Society*, *3*, 195–207. https://doi.org/10.1109/OJCS.2022.3206494

Hunhevicz, J. J., Motie, M., & Hall, D. M. (2022). Digital building twins and blockchain for performance-based (smart) contracts. *Automation in Construction*, *133*. https://doi.org/10.1016/j.autcon.2021.103981

Husin, A. E., & Priyawan, P. (2023). Implementation the last indonesian minister regulation of 2022 uses sem-pls and blockchain-bim to green cost efficiency. *Journal of Sustainable Architecture and Civil Engineering*, *2*(33), 96–112. https://doi.org/10.5755/j01.sace.33.2.34229

Husin, A. E., Priyawan, P., Kussumardianadewi, B. D., Pangestu, R., Prawina, R. S., Kristiyanto, K., & Arif, E. J. (2023). Renewable energy approach with indonesian regulation guide uses blockchain-bim to green cost performance. *Civil Engineering Journal*, *9*(10), 2486–2502. https://doi.org/10.28991/CEJ-2023-09-10-09

Javaherikhah, A., & Lopez, M. V. (2023a). Effective factors for implementing building information modeling using fuzzy method to manage buildings on mars. *Buildings*, *13*(12), 1–21. https://doi.org/10.3390/buildings13122991

Javaherikhah, A., Lopez, M. V., & Mohandes, S. R. (2023b). Developing an inspector-centric blockchain-enabled conceptual framework for bim management in Mars buildings. *Buildings*, *13*(11), 1–21. https://doi.org/10.3390/buildings13112858

Kamel, M. A., Bakhoum, E. S., & Marzouk, M. M. (2023). A framework for smart construction contracts using BIM and blockchain. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-37353-0

Kao, C., Chen, W., & Ho, C. (2023). Using network analysis theory to extract critical data from a construction project. *Buildings*, *13*(6), 1–18. https://doi.org/10.3390/ buildings13061539

Khan, A., Sepasgozar, S., Liu, T., & Yu, R. (2021). Integration of bim and immersive technologies for aec : A scientometric swot analysis and critical content review. *Buildings*, *11*(3). https://doi.org/10.3390/buildings11030126

Kiu, M. S., Lai, K. W., Chia, F. C., & Wong, P. (2024). Blockchain integration into electronic document management (edm) system in construction common data environment. *Smart and Sustainable Built Environment*, *13*(1), 117–132. https://doi.org/10.1108/SASBE-12-2021-0231

Lawal, O., & Nawari, N. O. (2023). Blockchain and city information modeling (cim): A new approach of transparency and efficiency. *Journal of Information Technology in Construction*, *28*, 711–734. https://doi.org/10.36680/J.ITCON.2023.037

Lee, H. L., & Billington, C. (1995). The evolution of supply-chain-management models and practice at hewlett-packard. *Informs Journal on Applied Analytics*, *25*(5), 42–63. https://doi.org/10.1287/inte.25.5.42

Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry : A systematic review, conceptual models and practical use cases. *Automation in Construction*, *102*, 288–307. https://doi.org/10.1016/j.autcon.2019.02.005

Li, W., Duan, P., & Su, J. (2021). The effectiveness of project management construction with data mining and blockchain consensus. *Journal of Ambient Intelligence and Humanized Computing*, 1–10. https://doi.org/10.1007/s12652-020-02668-7

Li, X., Asce, A. M., Lu, W., Xue, F., Wu, L., Zhao, R., Lou, J., & Xu, J. (2022). Blockchain-enabled iot-bim platform for supply chain management in modular construction. *Journal of Construction Engineering and Management*, *148*(2), 1–18. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002229

Liu, H. (2023). Enabling technologies and recent advancements of smart facility management. *Buildings*, *13*(6), 1–28. https://doi.org/10.3390/ buildings13061488

Liu, Z., Gong, S., Tan, Z., & Demian, P. (2023). Immersive technologies-driven building information modeling (bim) in the context of metaverse. *Buildings*, *13*(6), 1–30. https://doi.org/10.3390/buildings13061559

Liu, Z., Jiang, L., Osmani, M., & Demian, P. (2019). Building information management (bim) and blockchain (bc) for sustainable building design. *Electronics*, *8*(7), 1–15. https://doi.org/10.3390/electronics8070724

Liu, Z., Wu, T., Wang, F., Osmani, M., & Demian, P. (2022a). Blockchain enhanced construction waste information management : A conceptual framework. *Sustainability*, *14*(19), 1–35. https://doi.org/10.3390/su141912145

Liu, Z., Yang, Z., Liang, M., Liu, Y., Osmani, M., & Demian, P. (2022b). A conceptual framework for blockchain enhanced information modeling for healing and therapeutic design. *International Journal of Environmental Research and Public Health, 19(13),* 1–27. *https://doi.org/10.3390/ijerph19138218*

Loo, B. P. Y., & Wong, R. W. M. (2023). Towards a conceptual framework of using technology to support smart construction : The case of modular integrated. *Buildings*, *13(2).* https://doi.org/10.3390/buildings13020372

Macchi, M., Roda, I., Negri, E., & Fumagalli, L. (2018). Exploring the role of digital twin for asset lifecycle management. *IFAC-PapersOnLine*, *51*(11), 790–795. https://doi.org/10.1016/j.ifacol.2018.08.415

Motawa, I., & Almarshad, A. (2013). A knowledge-based BIM system for building maintenance. *Automation in Construction*, *29*, 173–182. https://doi.org/10.1016/j.autcon.2012.09.008

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3977007

Nawari, N. O., & Ravindran, S. (2019a, June 13). *Blockchain technologies in BIM workflow environment.* Computing in civil engineering 2019: Visualization, information modeling, and simulation - selected papers from the asce international conference on computing in civil engineering 2019. https://doi.org/10.1061/9780784482421.044

Nawari, N. O., & Ravindran, S. (2019b). Blockchain technology and BIM process: Review and potential applications. *Journal of Information Technology in Construction*, *24*, 209–238.

Ni, Y., Sun, B., & Wang, Y. (2021). Blockchain-based bim digital project management mechanism research. *IEEE Access*, *9*. https://doi.org/10.1109/ACCESS.2021.3130270

Pellegrini, L., Campi, S., Locatelli, M., Pattini, G., Martino, G., Giuda, D., & Tagliabue, L. C. (2020). Digital transition and waste management in architecture , engineering , construction , and operations industry. *Frontiers in Energy Research*, *8*, 1–21. https://doi.org/10.3389/fenrg.2020.576462

Penzes, B. (2018, December). *Blockchain technology in the construction industry: Digital transformation* *for high productivity*. Institution of Civil Engineers (ICE), London. https://www.ice.org.uk/ICEDevelopmentWebPortal/media/Documents/

Perera, S., Nanayakkara, S., Rodrigo, M. N. N., Senaratne, S., & Weinand, R. (2020). Blockchain technology: Is it hype or real in the construction industry?. *Journal of Industrial Information Integration*, *17*. https://doi.org/https://doi.org/10.1016/j.jii.2020.100125

Prakash, A., & Ambekar, S. (2021). Digital transformation using blockchain technology in the construction industry. *Journal of Information Technology Case and Application Research*, *22*(4), 256–278. https://doi.org/10.1080/15228053.2021.1880245

Raval, S. (2016). *Decentralized applications (1st ed.).* O'Reilly Media, Inc, https://www.oreilly.com/library/view/decentralized-applications/9781491924532/

Sai, A., Pradeep, E., Wing, T., Zou, Y., & Amor, R. (2021). Blockchain-aided information exchange records for design liability control and improved security. *Automation in Construction*, *126*. https://doi.org/10.1016/j.autcon.2021.103667

Sarkar, D., & Dhaneshwar, D. (2023). Automation in monitoring of construction projects through bim - iot- blockchain model. *Journal of The Institution of Engineers (India): Series A*, *104*(2), 317–333. https://doi.org/10.1007/s40030-023-00727-8

Selvanesan, H., & Satanarachchi, N. (2023). Potential for synergetic integration of building information modelling, blockchain and supply chain management in construction industry. *Journal of Information Technology in Construction*, *28.* https://doi.org/10.36680/j.itcon.2023.035

Sigalov, K., Ye, X., König, M., Hagedorn, P., Blum, F., Severin, B., Hettmer, M., Hückinghaus, P., Wölkerling, J., & Grob, D. (2021). Automated payment and contract management in the construction industry by integrating building information modeling and blockchain-based smart contracts. *Applied Sciences*, *11*(16), 1–23. https://doi.org/10.3390/app11167653

Singh, A. K., & Kumar, V. R. P. (2023). Analyzing the barriers for blockchain-enabled bim adoption in facility management using best-worst method approach. *BEPAM*, *14*(2), 164–183. https://doi.org/10.1108/bepam-04-2023-0080

Sonmez, R., Ahmadisheykhsarmast, S., & Güngor, A. A. (2022). Bim integrated smart contract for construction project progress payment administration. *Automation in Construction*, *139*, 1–12. https://doi.org/10.1016/j.autcon.2022.104294

Sood, R., & Laishram, B. (2022). A review on unexploited features of n-dimensional bim : An indian construction scenario. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (eds). *Proceedings of the 10th World Construction Symposium*, 24-26 June 2022, Sri Lanka. [Online]. (pp. 39-49). https://doi.org/10.31705/WCS.2022.4.

Suliyanti, W. N., & Sari, R. F. (2021). Blockchain-based implementation of building information modeling information using hyperledger composer. *Sustainability*, *13*(1), 1–12. https://doi.org/10.3390/su13010321

Suliyanti, W. N., & Sari, R. F. (2023). Blockchain-based double-layer byzantine fault tolerance for scalability enhancement for building information modeling information exchange. *Big Data and Cognitive Computing*, *7*(90), 18. https://doi.org/10.3390/bdcc7020090

Tao, X., Das, M., Liu, Y., & Cheng, J. C. P. (2021). Distributed common data environment using blockchain and interplanetary file system for secure bim-based collaborative design. *Automation in Construction*, *130*. https://doi.org/10.1016/j.autcon.2021.103851

Tao, X., Liu, Y., Wong, P. K., Chen, K., Das, M., Jack, C., & Cheng, P. (2022). Confidentiality-minded framework for blockchain-based bim design collaboration. *Automation in Construction*, *136*. https://doi.org/10.1016/j.autcon.2022.104172

Tao, X., Das, M., Zheng, C., Liu, Y., Wong, P. K., Xu, Y., Liu, H., Gong, X., & Cheng, J. C. P. (2023a). Enhancing bim security in emergency construction projects using lightweight blockchain-as-a-service. *Automation in Construction*, *150.* https://doi.org/10.1016/j.autcon.2023.104846

Tao, X., Wong, P. K., Xu, Y., Liu, Y., Gong, X., Zheng, C., Das, M., & Cheng, J. C. P. (2023b). Smart contract swarm and multi-branch structure for secure and efficient bim versioning in blockchain-aided common data environment. *Computers in Industry*, *149*. https://doi.org/10.1016/j.compind.2023.103922

Teisserenc, B., & Sepasgozar, S. (2021a). Adoption of blockchain technology through digital twins in the construction industry 4.0: A pestels approach. *Buildings*, *11*(670), 28. https://doi.org/10.3390/buildings11120670

Teisserenc, B., & Sepasgozar, S. (2021b). Project data categorization, adoption factors, and non-functional requirements for blockchain based digital twins in the construction industry 4.0. *Buildings*, *11*(12), 1–51. https://doi.org/10.3390/buildings11120626

Teisserenc, B., & Sepasgozar, S. M. E. (2022). Software architecture and non-fungible tokens for digital twin decentralized applications in the built environment. *Buildings*, *12*(9), 1–38. https://doi.org/10.3390/buildings12091447

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, *14*(3), 207–222. https://doi.org/10.1111/1467-8551.00375

Tsay, G. S., Staub-French, S., & Poirier, É. (2022). Bim for facilities management: An investigation into the asset information delivery process and the associated challenges. *Applied Sciences*, *12*(19), 35. https://doi.org/10.3390/app12199542

Turk, Ž., & Klinc, R. (2017). Potentials of blockchain technology for construction management. *Procedia Engineering*, *196*, 638–645. https://doi.org/10.1016/j.proeng.2017.08.052

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European Journal of Purchasing & Supply Management*, *6*(3), 169–178. https://doi.org/10.1016/s0969-7012(00)00013-7

Wang, J., Shen, Y., Xiong, X., Wang, X., & Fang, X. (2022). Research on multi-person collaborative design of bim drawing based on blockchain. *Scientific Reports* *12*(1), 1–26. https://doi.org/10.1038/s41598-022-20321-5

Wang, J., Wu, P., Wang, X., & Shou, W. (2017). The outlook of blockchain technology for construction engineering management. *Frontiers of Engineering Management*, *4*(1), 67–75. https://doi.org/10.15302/j-fem-2017006

Wijekoon, C., Manewa, A., & Ross, A. D. (2020). Enhancing the value of facilities information management (fim) through bim integration. *Engineering, Construction and Architectural Management*, *27*(4), 809–824. https://doi.org/10.1108/ECAM-02-2016-0041

Wong, R. W. M., & Loo, B. P. Y. (2022). Sustainability implications of using precast concrete in construction: An in-depth project-level analysis spanning two decades. *Journal of Cleaner Production*, *378*. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.134486

Wood, G. (2014). Ethereum: A secure decentralised generalised transaction ledger. *Ethereum Project Yellow Paper*, *151*, 1–32. https://blossom.informatik.uni-rostock.de/28/

Wu, L., & Lu, W. (2022). Linking permissioned blockchain to internet of things (iot)-bim platform for off-site production management in modular construction. *Computers in Industry*, *135*. https://doi.org/10.1016/j.compind.2021.103573

Xue, F., & Lu, W. (2020). A semantic differential transaction approach to minimizing information redundancy for bim and blockchain integration. *Automation in Construction*, *118*. https://doi.org/10.1016/j.autcon.2020.103270

Ye, Z., Kapogiannis, G., Tang, S., Zhang, Z., Jimenez-bescos, C., & Yang, T. (2023). Influence of an integrated value-based asset condition assessment in built asset management. *Construction Innovation*. https://doi.org/10.1108/CI-11-2021-0216

Yung, P., & Wang, X. (2014). A 6d cad model for the automatic assessment of building sustainability. *International Journal of Advanced Robotic Systems*, *11*(8). https://doi.org/10.5772/58446

Zandee, D. (2024). Aiming for bullseye : A novel gameplan for circular economy in the construction industry. *Engineering, Construction and Architectural Management*, *31*(2), 593–617. https://doi.org/10.1108/ECAM-03-2022-0288

Zheng, R., Jiang, J., Hao, X., Ren, W., Xiong, F., & Ren, Y. (2019). Bcbim :A blockchain-based big data model for bim modification audit and provenance in mobile cloud. *Mathematical Problems in Engineering*, *13*(1). https://doi.org/10.1155/2019/5349538

Zheng, Z., Xie, S., Dai, H.-N., Chen, X., & Wang, H. (2018). Blockchain challenges and opportunities: a survey. *International Journal of Web and Grid Services*, *14*(4), 352–375. https://doi.org/10.1504/ijwgs.2018.10016848

Zhengdao, C., Chen, Z., Xue, F., Kong, X. T. R., Xiao, B., & Lai, X. (2021). A blockchain- and iot-based smart product-service system for the sustainability of prefabricated housing construction. *Journal of Cleaner Production*, *286*. https://doi.org/10.1016/j.jclepro.2020.125391

Zhong, B., Wu, H., Ding, L., Luo, H., Luo, Y., & Pan, X. (2020). Hyperledger fabric-based consortium blockchain for construction quality information management. *Frontiers of Engineering Management*, *7*(4), 512–527. https://doi.org/10.1007/s42524-020-0128-y

Saparamadu, P.V.I.N., Jayasena, H.S. and Eranga, B.A.I., 2024. **Blueprint for a natural language processing powered nexus for** regulatory and legal landscape in construction. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 306-317. DOI: https://doi.org/10.31705/WCS.2024.24. Available from: https://ciobwcs.com/papers/

BLUEPRINT FOR A NATURAL LANGUAGE PROCESSING POWERED NEXUS FOR REGULATORY AND LEGAL LANDSCAPE IN CONSTRUCTION

P.V.I.N. Saparamadu[1], H.S. Jayasena[2], and B.A.I. Eranga[3]

ABSTRACT

The recent exponential advancements in Natural Language Processing (NLP) are catalysing a paradigm shift in the world, directing the construction industry towards an era of smart construction. The proficiency of NLP in comprehending and assimilating vast quantities of human language data aligns aptly with the construction sector's exigency for enhanced management of its unstructured textual data. Given the frequent alterations in regulatory frameworks and the dispersed nature of project data, there arises a compelling need for a Natural Language Processing Powered Compliance Management Nexus (NLP-PCMN), which facilitates expedited access to consolidated information via mobile platforms. This study aims to develop a blueprint for implementing an NLP-PCMN in the construction industry. By conducting semi-structured interviews with 20 experts spanning the domains of construction and Artificial Intelligence (AI) alongside a focus group to outline the technological framework of the NLP-PCMN, the research underscores the need to implement such a system. The envisaged system is poised to address challenges such as navigating contract clauses, correspondence analysis and ensuring legal compliance with planning and building codes and legal provisions. The proposed NLP-PCMN presents a comprehensive solution integrating these features through large language models that work as a question-and-answering system. Key findings include the necessity of automating the regulatory and legal data in construction, stakeholder empowerment through NLP-PCMN, identifying the nodes of the NLP-PCMN and the technical blueprint to implement the NLP-PCMN.

Keywords: *Artificial Intelligence (AI); Construction Law; Natural Language Processing (NLP); Smart Construction.*

1. INTRODUCTION

As compelling evidence of the contemporary paradigm shift in AI technologies, the global AI in construction market size was valued at USD 696 million in 2023 and is projected to reach fivefold by 2032 (360iResearch, 2023). Among those technologies, Natural Language Processing (NLP) technology made a significant leap in the last five

[1] Research Student, Department of Building Economics, University of Moratuwa, Sri Lanka, ishini@concolabs.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, suranga@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurue@uom.lk

years as AI exceeded human performance levels on basic reading comprehension benchmarks (Stone et al., 2021). NLP is a subfield of AI for difficult language-related problems, such as machine translation, question-answering and summarisation (Lauriola et al., 2022). The recent trend of NLP applications is a consequence of introducing Large Language Models (LLMs) such as OpenAI's ChatGPT, Google's BERT and MT5 (Zhang et al., 2022). LLMs are a subset of NLP, representing advanced models that emerged in 2018 (Cambria & White, 2014).

Although NLP applications in various fields began in the 1960s, their adaptation to the construction industry commenced in the 1990s (Khurana et al., 2023). The first application of NLP to the construction industry was developed in 1989, aiming to aid construction managers in retrieving vital information for decision-making (Khurana et al., 2023). NLP applications have been developed for its thematic areas in the construction industry. These include enhancing information and document management processes, improving compliance management, evaluating public perceptions of construction projects and optimising contract management (Hassan & Le, 2020).

Babatunde et al. (2023) revealed that proficient compliance management can be achieved through NLP by enhancing contract accuracy, efficiency and transparency. Legal and regulatory compliance in the construction industry is of paramount importance due to the complex and stringent laws governing this sector (Beach et al., 2015). Regulatory compliance ensures that construction projects adhere to established standards, codes and regulations. According to Marzouk and Enaba (2019), legal compliance includes contract management, appropriate documentation and correspondence procedures. Automating compliance processes in construction can streamline operations, reduce human error, and enhance efficiency (Beach et al., 2015). Furthermore, an automated compliance management system provides real-time monitoring and reporting capabilities (Beach et al., 2020). Integrating automation into legal and regulatory compliance processes in construction is essential for ensuring project success.

Parikh et al. (2023) documented the landmark court case that used NLP to form a judicial decision for the first time. It is a result of the evolution of NLP technology in recent years, driven by advancements in deep learning and machine learning (Khurana et al., 2023). One of the key breakthroughs has been the development of powerful language models, which have been trained on vast amounts of textual data that can capture the nuanced relationships between words and the context in which they are used (Zhang et al., 2022).

Yan et al. (2020) emphasised that the legal and regulatory data in the construction domain are available as unstructured data sources such as text documents. Therefore, efficient and intelligent extraction and interpretation of this textual data is vital for the cost-effective management of projects (Wu et al., 2022). NLP provides the solution for it through the analysis of text structures and words (Nadkarni et al., 2011). Thus, with NLP advancements continuing to unfold, it has become increasingly important for construction professionals to rethink how to leverage it to enhance their practices and processes.

It was found that numerous models have been developed for legal and contractual domains, utilising various advancements in NLP technology. For example, Beach et al. (2020) and Lee et al. (2023) have contributed models geared towards regulatory compliance automation, while Hand et al. (2021) and Lee et al. (2020) have focused on models for contract management. After testing these models, the above-mentioned literature found a significant increase in the accuracy of compliance management.

Although several NLP models have been developed in the literature, NLP adoption in the construction industry is still in its infant stage (Madan & Ashok, 2023). Wu et al. (2022) identified that the lack of awareness in the industry on utilising LLMs for their business purposes was a fundamental reason for the current state of adoption. Adding to the statement above, Madan and Ashok (2023) highlighted the limited adoption of NLP because there is not a widely recognised NLP model in commercial use, and the existing models aren't feasible for practical application in the construction sector.

Hence, it can be suggested that an ideal approach to harnessing the potential of NLP entails establishing a robust nexus comprising specialised tools tailored to be used by all stakeholders of the industry. This nexus-oriented strategy facilitates seamless integration and synergy among various NLP capabilities, avoiding the need for disparate toolsets (Mitchell & Mancoridis, 2006). A single platform housing all software tools is crucial for several reasons. It simplifies the management process by reducing the complexity and overhead associated with managing multiple systems. This approach also reduces the risk of data inconsistencies by storing and processing data within a single system (Mitchell & Mancoridis, 2006). Thus, there is a timely need for an NLP-powered nexus for effective adoption in the construction industry.

While ChatGPT has demonstrated significant capabilities in NLP, it is insufficient as a standalone solution for specialised applications such as legal research. ChatGPT's general-purpose design lacks the domain-specific knowledge (Parikh et al., 2023). Studies have shown that domain-specific NLP models significantly outperform general models in specialised fields (Jurafsky & Martin, 2021). Therefore, a tailored approach incorporating domain-specific NLP tools is essential.

Despite the growing interest in NLP tools, there remains a shortage of research on their application across various domains, including the construction industry. Jallan et al. (2019) studied the development of an NLP model to conduct a comprehensive survey of legal cases; however, they used statistical algorithms rather than LLMs. However, a study by Moon et al. (2022) used recent developments in NLP to review specifications. Furthermore, while recent research by Shaikh and Gohar (2024) has investigated the use of chatbots in contract management, it does not offer a comprehensive solution for the entire legal landscape. Therefore, this study seeks to pioneer such a concept of an accessible legal database tailored explicitly for the construction industry. Hence, it aims to develop a blueprint for implementing an NLP-powered Construction Management Network (NLP-PCMN). The paper begins with a literature review and continues by investigating the need for an NLP-PCMN. Finally, it presents an implementation blueprint detailing the architecture and key components necessary for its development.

2. LITERATURE REVIEW

2.1 NLP APPLICATIONS IN THE CONSTRUCTION INDUSTRY

Studies suggest that NLP has been used in the construction industry for following application scenarios, including filtering information, organising documents, using expert systems and automating compliance checking (Wu et al., 2022). From the literature analysis, 91 NLP models were identified for various domains, as illustrated in Figure 1. The models discussed in the literature were developed using obsolete advancements in NLP, such as rule-based techniques, probability models and neural networks. Among the main application areas, NLP for contract management accounted for 31%, making it the domain with the highest number of applications. Compliance checking application domain constituted 23% of the NLP models. Thus, the NLP models developed for the regulatory and legal landscape of the construction industry amounted to 54% of all models developed. Figure 1 shows the distribution of these models across the literature.

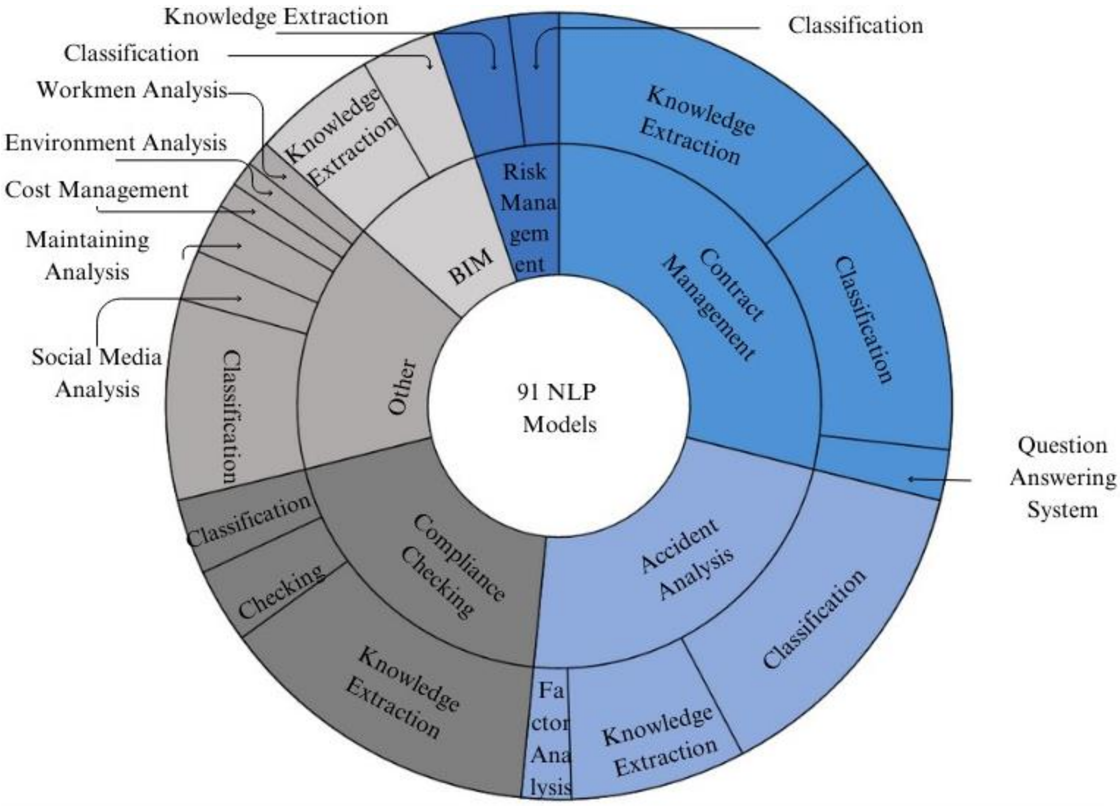


Figure 1: Distribution of NLP models across application areas (Source: Developed by authors)

2.2 STATE OF THE ART OF NLP MODELS IN CONSTRUCTION

Recent advancements in NLP have revolutionised the construction industry's approach to contract analysis and management. Notably, Padhy et al. (2021) demonstrated an 80% increase in efficiency with an NLP model designed to detect exculpatory sentences. As validated by Hand et al. (2021), F1 scores exceeding 70% indicate a reliable and effective model. Lee et al. (2019) and Lee et al. (2020) further demonstrated the competence of NLP in automatically detecting problematic clauses with impressive F1 scores of 81.8% and 80%, respectively. These findings highlight the robustness of NLP in scrutinising contractual documents, flagging critical clauses, and enhancing decision-making processes in the construction industry.

2.3 REGULATORY AND LEGAL CONSIDERATIONS IN CONSTRUCTION

To formulate a nexus facilitating efficient regulatory and legal compliance within construction projects, it is crucial to identify the textual data necessitating analysis. Through literature analysis, various types of data were identified, as outlined in Table 1.

Table 1: Sources of textual data in a construction project

Citation	Sources of Textual Data
Soibelman et al., 2008	conditions of contracts, specifications, change orders, requests for information, meeting minutes
Kelley, 2012	Statutes and ordinances, agency regulations, international treaties, case law, contract clauses
Szewc, 2022	environmental protection law, civil law regulations, public procurement regulations, property law, planning law
Murdoch & Hughes, 2002	insurance law, contract law, dispute resolution procedures, case law, standard conditions, contract data, construction service agreements, procurement law
Marzouk & Enaba, 2019	contract, variation order log, site instruction, progress reports, request for information log, cost schedule data, claim data

3. RESEARCH METHODOLOGY

Qualitative research, particularly grounded in interpretivism, stands as the optimal approach for the development of an NLP-PCMN. At the core of interpretivism lies the belief that reality is subjective, emphasising the importance of understanding the unique perspectives of the individuals involved in the data collection (Potrac et al., 2014). In the context of NLP-PCMN, this study aims to find a speculative ideal for a prospective technology that is well suited to the interpretive philosophy. By embracing qualitative methodologies, the fluidity of different experiences can be seen while shedding light on emergent patterns (Saunders et al., 2018).

The research process encompassed two phases of data collection. Initially, 20 semi-structured interviews were conducted to ascertain the need to implement a nexus for construction management within the construction domain. The interview questions were designed to understand the necessity of automating activities suitable for NLP integration and identify the nodes of the nexus. These experts were purposively selected to ensure a balanced representation across construction, digitalisation and AI industries. Table 2 provides an overview of the experts' profiles in the study.

Table 2: Profile of the experts

Nr	Designation/ Field	Experience (Years)	Country
R1	Director - Consultant QS	22	Sri Lanka
R2	Director – Contractor QS	18	Sri Lanka
R3	Engineer - Transportation Sector	18	Australia
R4	LLM Developer for Procurement	10	Australia
R5	NLP model developer for Translations	8	USA
R6	Consultant QS/5D BIM Agent	32	Sri Lanka
R7	Professor – Construction Law	20	UK
R8	Construction Contract Manager	24	UK
R9	Construction Data Analyst	8	UK
R10	Construction Project Manager	18	Sri Lanka
R11	Expert Witness in Delay Analysis	32	Sri Lanka

Nr	Designation/ Field	Experience (Years)	Country
R12	Development Manager	15	UK
R13	Contract Manager	10	Nigeria
R14	Construction Lawyer	9	UK
R15	Construction Automation Professor	20+	Australia
R16	Data Science Professor	30+	Germany
R17	Commercial Manager	15+	UK
R18	Claims Specialist	27	UAE
R19	Contract Specialist	24	UAE
R20	Chief Executive Officer/ Architect	12	UK

Following the analysis of the requirements outlined by these experts, the need to establish an NLP-PCMN was substantiated. Subsequently, a focus group was convened involving experts R4, R5, R9, and R16, proficient in AI model development, to formulate the blueprint of an NLP-PCMN. Qualitative data obtained from the discussions were subjected to content analysis, with the software NVivo 12 software facilitating systematic analysis and interpretation of the data.

4. RESEARCH FINDINGS AND ANALYSIS

4.1 IMPERATIVE FOR IMPLEMENTING AN NLP-PCMN

The importance of implementing an NLP-PCMN was investigated through expert interviews. A consensus among all respondents emphasised the criticality of effective construction management, necessitating the storage and management of a vast repository of indexed textual data within the construction domain. R1 interpreted this by stating that "*a human can't store all the information and access the information all together.*" R2, R8, R10 and R13 confirmed this by stating that this complexity can overwhelm humans, especially when sources precede the other. However, as explained by R5, AI is capable of "*Long Short-Term Memory that can access a large amount of data for a short period.*" Supporting this notion, nearly all respondents suggested that automation addresses this challenge by alleviating reliance on human memory, thereby ensuring that critical points are not overlooked. However, R14 presented a contrasting viewpoint, arguing that human interaction remains indispensable as not all information may be pertinent to resolving a legal matter. This contention was contested by R4, who proposed a model capable of training on identifying precedence.

Moreover, R7, R8, R9, R17, and R20 highlighted that many professionals engaged in contract management lack proficiency in legal affairs, often necessitating reliance on legal experts for guidance. This dependency can result in delays, costs and inefficiencies. Nevertheless, integrating legal considerations into automation fosters self-empowerment among professionals and minimises inefficiencies. Furthermore, R11 and R14 emphasised the significance of staying current with case laws, albeit interpreting them amidst evolving conditions and constantly changing planning regulations that can pose challenges. Additionally, adherence to various building codes, which may vary by location, is vital. As suggested by R20, automation streamlines this process by centralising and organising information, thereby enhancing accessibility.

4.2 STAKEHOLDER EMPOWERMENT THROUGH NLP-PCMN

The expert interviews identified all types of users that will benefit from a proposed NLP-PCMN and particular use cases of the nexus. Project managers at the site were referenced most by experts for the professionals who would be empowered the most. Furthermore, using this nexus as a legal handbook was predicted to be a use case for all its potential users. R1 described it: "*Although I might use books normally, I will use this in meetings because turning pages is not nice.*" Furthermore, R1, R12, R13, R15 and R17 addressed that the chatbot will provide a significant quality of life for entry-level professionals in the industry. Furthermore, 80% of the experts mentioned that clients will benefit from this innovation as they can "*stay in touch and understand the legal considerations of their project.*"

4.3 NODES OF THE NATURAL LANGUAGE-POWERED CONTRACT MANAGEMENT NEXUS

An NLP-PCMN ideally should provide a comprehensive solution to tackle diverse legal and regulatory compliance challenges within the construction industry. Through collaboration with experts, the focus group discerned that the main features are paramount: 'Contract Administration', 'Dispute Resolution and Litigation', 'Planning Code Compliance', 'Procurement Guidelines', 'Project Management' and 'Correspondence Analysis'. To effectively support these features, the nexus must be underpinned by vector databases capable of storing essential legal and regulatory data. Furthermore, a blueprint that seamlessly integrates suitable vector databases is paramount to addressing the concerns raised by R4 and R14 in assessing the need for an NLP-PCMN.

The primary requirement for 'Contract Administration' is enabling users to access pertinent contractual provisions governing specific scenarios, as R1, R18, and R19 emphasised. This process involves analysing contract documents, including clauses, legal requirements and particular conditions. Similarly, incorporating a case law library involves creating a classification system, metadata tagging and indexing. This integration facilitates informed decision-making in the contract administration by consolidating all required information. A case law library with databases for contract law provisions and dispute resolution procedures vector database will formulate a 'Dispute Resolution and Litigation' feature as proposed by R11.

Procurement guidelines are often subject to updates by government agencies, and they present a challenge in tracking and incorporating the latest amendments. As highlighted by R2, the ideal solution should furnish users with answers based on the most recent or recent past guidelines, identifying and integrating the latest changes. A similar mechanism can indeed be implemented for 'Correspondence Analysis' within the NLP-PCMN framework. Various records such as letters, requests for information documents, meeting minutes, progress reports, and instructions can be stored systematically, akin to the approach outlined previously. This repository of documents helps project managers stay up to date on all project-related correspondence.

Furthermore, statutes and ordinances pertinent to environment law protocols, labour law provisions, and health and safety guidelines can be made accessible through vector databases, enabling project management professionals to access this critical information swiftly. Building code compliance is another crucial regulatory aspect that project managers must adhere to. This can be achieved through specialised LLMs.

As articulated by R20, planning codes exhibit variations and are often dispersed across different urban councils. The 'Planning Code Compliance' solution involves storing these guidelines in a database and referencing attributes such as building type, location, height requirements and diverse compliance constraints for building elements. Subsequently, users can query the database by providing these attributes to ascertain the appropriate constraints governing the design of a building on a vacant plot. This approach streamlines the process of accessing and navigating planning codes during the design phase of construction projects.

4.4 IMPLEMENTATION BLUEPRINT OF THE NLP - PCMN

To implement the NLP-PCMN, in the focus group stage, the R4, R5, R9 and R16 concluded the following blueprint for its architecture. The dash lines represent the vector databases that provide sources for the specific LLM, such as 'Contract Administration'. All those primary services are connected, representing a nexus that provides an all-in-one solution for legal and regulatory compliance management, as presented in Figure 2.

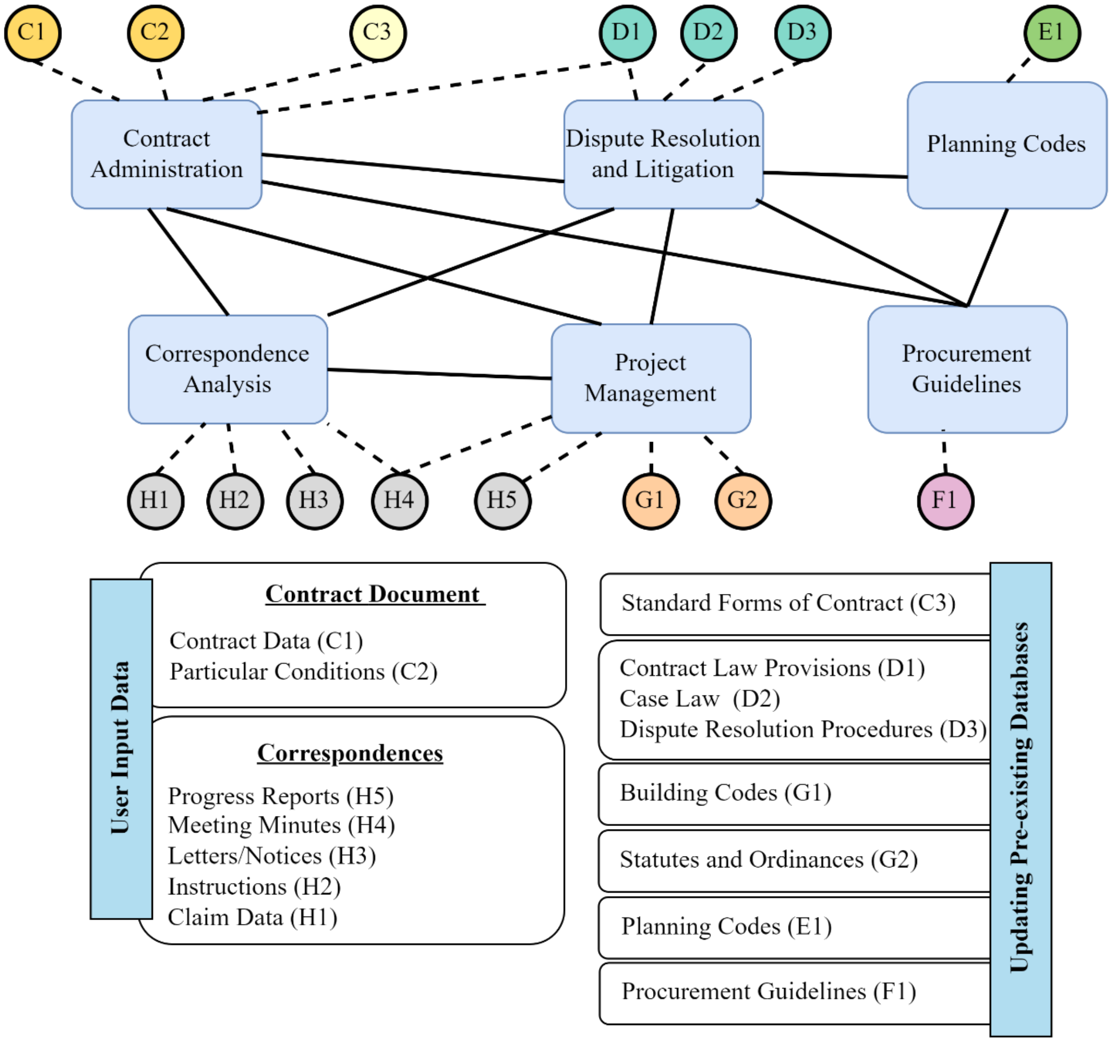


Figure 2: Blueprint for the NLP-PCMN (Source: Developed by authors)

A multi-step approach should be designed for 'Contract Administration', where a user input and pre-existing database are used. The process starts by analysing the contract document and identifying clauses, particular conditions, and contract data through keyword detection and a domain-specific LLM. Then, the document is segmented and converted into vector embeddings for efficient retrieval. When a user asks a question, the system utilises an information retrieval algorithm to extract relevant vectors. The retrieved vectors are then fed into an LLM specifically trained for contract interpretations, generating a comprehensive response that includes the answer, related clauses and document references. Figure 3 illustrates the above process.

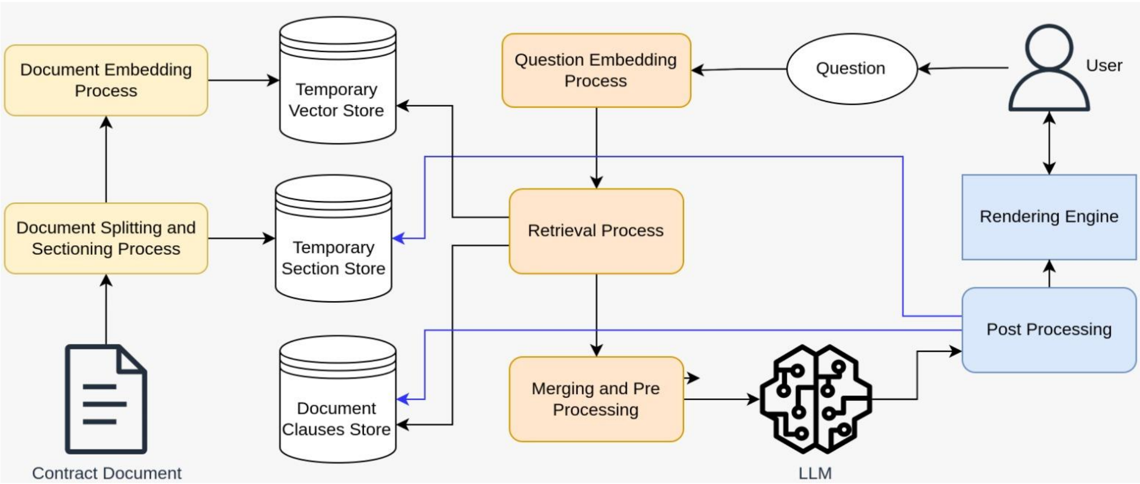


Figure 3: Synthesising user input data with pre-existing databases (Source: Developed by authors)

For ‘Correspondence Analysis’ and ‘Procurement Guidelines Compliance’, it is vital that up-to-date information is updated within the database. The following paragraphs describe the implementation of such a system as proposed by R4. An information retrieval algorithm segments the guidelines into individual clauses and extracts crucial information such as the procurement guideline and the year. Incorporating new guidelines requires adding them as new rows in the vector database. When users pose questions, the query undergoes embedding using the same mechanism as Figure 3. Following the retrieval of relevant clauses, a prompt is formulated utilising the retrieved information and the user’s question. A check is conducted to identify any duplicate clauses for the same clause number, if applicable, indicating them as “Previous” and “New” within the prompt. Subsequently, a comprehensive answer is generated.

After analysing the literature alongside this study’s findings, several key points emerge. The models discussed address specific tasks within contract management or the legal landscape. In contrast, the proposed architecture aims to integrate all necessary functions for managing legal and contractual aspects in the construction industry into one comprehensive nexus. This holistic approach ensures that various tasks are handled within a single, integrated system. Nevertheless, this study pioneers a consolidated NLP-PCMN architecture. Moreover, this architecture leverages the capabilities of LLMs, representing the forefront of NLP technology (Cambria & White, 2014). By using LLMs, the system can provide more accurate and context-aware insights, making it a powerful tool for construction’s legal and contract landscape.

Furthermore, the NLP-powered models that were introduced in the literature are tailored to particular organisations. As concluded by R1, a publicly accessible NLP-PCMN can democratise access to legal information. As Mitchell and Mancoridis (2006) highlighted this architecture offers significant advantages. This enables individuals and businesses to navigate the law without expensive legal consultations (Mitchell & Mancoridis, 2006).

5. CONCLUSIONS AND RECOMMENDATIONS

This study was directed to develop a blueprint for implementing an NLP-PCMN in the construction industry. The experts that were interviewed all highlighted the potential use cases and the need to implement an NLP-PCMN. One of the key considerations was the complexity and vast amount of textual data in construction. Therefore, effective construction management necessitates efficient storage and management of vast textual data, a task beyond human capacity alone. Automation through NLP-PCMN not only addresses this challenge by alleviating reliance on human memory but also empowers stakeholders across various levels of expertise. Stakeholder empowerment through NLP-PCMN extends to project managers, entry-level professionals, legal experts, and clients alike. By serving as a legal handbook accessible during meetings and enhancing the quality of life for industry newcomers, the NLP-PCMN promises to revolutionise workflows and decision-making processes.

The implementation blueprint for NLP-PCMN, carefully crafted by expert focus groups, underscores six significant features required to realise its full potential i.e. (i) 'Contract Administration', (ii) 'Dispute Resolution and Litigation', (iii) 'Planning Code Compliance', (iv) 'Procurement Guidelines', (v) 'Project Management' and (vi) 'Correspondence Analysis'. The nexus is powered by the integration of domain-specific vector databases. Those databases are formed by segmenting different documents in the construction industry through keyword detection and metadata tagging and then converted into vector embeddings for efficient retrieval. Furthermore, by facilitating the constantly updating legal framework, the nexus model minimises the risk of non-conformance.

Overall, by analysing all these findings, the NLP-PCMN represents a significant advancement in the construction industry, offering a comprehensive solution that addresses the intricate challenges faced by professionals in the legal and regulatory landscape. Furthermore, it could lay the foundation for enhanced collaboration, compliance and decision-making in the future of the construction industry.

To enhance the effectiveness and relevance of the NLP-PCMN, several key recommendations are proposed. Firstly, the research findings emphasise the need for NLP-powered tools in the construction industry. Therefore, it is recommended that construction industry practitioners invest in integrating NLP-PCMN systems into their existing management frameworks. Ideally, government agencies and professional institutes should develop a publicly accessible NLP-PCMN system to ensure reliability and widespread use. For research purposes, user-centric and publicly available NLP models should be developed. Developers should use the requirements of the construction industry, as identified in this study, to create effective solutions for the legal and contractual management landscape in the construction industry.

This research contributes to academia by filling the gap for a consolidated architecture of an NLP-PCMN. Additionally, it pioneers the concept of a consolidated NLP solution to the construction industry as an NLP-PCMN. It is also important to acknowledge the limitations of this study. This research considers the technological advancements up to April 2024. Grounded in interpretivism, the study acknowledges the subjectivity inherent in qualitative research, particularly when combining the knowledge from NLP developers and construction practitioners. These limitations highlight the need for future studies to consider broader samples and employ rigorous methods for interpreting qualitative data. Furthermore, Future research should include a case study using a developed model to identify potential time and cost savings as well as studies on technology adoption of NLP-powered models in the construction industry.

6. REFERENCES

360iResearch (2024). *Global AI in construction market by offering (services, solutions), deployment type (cloud, on-premises), organisation size, application, industry type: Forecast 2024-2030* (Report No. 5789100). United States. G. M. I. Inc. https://www.researchandmarkets.com/report/construction#:~:text=The%20AI%20in%20Construction%20Market,USD%203%2C226.92%20million%20by%202030

Babatunde, I., Ezirim, A., & Bid, O. (2023, September 3-9). *Enhancing contract management through Natural Language Processing(NLP): A case study of three African countries* [Paper presentation]. 5th Deep Learning Indaba, Accra, Ghana. https://openreview.net/forum?id=DUrRx78LEw

Beach, T. H., Hippolyte, J. L., & Rezgui, Y. (2020). Towards the adoption of automated regulatory compliance checking in the built environment. *Automation in Construction*, *118*(12). https://doi.org/10.1016/j.autcon.2020.103285

Beach, T. H., Rezgui, Y., Li, H., & Kasim, T. (2015). A rule-based semantic approach for automated regulatory compliance in the construction sector. *Expert Systems with Applications*, *42*(12), 5219-5231. https://doi.org/10.1016/j.eswa.2015.02.029

Cambria, E., & White, B. (2014). Jumping NLP curves: A review of natural language processing research. *IEEE Computational Intelligence Magazine*, *9*(2), 48-57. https://doi.org/10.1109/MCI.2014.2307227

Hand, D. J., Christen, P., & Kirielle, N. (2021). F*: An interpretable transformation of the F-measure. *Machine Learning*, *110*(3), 451-456. https://doi.org/10.1007/s10994-021-05964-1

Hassan, F., & Le, T. (2020). Automated requirements identification from construction contract documents using natural language processing. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *12*(2). https://doi.org/10.1061/(ASCE)LA.1943-4170.0000379

Jallan, Y., Brogan, E., Ashuri, B., & Clevenger, C. M. (2019). Application of natural language processing and text mining to identify patterns in construction-defect litigation cases. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *11*(4). https://doi.org/10.1061/(ASCE)LA.1943-4170.0000308

Kelley, G. (2012). *Construction law: An introduction for engineers, architects, and contractors*. Wiley & Sons. http://ndl.ethernet.edu.et/bitstream/123456789/13047/1/116.pdf

Khurana, D., Koli, A., Khatter, K., & Singh, S. (2023). Natural language processing: State of the art, current trends and challenges. *Multimedia Tools and Applications*, *82*(3), 3713-3744. https://doi.org/10.1007/s11042-022-13428-4

Lauriola, I., Lavelli, A., & Aiolli, F. (2022). An introduction to deep learning in natural language processing: Models, techniques, and tools. *Neurocomputing*, *470*, 443-456. https://doi.org/10.1016/j.neucom.2021.05.103

Lee, J., Ham, Y., Yi, J.-S., & Son, J. (2020). Effective risk positioning through automated identification of missing contract conditions from the contractor's perspective based on FIDIC contract cases. *Journal of Management in Engineering*, *36*(3). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000757

Lee, J.-K. et al. (2023). High-level implementable methods for automated building code compliance checking. *Developments in the Built Environment*, *15*(12). https://doi.org/10.1016/j.dibe.2023.100174

Lee, J., Yi, J.-S., & Son, J. (2019). Development of automatic-extraction model of poisonous clauses in international construction contracts using rule-based NLP. *Journal of Computing in Civil Engineering*, *33*(3). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000807

Madan, R., & Ashok, M. (2023). AI adoption and diffusion in public administration: A systematic literature review and future research agenda. *Government Information Quarterly*, *40*(1). https://doi.org/10.1016/j.giq.2023.101881

Marzouk, M., & Enaba, M. (2019). Text analytics to analyse and monitor construction project contract and correspondence. *Automation in Construction*, *98*, 265-274. https://doi.org/10.1016/j.autcon.2018.11.018

Mitchell, B. S., & Mancoridis, S. (2006). On the automatic modularisation of software systems using the bunch tool. *IEEE Transactions on Software Engineering*, *32*(3), 193-208. https://doi.org/10.1109/TSE.2006.31

Moon, S., Lee, G., & Chi, S. (2022). Automated system for construction specification review using natural language processing. *Advanced Engineering Informatics*, *51*. https://doi.org/10.1016/j.aei.2021.101495

Murdoch, J., & Hughes, W. (2002). *Construction contracts: Law and management* (5th ed.). Routledge. https://www.nibmehub.com/opac-service/pdf/read/Construction%20Contracts%20Law%20and%20Management%205th%20Edition.pdf

Nadkarni, P. M., Ohno-Machado, L., & Chapman, W. W. (2011). Natural language processing: An introduction. *Journal of the American Medical Informatics Association*, *18*(5), 544-551. https://doi.org/10.1136/amiajnl-2011-000464

Padhy, J., Jagannathan, M., & Delhi, V. (2021). Application of natural language processing to automatically identify exculpatory clauses in construction contracts. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *13*(4). https://doi.org/10.1061/(ASCE)LA.1943-4170.0000505

Parikh, P. M., Shah, D. M., & Parikh, K. P. (2023). Judge Juan Manuel Padilla Garcia, ChatGPT, and a controversial medicolegal milestone. *Indian Journal of Medical Sciences*, *75*(1), 3-8. https://doi.org/10.25259/IJMS_31_2023

Potrac, P., Jones, R. L., & Nelson, L. (2014). Interpretivism. In L. Nelson, R. Groom & P. Potrac (Eds.), *Research Methods in Sports Coaching* (pp. 31-41). Routledge. https://doi.org/10.4324/9780203797549-4

Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., Burroughs, H., & Jinks, C. (2018). Saturation in qualitative research: Exploring its conceptualisation and operationalisation. *Quality & Quantity*, *52*(4), 1893-1907. https://doi.org/10.1007/s11135-017-0574-8

Shaikh, A., & Gohar, S. (2024, May 30-31). *Study on use of text based AI Tool in construction industry Contracts* [Paper Presentation]. 3rd IBA SBS International Conference 2024, Karachi, Pakistan. https://ir.iba.edu.pk/sbsic/2024/program/59

Soibelman, L., Wu, J., Caldas, C., Brilakis, I., & Lin, K.Y. (2008). Management and analysis of unstructured construction data types. *Advanced Engineering Informatics*, *22*(1), 15-27. https://doi.org/10.1016/j.aei.2007.08.011

Stone, P., Brooks, R., Brynjolfsson, E., Calo, R., Etzioni, O., Hager, G., Hirschberg, J., Kalyanakrishnan, S., Kamar, E., & Kraus, S. (2021). *Artificial intelligence and life in 2030: The one hundred year study on artificial intelligence*. United States. University of Stanford. https://doi.org/10.48550/arXiv.2211.06318

Szewc, T. (2022). The impact of legal regulations on investment project management in construction. *Organisation and Management: Scientific Quarterly*, *1*(5), 145-154. https://doi.org/10.29119/1899-6116.2021.57.10

Wu, C., Li, X., Guo, Y., Wang, J., Ren, Z., Wang, M., & Yang, Z. (2022). Natural language processing for smart construction: Current status and future directions. *Automation in Construction*, *134*. https://doi.org/10.1016/j.autcon.2021.104059

Yan, H., Yang, N., Peng, Y., & Ren, Y. (2020). Data mining in the construction industry: Present status, opportunities, and future trends. *Automation in Construction*, *119*(1). https://doi.org/10.1016/j.autcon.2020.103331

Zhang, D., Mishra, S., Brynjolfsson, E., Etchemendy, J., Ganguli, D., Grosz, B., Lyons, T., Manyika, J., Juan, Sellitto, M., Shoham, Y., Clark, J., & Perrault, R. (2022). *The AI index 2022 annual report*. Stanford University. https://doi.org/10.48550/arXiv.2205.03468

Koralage, M.B., Kulatunga, U. and Ingirige, B., 2024. Building community resilience to economic impacts of climate change on livelihoods: The methodological perspective. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chananie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 318-329. DOI: https://doi.org/10.31705/WCS.2024.25. Available from: https://ciobwcs.com/papers/

BUILDING COMMUNITY RESILIENCE TO ECONOMIC IMPACTS OF CLIMATE CHANGE ON LIVELIHOODS: THE METHODOLOGICAL PERSPECTIVE

Malsha Buddha Koralage[1], Udayangani Kulatunga[2] and Bingunath Ingirige[3]

ABSTRACT

Climate change increasingly impacts the livelihoods of communities worldwide, damaging their economies. This raises the necessity of investigating approaches to build community resilience to the economic impacts of climate change. Thus, this study aims to propose a suitable methodology for investigating the economic impacts of climate change on communities using Causal Loop Diagrams (CLDs), an approach under system thinking. A systematic literature review of economic models of climate change was adopted as the best-suited secondary data collection method to identify economic parameters to be investigated. Then, following the philosophical position of interpretivism, with an abductive approach for theory development, is justified as suitable. Considering the credibility of the study, which had more than one data collection method, a multimethod qualitative study was conducted following a survey and case study research strategies. Four staged data collection was conducted following preliminary interviews, focus group discussions, key informant interviews, and expert interviews. Three data analysis techniques of content analysis, cross-case analysis and CLDs, were used to analyse the primary data. Then, the steps taken in this study to achieve reliability, validity, and generalisability are mentioned. These findings will be helpful for researchers in structuring research methodologies to apply system thinking in social science research, ensuring reliability, validity, and ethics.

Keywords: *Causal Loop Diagrams; Climate change; Community Resilience; Economic Impacts; Livelihood; Methodology.*

1. INTRODUCTION

Conventional wisdom holds that climate change, which is “a dynamic, multidimensional system of changes in environmental conditions that will likely influence human behaviour” (Evans, 2019), results in drastic impacts on community livelihoods, being a fundamental cause for poverty (Feulner, 2017). It results in economic losses, which worsen the living conditions of the population and thereby intensify social issues (Falco et al., 2018). The ability of the global community to respond to climate change has

[1] Research Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, nadeetharubkm.22@uom.lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Professor, School of Science, Engineering and Environment, University of Salford, UK, m.j.b.ingirige@salford.ac.uk

become more challenging, and consequently, this has created unexpected economic and/or social changes (Lotstein, 2013). For instance, Falco et al. (2018) predict that climate change will create substantial negative impacts on the global economy, especially in developing countries, and damages will be more apparent in sectors like agriculture. Hence, the economic challenges of climate change are inevitable, and there is an immediate requirement to build community resilience to these economic challenges.

Economic modelling of climate change has been identified as a prompt methodology to determine the impacts of climate change on community livelihoods, as it helps to derive the costs and benefits of climate change and guide the decision-making process in the economy (Rising et al., 2022). Further, Dekens and Hammill (2021) state that economic models of climate change are an assessment mechanism for investigating livelihood impacts as they help to determine costs, benefits, and potential trade-offs of climate change and contribute to ensuring climate change adaption in the economy. However, despite the plenty of studies which use economic models to identify parameters of climate change, which impacts the livelihoods of communities, there is a dearth of studies which apply parameters conveyed in economic models to identify their holistic impacts considering all the parameters and develop strategies to build community resilience to climate change. Here, only the direct impacts of climate change on livelihoods of the communities are considered, without extending to the associated economic impacts like damages to assets etc. Hence, the overarching aim of the study was to contribute to enhancing community resilience to the economic impacts of climate change in Sri Lanka by applying economic models.

Research methodology plays a crucial role in accomplishing research objectives as it contributes to establishing reliable and appropriate research outcomes to achieve the research aim. While there can be multiple research methodologies to accomplish a research aim, good methodology with proper research design is vital to convey reliable, precise, and valid research findings. Thus, this paper focuses on highlighting the methodological perspectives in designing a research methodology to contribute to building community resilience to climate change's economic impacts on Sri Lanka's livelihoods, unveiling evidence on unique experiences, foreseeable research challenges, ethical considerations, and best practices. The investigation and implementation of this methodology will support current and upcoming initiatives to advance the community's resilience to the economic impacts of climate change.

2. RESEARCH PROCESS DESIGN

The research process refers to the plan of structuring a research problem to arrive at conclusions (either implicit or explicit), which can be explained as the logical framework (Yin, 2013). It is iterative and dynamic process, which involves collaboration, reflection, and adaptation. Thus, the overall research was divided into five main objectives as listed below to structure next stages.

I. Review economic models of climate change and the different climatic conditions and economic parameters used in economic models of climate change.

II. Identify the economic impacts of climate change conveyed in economic models.

III. Investigate the different climatic conditions and economic parameters applicable to the Sri Lankan context.

IV. Investigate the economic impacts of different climate conditions on the livelihoods of communities in Sri Lanka.

V. Provide recommendations to increase community resilience against the economic impacts of climate change on livelihoods.

Each objective focused on some related but distinct aspects of climate resilience of community livelihoods and thus need different levels of investigations, interactions, and data collection instruments. Hence, development of a proper research methodology from the initial point of research is critical. Thus, for the literature review, 32 research studies that used economic models of climate change in the context of agriculture were selected using a Systematic Literature Review (SLR) with PRISMA search protocol, which is considered as a credible research methodology for a literature review. This is used to determine the parameters to be investigated with primary data collection along with the data collection and analysis techniques. Then, following the Saunders research onion (Saunders et al., 2019), as shown in Figure 1, an appropriate research methodology for this context has been developed, which is discussed in the following sections.

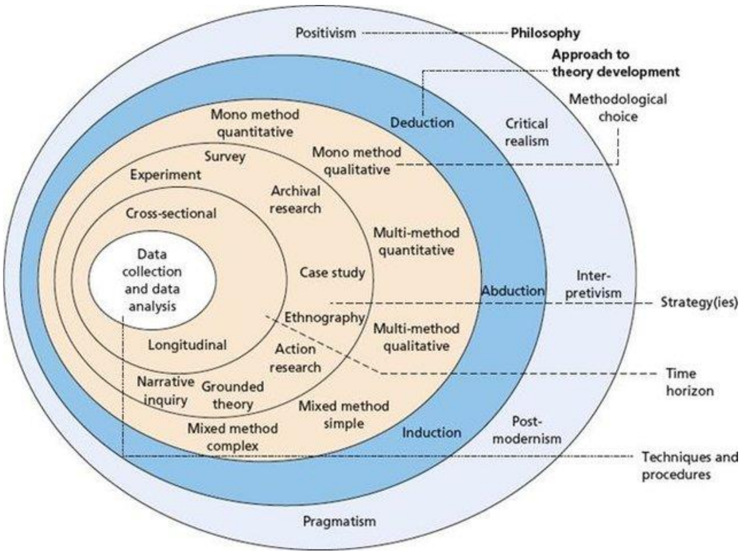


Figure 1: Saunders research onion (Source: Saunders et al., 2019)

2.1 RESEARCH PHILOSOPHY

The researcher's philosophical perspective determines how data is gathered, analysed, and interpreted in research to arrive at conclusions (Walliman, 2021). Accordingly, Ontology, epistemology, methodology, and methodologies are thus included in the philosophical components of the research philosophy (Rehman & Alharthi, 2016). The research onion by Saunders et al. (2019) identifies five research philosophies, and the conclusion was that this study suits the philosophy of interpretivism.

Interpretivism assumes that there is no universal truth (Dudovskiy, 2022), and reality can be perceived through subjective measures depending on the context. Further, interpretivists argue that humans cannot be separated from the knowledge that is created (Saunders et al., 2019) and that they provide researchers with the ability to be a part of the research where the findings are value laden. This study focused on identifying the economic impacts of climate change on communities, where the communities cannot be separated from what is being found, and different views and perspectives of human beings provide rich insights into the research problem. Further, providing recommendations to issues identified within the context of the industries requires the opinions of the most knowledgeable people on the problem and are not predefined theories but are those emerging from the context. Therefore, this study promotes subjective values and data created by the affected society. Thus, the interpretivism research philosophy was identified as the most suitable philosophy in this context.

2.2 APPROACH TO THEORY DEVELOPMENT

As indicated in the second layer of the research onion, three approaches to theory development can be identified: induction, deduction, and abduction. Furthermore, according to Saunders et al. (2019), the deductive approach involves testing the existing theories, while the inductive approach produces or generates new theories. The abductive research approach facilitates a combination of both inductive and deductive approaches. The aim of the original study is to contribute to enhancing community resilience to the economic impacts of climate change in Sri Lanka through the application of economic models. This aligns with the generation of knowledge and testing or verifying the existing economic parameters from the global context. It is context-specific, and economic impacts are required to be generated from the context simultaneously with the use of parameters identified from the literature review. Thus, the abductive research approach can be justified as the most suitable research approach for this study.

2.3 METHODOLOGICAL CHOICE

The next layer of the Saunders et al. (2019) research onion refers to the methodological choice, which can be identified in three main choices: qualitative, quantitative, and mixed method. According to Walliman (2021), the questions in terms of “how much”, “how many”, “what”, “who”, and “where” were used for quantitative research methods. In contrast, qualitative research methods study the textual data gathered through the views, experiences, attitudes, and beliefs of humans and, therefore, generally follow the question types of “how” and “why” (Fellows & Liu, 2015). As suggested by its name, the mixed method combines qualitative and quantitative methods (Doyle et al., 2009). This study deals with the research question of “How the resilience of different livelihoods of communities in Sri Lanka can be built up against climate change”, providing textual evidence. There are multiple possibilities to address this research question via qualitative or mixed method research. However, considering the time limitation, and lack of required sample to perform quantitative study, this study was aligned to qualitative research methods following below concerns. This requires input from various community groups, including the people whose livelihoods are affected, authorities currently connected to handle the impacts on livelihoods, and academic or theoretically feasible strategies to be implemented through expert groups. Following the two above requirements, this study incorporates the “multi-method qualitative” methodological choice.

2.4 RESEARCH STRATEGY

The research strategy refers to a general plan which structures the path to conducting research (Yin, 2014). Furthermore, it helps to identify the research problem in detail and develop accurate solutions to it (Mohajan, 2017). As per Saunders et al. (2019), research strategies suitable for a particular study are determined based on the selected research approach. Further to Yin (2014), there is no extant strategy or set of strategies for a research problem and it can be investigated through multiple appropriate possibilities based on reliable arguments and structure. Following that, this study uses two different research strategies of a survey, which is for Stage 01 (preliminary interviews) and Stage 04 (expert interviews), and case studies for Stage 02 (focus group discussions) and Stage 03 (key informant interviews) of data collection. The following subsections describe the rationale for adhering to particular research strategies. Though the research question, suits "action research" methodology as well, considering the time-consuming nature of action research, the below two strategies were used.

2.4.1 Survey Research Strategy

A survey is a research strategy suitable for both qualitative and quantitative data collection in a study (Cherry, 2023) to collect data from a population or a sample using a systematic procedure (Mathiyazhagan & Nandan, 2010). Furthermore, it is appropriate for answering questions which involve "who", "what", "where", "when", "how many", and "how much" (Fellows & Liu, 2015). As the preliminary interviews of this study focused on identifying "the parameters and climatic conditions derived from the economic models are prevailing in Sri Lanka", carrying out a survey was considered as the most appropriate strategy for Stage 01 - preliminary interviews data collection. Moreover, for identifying a set of strategies to build up community resilience against climate change, a survey strategy was identified as suitable, as it focuses on the question of "how community resilience to climate change is ensured in tea and paddy industries?".

2.4.2 Case Study Research Strategy

Case study refers to "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, when the boundaries between the phenomenon and context are not clearly evident and in which multiple sources of evidence are used" (Yin, 2009). According to Yin (2014), case studies can be identified as the most suitable research strategy for research problems comprising of "why" or "how" questions as they provide an in-depth investigation to answer the research question. As this study required in-depth empirical investigations to identify the economic issues experienced by the community consequent to climate change, case studies were selected as the suitable strategy for that. Accordingly, Objective 04 utilised the data collection methods followed by case studies.

Design of Case Studies

There are two case study designs, as Yin (2009) revealed: single case study design or multiple case study design. A single case study design is used in situations where a common case, longitudinal case, critical case, unusual case, or revelatory case were studied (Yin, 2014). Since this study focuses on investigating the economic impacts of climate change on the livelihoods of communities in Sri Lanka evidence from multiple case studies were deemed appropriate.

Selection of Cases

The selection criteria of cases of the case study depend on the parameters of judgement, convenience, and time and cost limitations (Yin, 2014). The selection is based on "replication", which is two types: theoretical replication and literal replication (Saunders et al., 2019). Literal replication forecasts similar results from multiple cases, whereas theoretical replication predicts contrasting results in multiple cases for predicted reasons (Yin, 2017). This study selected literal replication as the appropriate replication logic because of the expectation of seeing similar results in multiple case studies. A study conducted in Kerala, India, regarding the impacts of climate change on different cropping systems, stated that climate change tends to similarly impact both paddy and tea cultivation and act as a cause to reduce harvest (Rao et al., 2008). Another study in Eastern Africa also conveyed a similar view and stated that climate change causes a reduction of the output in both tea and paddy cultivation (Adhikari et al., 2015). Following that, this study uses literal replication in selecting cases. However, this study aims to investigate multiple impacts of climate change on the two crops, tea and paddy, in addition to reducing output. Henceforth, the findings are predicted to differ depending on the nature of the industry.

Since Sri Lanka displays different climatic patterns across various regions which are differently affected by climatic impacts, this research selected the low-country wet zone as the region for investigation based on the findings of Wickramashinghe et al. (2021), which identified the low-country wet zone as a highly vulnerable area to climate change, especially the southwestern part of it. Since the research aim was to contribute to enhancing community resilience to the economic impacts of climate change in Sri Lanka by applying economic models within the context of agriculture, different livelihoods under agriculture were selected as the case study boundary. Following time constraints, the number of cases was limited to two. The rationale for selecting two different livelihoods from agriculture is mentioned below.

Justification of Selected Livelihoods and Selected Case from Each Livelihood

Being paddy the primary food crop of Sri Lanka, and tea is identified as the primary source of foreign exchange ("Sri Lanka-Country Commercial Guide", 2024), these two crops have been selected for this study. Furthermore, tea and paddy were determined to be the two most vulnerable industries in Sri Lanka by the end of 2022 for several reasons, including weather challenges (Chandrasiri et al., 2023). Accordingly, "tea" and "paddy" were selected as two livelihoods for the case studies.

Selection of appropriate case for research is based on the researcher's judgement, followed by convenience and accessibility to data. Accordingly, cases were judged based on the frequency of damages to cases during the last five years, followed by the inclusion of any extreme events. The selection of cases was based on the criteria including, (1) cases should be based on low country wet zone, (2) industry (tea or paddy as per the case) should be the primary source of income of the participants, (3) should undergo challenges consequent to at least one of the main climatic conditions identified, (4) should have at least 12 farming families who suffer from the difficulty of continuing their livelihood mainly due to climatic barriers, and (5) accessibility to community, officers, and documents (if required).

Defining the Unit of Analysis

The selection of a unit of analysis in a case study is directly related to the research question being investigated (Yin, 2014), which is the economic impacts of climate change on different livelihoods in this research study. Accordingly, holistic cases refer to cases with a single unit of analysis, while embedded cases follow multiple units of analysis (Rowley, 2002). In this case, the data is collected on the economic impacts based on different livelihoods as the boundary. Thus, the unit of analysis has determined the "economic impacts of climate change" in these two cases, which follows a holistic case study design with a single unit of analysis.

2.5 TIME HORIZON

The next layer of the research onion proposed by Saunders et al. (2019) is the time horizon, which is identified under the cross-sectional and longitudinal categories. Cross-sectional refers to studies where data is collected at a particular time, while longitudinal conveys periodical studies in which data collection occurs over a period of time. Thus, this study falls into the category of cross-sectional approach where the study is conducted in the prevailing context. Longitudinal studies also suitable for this context, since climate change is an evolving concern, and however again it is restricted because of time constraints.

2.6 DATA COLLECTION TECHNIQUES

Data collection is the innermost layer of research onion of Saunders et al. (2019). The data used in this study falls under the two main categories of primary and secondary data. Secondary data was collected through the literature review, based on a SLR methodology following a PRISMA protocol. Since, this is a community-based research, primary data collection methods were determined considering several factors. Knowledge of the participants to understand the context, availability of participants who experienced the relevant issue and have metacognition on it, lack of technical capabilities of participants to access digital data collection tools like questionnaires, their lack of literacy and desire to spend time on manually filling research instruments, language barriers, and access to data in upcoming data collection rounds (after the community, access to key informants in the particular case should be there) are considered as main factors to determine data collection methods, instruments and sampling techniques. Thus, the primary data collection for this study is aligned in four stages within the two research strategies. Accordingly, preliminary interviews have been conducted with two academic experts selected based on convenience to refine the identified parameters from economic models to the Sri Lankan context. The next three stages of data collection followed judgemental sampling. A case study strategy was selected for the following two stages of data collection to conduct focus group discussions and key informant interviews, respectively, for each case. Finally, expert interviews were conducted to identify suitable strategies to build up community resilience to the economic impacts of climate change on two livelihoods. All four stages of data collection were conducted physically (face-to-face). The data collection language was English in Stage 01, Stage 03 and Stage 04. Stage 02 of data collection was conducted in Sinhala (the native language in Sri Lanka) as the community is unfamiliar with English. Further, prior to attending Stages 02 and 03 data collection, a background search was done to ensure whether all the participants can understand “Sinhala” language, since there are Tamil speaking communities are in Sri Lanka.

Ethical consideration is a significant aspect to be concerned in proper research and several strategies to maintain ethical nature of the study were incorporated. Formal procedures were followed in taking approvals to data collection like formal letters. Moreover, checklists were prepared for participant selection including both mandatory and optional criteria. Further, respect participants’ availability and give them priority in deciding time and location. Also, the research background, aim, and benefits of the outcomes of the study was explained in laymen language and provide them with opportunity to clarify any questions they have before participation. Their individual consent is obtained regarding participation and recording to ensure voluntary participation and provide them with the opportunity to withdraw at any time of the data collection.

2.7 DATA ANALYSIS TECHNIQUES

Since this study involves qualitative data, three qualitative data analysis techniques were selected for data analysis. Thus, the findings of Stage 01 were analysed through content analysis as it is the most popular analysis method for text data, which encrypts data with clear codes (Hsieh & Shannon, 2005). Acknowledging two methods of content analysis as manual and software based, this study utilised manual content analysis, considering the researcher's requirement to have an in-depth investigation of the data and the capacity of the data to be handled manually. The next three stages of data collection were followed by multiple methods of data analysis, such as manual content analysis, cross-case analysis and causal loop diagrams (CLDs) in system thinking for all three stages. As stated by Rose et al. (2014), the findings of the case studies are helpful and rational if cross-case analysis and tabular presentation are used. Thus, cross case analysis was conducted for the findings of two case studies. Further, since the researcher aimed to analyse the data using system thinking and CLDs (justification for using this approach is explained in subsection 3.7.1), questions were directed to have a detailed investigation on both causes and effects of climate variability and causes and consequences of change in the parameters identified through the SLR.

2.7.1 System Thinking and Causal Loop Diagrams (CLDs)

System thinking refers to the process of providing a holistic view of a problem where the components associated with the problem are presented in a graphical way that emphasises their relationships. This helps determine the behaviour of the components over time (Dhirasasna & Sahin, 2019). Further, it helps to develop a conceptual model of the parameters associated with a particular context by considering the context as a system. It helps to visualise their relationships (Crielaard et al., 2022). CLDs are conceptual models (qualitative) or structures that link the relationships between a set of causes and effects (causalities) of a particular instance or problem (Haraldsson & Bonin, 2021). It follows system thinking and considers the instance/problem and its causes and effects as a system (Groundstroem & Juhola, 2021).

As Dhirasasna and Sahin (2019) explain, CLDs are suitable for complex problems that change over time. Climate change can be considered a complex problem that changes over time (Evans, 2019) and creates concurrent impacts on the livelihoods of the community (Feulner, 2017). Accordingly, a visual representation of the impacts of climate change on livelihoods as a holistic system helps to determine the causes and consequences of the impacts on livelihood and their relationships, which will assist the users and decision-makers in studying the behaviours, predicting actions and controlling the impacts. Thus, CLDs have been identified as an effective way of analysing the identified parameters within the context of the economic impacts of climate change on livelihoods. Moreover, CLDs provide reliable results when incorporating the perspectives of multiple stakeholders (Dhirasasna & Sahin, 2019). As this study includes data collection from a wide range of respondents (focus groups of farmers, officers from administration and academic experts), the construction of reliable CLDs can be ensured.

Overall, according to Jonker and Pennik (2010), the research methodology is one that outlines the most logical, transparent, and explicit route the researcher desires to follow to address the study problem, including ideas for the origination of research, its direction, and action plan, as well as the most appropriate methods for data collecting and analysis. Accordingly, Figure 2 demonstrates the graphical framework of the research process adhered to in this study.

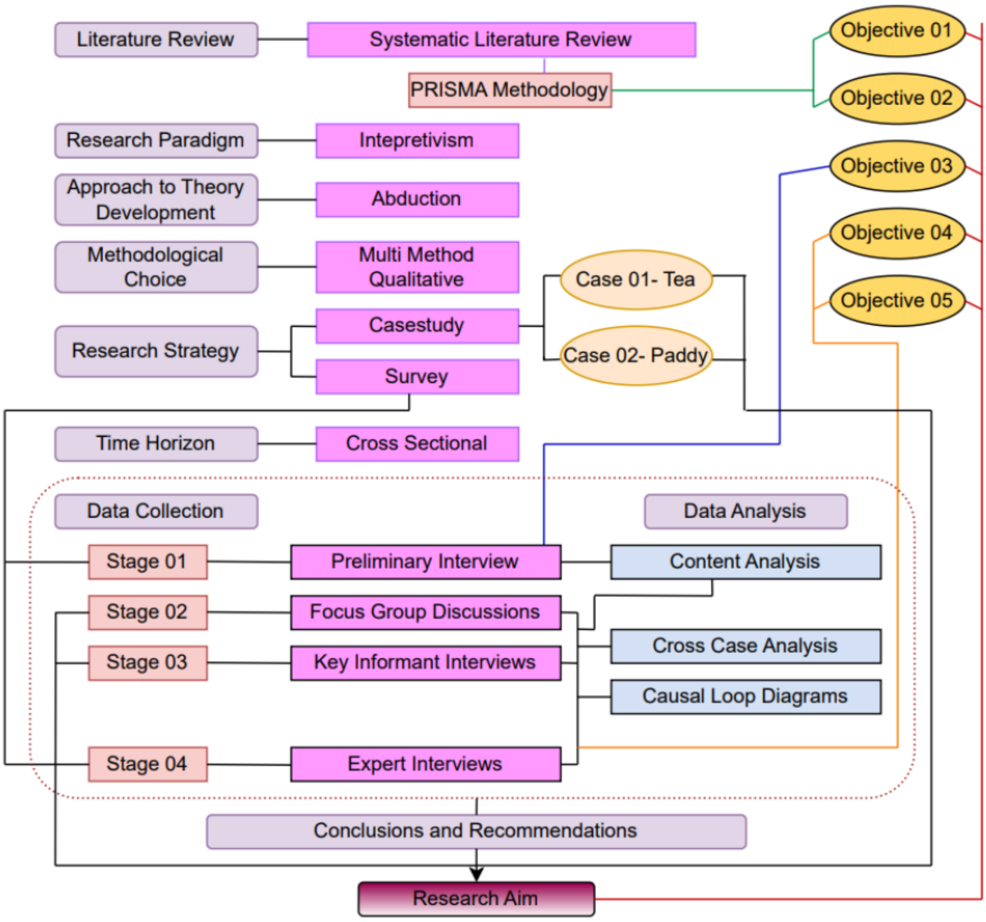


Figure 2: Research process

Through the experience of conducting this study, some best practices for research design in community research are to analyse different options with related strengths and weaknesses, acknowledge time and resource constraints, convey the participants about the need of the outcomes of the study in understandable vocabulary, acknowledge value of their participation with a proper welcome, always respect participants privacy and prioritise their convenience, maintain dynamic relationships with participants to ensure their active participation, arrange the order of the questions to maintain participants enthusiasm without feeling bored, and respect their questions. Further, being prepared and obtaining help of peers in organising the events also ensure successful outcomes.

3. RELIABILITY, VALIDITY, AND GENERALISABILITY OF RESEARCH FINDINGS

The ability of a researcher to reach the same findings and conclusions by using the same methods as the original researcher is what constitutes a study's reliability (Yin, 2017). Henceforth, reliability aims to reduce the biases and inaccuracies of the research. Further to Yin (2017), proper and detailed documentation of information and procedures followed is essential to derive an appropriate conclusion. Accordingly, Section 02 explains the detailed procedures followed in the four data collection and analysis stages. Moreover, adhering to SLR also increased the reliability of the study. The CLDs developed were validated with pattern matching with the literature, internal validity, construct validity and validation from a CLD expert external to the study. This study follows the data validation approach through the subsequent data collection round. Thus, the findings of Stage 01 were further investigated to validate Stage 02 - focus group discussions; findings of Stage 02 were validated with key informants (Stage 03), and findings of Stage 03 were validated through experts (Stage 04). Accordingly, this study used multiple sources of evidence to validate case studies, known as construct validity (Rowley, 2002).

Generalisability is limited in qualitative research as it focuses on developing content-specific and theme development instead of obtaining generalised findings (Creswell & Creswell, 2018). Nevertheless, there is an ability to generalise the findings of the case studies outside the immediate study. This can be referred to as transferability rather than generalisability, as this follows a discussion of other situations where the obtained findings might be relevant (Shemilt et al., 2011). This study uses two cases in the low country wet zone, the tea and paddy industry, which can be appropriate and transferable into other wet zone areas of Sri Lanka. Moreover, the findings can be relevant and transferable to tea growers who are suffering from landslides, as well as paddy growers who are subjected to floods. Since climate change is a global issue affecting the entire world community, the findings generated may be transferable to other industries of tropical countries subjected to similar climatic conditions and threats.

To sum up, this overall research design helps in fulfilling the research aim while maintaining research ethics, reliability and validity of findings, and good practices.

4. CONCLUSIONS

This paper discusses the authors' effort to develop a suitable methodology to investigate the economic impacts of climate change on the livelihoods of the communities to build resilience, focusing on agricultural livelihoods in Sri Lanka, maintaining research ethics and credibility. Thus, the adopted method played a significant role in disclosing valuable information and recommendations. Specifically, the methodology based for literature to identify parameters to determine economic impacts provides a holistic and reliable set of parameters for further investigation. Moreover, using case studies to investigate the problem in a real-life context ensures an accurate representation of the problem from those who have suffered. Besides, key informant interviews also disclosed real-life views from a decision-making perspective, which was finally helpful in developing reliable strategies. Overall, designing the research method from a descriptive perspective keeping records from the initial stage about expected outcomes, exploring multiple options, understanding challenges and limitations, and reviewing the reliability of research methods, help to mitigate the challenges of this study to ensure reliable outcome. The findings of this study will be beneficial for researchers who focus on applying CLDs to climate change and disaster contexts to structure a proper methodology for their data collection. Moreover, future studies can be conducted by applying the same methods to different climate contexts, climate-induced disaster contexts, and livelihood contexts in other geographical areas.

5. ACKNOWLEDGEMENTS

The authors significantly acknowledged the financial support the Global Research Fund of the University of Salford provided.

6. REFERENCES

Adhikari, U., Nejadhashemi, A. P., & Woznicki, S. A. (2015). Climate change and eastern Africa: A review of impact on major crops. *Food and Energy Security, 4*(2), 110–132. https://doi.org/10.1002/fes3.61

Chandrasiri, C. K., Tsusaka, T. W., Ho, T. D. N., Zulfiqar, F., & Datta, A. (2023). Impacts of climate change on paddy yields in different climatic zones of Sri Lanka: A panel data approach. *Asia-Pacific Journal of Regional Science, 7,* 455-489. https://doi.org/10.1007/s41685-022-00264-5

Cherry, K. (2023, November 15). *When to use surveys in psychological research.* Verywellmind. https://www.verywellmind.com/what-is-a-survey-2795787

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed method approaches* (5th ed.). Sage Publications. https://spada.uns.ac.id/pluginfile.php/510378/mod_resource/content/1/creswell.pdf

Crielaard, L., Uleman, J. F., Châtel, B. D. L., Epskamp, S., Sloot, P. M. A., & Quax, R. (2022). Refining the causal loop diagram: A tutorial for maximizing the contribution of domain expertise in computational system dynamics modeling. *Psychological Methods, 29*(1), 169-201. https://doi.org/10.1037/met0000484

Dekens, J., & Hammill, A. (2021). *Using climate economic modelling for sustainable economic development.* https://policycommons.net/artifacts/1806233/using-climate-economic-modelling-for-sustainable-economic-development/2539474/

Dhirasasna, N., & Sahin, O. (2019). A multi-methodology approach to creating a causal loop diagram. *Systems, 7*(3), 42. https://doi.org/10.3390/systems7030042

Doyle, L., Brady, A. M., & Byrne, G. (2009). An overview of mixed methods research. *Journal of Research in Nursing, 14*(2), 175–185. https://doi.org/10.1177/1744987108093962

Dudovskiy, J. (2022). *An ultimate guide to writing a dissertation in business studies: A step-by-step assistance* (6th ed.). http://research-methodology.net/about-us/ebook/

Evans, G. W. (2019). Projected behavioral impacts of global climate change. *Annual Review of Psychology, 70*, 449–474. https://doi.org/10.1146/annurev-psych-010418-103023

Falco, C., Donzelli, F., & Olper, A. (2018). Climate change, agriculture and migration: A survey. *Sustainability, 10*(5), 1405. https://doi.org/10.3390/su10051405

Fellows, R., & Liu, A. (2015). *Research methods for construction* (4th ed.). Wiley-Blackwell. https://www.wiley.com/en-us/Research+Methods+for+Construction%2C+4th+Edition-p-9781118915738

Feulner, G. (2017). Global challenges: Climate change. *Global Challenges, 1,* 5-6. https://doi.org/10.1002/gch2.1003

Groundstroem, F., & Juhola, S. (2021). Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems. *Mitigation and Adaptation Strategies for Global Change. 26*(29). https://doi.org/10.1007/s11027-021-09967-0

Haraldsson, H., & Bonin, D. (2021). *Using systems approach to integrate causal loop diagrams modelling in the foresight project scenarios for a sustainable Europe 2050.* Swedish Environmental Protection Agency. https://www.diva-portal.org/smash/get/diva2:1579896/FULLTEXT01.pdf

Hsieh, H. F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research, 15*(9), 1277–1288. https://doi.org/10.1177/1049732305276687

Sri Lanka-Country commercial guide. (2024, May 08). International Trade Administration. https://www.trade.gov/country-commercial-guides/sri-lanka-agricultural-sector

Jonker, J., & Pennink, B. (2010). *The essence of research methodology: A concise guide for master and PhD students in management science.* Springer Science & Business Media.

Lotstein, E. L. (2013). Global climate change impacts in the United States: A State of knowledge report from the U.S. global climate change research program. *Journal of Geography, 112*(4). https://doi.org/10.1080/00221341.2013.770905

Mathiyazhagan, T., & Nandan, D. (2010). Survey research method. *Media Mimansa, 4*(1), 34–45. https://krishanpandey.com/rpapersd/Surver-Content.pdf

Mohajan, H. K. (2017). Two criteria for good measurements in research: Validity and reliability. *Annals of Spiru Haret University. Economic Series, 17*(4), 59– 82. https://doi.org/10.26458/1746

Rao, G. S. L. H. P., Mohan, H. S. R., Gopakumar, C. S., & Krishnakumar, K. N. (2008). Climate change and cropping systems over Kerala in the humid tropics. *Journal of Agrometeorology, 10*(2), 286–291. https://www.cabidigitallibrary.org/doi/full/10.5555/20093179081

Rehman, A. A., & Alharthi, K. (2016). An introduction to research paradigms in distance education. *International Journal of Educational Investigations, 3*(8), 51–59.

Rising, J., Tedesco, M., Piontek, F., & Stainforth, D. A. (2022). The missing risks of climate change. *Nature, 610*, 643–651. https://doi.org/10.1038/s41586-022-05243-6

Rose, S., Spinks, N., & Canhoto, A. I. (2014). *Management research: Applying the principles* (1st ed.). Routledge. https://doi.org/10.4324/9781315819198

Rowley, J. (2002). Using case studies in research. *Management Research News, 25*(1), 16–27. https://doi.org/10.1108/01409170210782990

Shemilt, I., Mugford, M., Vale, L., Marsh, K., & Donaldson, C. (Eds.). (2011). *Evidence-based decisions and economics: Health care, social welfare, education and criminal justice*. John Wiley & Sons. https://doi.org/10.1002/9781444320398

Saunders, M., Lewis, P., & Thornhill, A. (2019). Research methods for business students (8th ed.). Pearson Education Limited. http://localhost:8080/xmlui/handle/123456789/490

Walliman, N. (2021). *Research methods: The basics.* Routledge. https://doi.org/10.4324/9781003141693

Wickramasinghe, M. R. C. P., De Silva, R. P., & Dayawansa, N. D. K. (2021). Climate change vulnerability in agriculture sector: An assessment and mapping at divisional secretariat level in Sri Lanka. *Earth Systems and Environment, 5*(3), 725–738. https://doi.org/10.1007/s41748-021-00206-9

Yin, R. K. (2009). *Case study research: Design and methods* (4th ed.). Sage Publications.

Yin, R. K. (2013). Validity and generalization in future case study evaluations. *Evaluation, 19*(3), 321–332. https://doi.org/10.1177/1356389013497081

Yin, R. K. (2014). *Case study research: Design and methods* (5th ed.). Sage Publications.

Yin, R. K. (2017). *Case study research and applications: Design and methods* (6th ed.). Sage Publications.

Rodrigo, N., Wijewickrama, M.K.C.S., Rajenthiran, N., Jayathilaka, W. and Chang, R., 2024. Challenges and solutions for women in construction industry related disciplines: A Literature Review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 330-340. DOI: https://doi.org/10.31705/WCS.2024.26. Available from: https://ciobwcs.com/papers/

CHALLENGES AND SOLUTIONS FOR WOMEN IN CONSTRUCTION INDUSTRY RELATED DISCIPLINES: A LITERATURE REVIEW

Navodana Rodrigo[1], M.K.C.S. Wijewickrama[2], Nirusika Rajenthiran[3], Wimarshi Jayathilaka[4] and Ruidong Chang[5]

ABSTRACT

The construction industry has been male dominated for a long time, making it challenging for women to enter or advance in their careers. Despite significant reserves and initiatives by governments, organisations, construction, and researchers, the industry still has a significant gender gap, with women being underrepresented both in terms of numbers and seniority. Although many studies have been conducted into the education, recruitment, and retention of women in the industry, the reasons for their underrepresentation are still not fully understood. Efforts to attract and retain women in construction have been implemented unevenly on an ad hoc basis. This study aims to examine the challenges that women face while developing their careers in the construction industry-related disciplines and provide solutions to mitigate those challenges. Moreover, this study seeks to investigate the challenges and solutions through an extensive literature review. This literature review has exposed that extreme and inflexible work hours, gendered culture and informal rules, limited career development opportunities, and undesirable perceptions of women's abilities are the main factors and problems that cause women to leave the construction industry. Moreover, considering solutions to overcome challenges in the career of women in construction mainly by training, targeting women in recruitment, developing new skills, mentoring, strong industry partnerships to create female-friendly work experiences and improved policies. This study would be beneficial for the government, construction organisations, and women who are willing to work in the construction industry-related disciplines.

Keywords: *Career; Challenges; Construction Industry; Solutions; Women.*

---

[1] Lecturer, School of Architecture and Civil Engineering, The University of Adelaide, Australia, navodana.rodrigo@adelaide.edu.au

[2] Lecturer, School of Architecture and Civil Engineering, The University of Adelaide, Australia, chamitha.wijewickrama@adelaide.edu.au

[3] Doctoral Researcher, School of Architecture and Civil Engineering, The University of Adelaide, Australia, nirusika.rajenthiran@adelaide.edu.au

[4] Doctoral Researcher, School of Architecture and Civil Engineering, The University of Adelaide, Australia, wimarshi.rathugamagedona@adelaide.edu.au

[5] Senior Lecturer, School of Architecture and Civil Engineering, The University of Adelaide, Australia, ruidong.chang@adelaide.edu.au

1. INTRODUCTION

The construction industry is overlooking numerous capable individuals who neither engage in nor pursue careers, hence women represent an underutilised resource for fulfilling the labour needs of this industry (Oo et al., 2020), and there is strong evidence that tackling the gender disparity has been necessary since the latter half of the 20th century (Carnemolla & Galea, 2021). Over the last two decades, the construction industry has seen a persistent underrepresentation of women in craft and trade occupations, with their employment fluctuating between a mere 5% and 15% of the total workforce worldwide (Hasan et al., 2021). In 2019, women made up 9.9% of all construction workers in the United States (Bureau of Labor Statistics [BLS], 2022). Likewise, women made up just 3.1% of all technicians and trade workers employed in Australia's construction sector in 2019 (Department of Corrections of New Zealand, 2021). The demand for more women participation in the construction industry has been highlighted to address the labour shortage, promote equality, and increase productivity (Norberg & Johansson, 2021). Despite the significant progress that has been made in terms of understanding the challenges faced by women in the construction sector, there are still fundamental causes for their persistent underrepresentation (Galea et al., 2015). To gain a comprehensive understanding of the root causes and develop effective strategies that can encourage women's full participation and advancement in the construction industry, it has to be thoroughly investigated (Oo et al., 2020).

To create practical solutions for improving women's career development in the construction industry, it is crucial to have a better understanding of the challenges faced by women working in construction and the factors that contribute to their career success. The solutions designed to support women's career development in construction should address the challenges women face and reinforce the factors that lead to their success. However, limited evidence shows the effectiveness of the existing solutions and their contribution to alleviating the challenges or strengthening the factors that lead to women's success in the construction industry. Therefore, this study has been conducted to identify the challenges faced by women in the construction industry and pose solutions for overcoming those challenges. This research examines the lack of representation of women in the construction industry, emphasising its global nature. The following sections of this paper have been structured as research methodology, research findings and discussions, and conclusion and recommendations.

2. RESEARCH METHODOLOGY

Conducting a literature review is imperative for strengthening the foundation of the research by gathering the most current and relevant knowledge in the field. To achieve the research aim, a comprehensive literature review was conducted on women in construction. The existing knowledge was obtained through secondary sources such as journal articles and conference papers. The study employed an exploratory research methodology with a qualitative approach. The exploratory design helped identifying the various issues faced by women in the construction industry and provided a deeper understanding of the situation with potential solutions.

As the methodology for this article, it is expected to apply a literature review approach. Various keywords were searched within the Scopus and Web of Science databases to find the relevant articles for review. Scopus and Web of Science databases are selected because they are two of the leading sources for scientific and technical research. The publishing period was decided to be between 2014-2024 to reduce the search scope. The selection of keywords was primarily based on the themes associated with women in the construction industry. Keywords like “women” OR “female” AND “challenge*” OR “barrier*” OR “participation” OR “career” AND “construction” OR “building” were considered important to capture relevant literature. These terms were chosen based on their significance in the field and their relevance to the research aim. However, articles were identified relating to the targeted topic in specific. The topics were broadened, and the articles' abstracts were carefully read to check their relevance.

The literature review included studies that examined various aspects of women's participation in the construction industry, including workforce representation, career advancement, organisational culture, and challenges to entry. Studies focusing on interventions to promote women in construction and solutions for mitigating challenges were also considered. Exclusion criteria were applied to filter out irrelevant publications, such as those not directly related to the construction sector.

3. RESEARCH FINDINGS AND DISCUSSION

The literature on challenges impacting women's careers and experiences within the construction sector has identified the most significant obstacles. These findings indicate that women in construction face marginalisation and insist on various stereotypes and informal regulations inherent to the profession. Subsections 3.1 and 3.2 discuss challenges faced by women and solutions for encouraging women's participation in the construction industry respectively.

3.1 CHALLENGES FACED BY WOMEN IN CONSTRUCTION

Women often face the challenge of having their professional competence scrutinised, questioned, or devalued (Galea et al., 2018). The authors further mentioned that this can be a frustrating experience that undermines their confidence and can make it difficult to advance in their careers. As a result of the review, this study highlighted fourteen significant challenges faced by women in the construction industry. Table 1 presents the identified challenges based on the review.

Table 1: Challenges faced by women in the construction industry.

No.	Challenges	Source
01	Difficulties in family and work life balance	[1], [2], [3], [4], [9], [10], [11], [12]
02	Stereotypes/Unfair perception of women’s capabilities	[2], [3], [4], [5], [6], [9], [10]
03	Gender segregation and discrimination	[2], [7], [8], [10], [12]
04	Sexual harassment	[2], [9], [10], [12]
05	Male-dominant industry image	[4], [9], [12]
06	Physical/mental health	[3], [4], [12]
07	Workplace culture	[4], [10], [11]
08	Leadership limitations/ Slow career progression	[2], [9]
09	Social interactions issues	[10], [11]

No.	Challenges	Source
10	Unfair recruitments	[2], [10]
11	Lack of appreciation /rewards for efforts	[4]
12	Lack of guidance/role models/mentors	[11]
13	Lack of sanitation facilities for women	[12]
14	Socio-cultural issues	[2]

Sources: [1] Bowen et al. (2017); [2] Navarro-Astor et al. (2017); [3] Rosa et al. (2017); [4] Sunindijo & Kamardeen (2017); [5] Galea et al. (2018); [6] Jenkins et al. (2018); [7] Bridges et al. (2019); [8] Nwaogu et al. (2019); [9] Emond (2020); [10] Tapia et al. (2020); [11] Oo et al. (2021); [12] Pamidimukkala & Kermanshachi (2023)

The construction sector's culture is seen as one of the most significant hurdles to women's participation in the sector (Oo et al., 2020). In addition to that, the authors determined that in a masculine culture, women find it challenging to integrate subordinates because it seems they are reluctant to receive orders from a female sometimes. Throughout their career paths, women confront obstacles and gender bias (Zhang et al., 2021). According to Table 1, previous studies pointed out that the difficulties in balancing family and work life are significant obstacles for women in the construction sector. Given the societal expectation for women to assume the primary responsibility for caring at home, achieving a harmonious equilibrium between their work and personal lives has been difficult, particularly for those pursuing professions in the construction industry (Rosa et al., 2017). Conversely, males are not burdened with the same domestic tasks and may consequently allocate more time to their professional pursuits (Sunindijo & Kamardeen, 2017). Moreover, stereotypes or unfair perceptions of women's capabilities are also major challenges faced by the women workforce in the construction industry (Emond, 2020). For example, the prevailing perception associated with the construction sector depicts it as a domain exclusively for individuals who embody traditional notions of masculinity, characterised by engaging in strenuous physical labour (Azhar & Amos, 2014). However, this caricature fails to acknowledge the presence of women in such roles. Consequently, this provides an obstacle for women as their entry into the sector would be seen as diverging from the established norms (Emond, 2020).

Gender segregation and discrimination, as well as sexual harassment, are also significant challenges for female workers in the construction industry (Tapia et al., 2020). As highlighted by Navarro-Astor et al. (2017), harassment involves intimidating verbal or physical conduct and exclusionary actions based on a person's distinctions. Discrimination, on the other hand, involves unequal treatment and a lack of advantageous opportunities. When a woman makes a mistake, it's often seen as a reflection of her gender rather than a simple individual error (Bridges et al., 2019). This double standard not only undermines her abilities but also perpetuates the notion that women are not as capable as men. Also, it's high time to break free from this flawed perception and start evaluating women based on their merit, not just their gender (Nwaogu et al., 2019). Gender disparity within the construction sector poses challenges for women employed in the industry and those excluded from secure, high-paying employment (Afolabi et al., 2019).

In the construction industry, which is primarily male-dominated, many biases persist against women, both on the job site and in leadership roles (Azhar & Amos, 2014). Some people have low expectations of women's talents, especially regarding physically demanding tasks on construction sites (Emond, 2020). Women experience a lack of support after returning from maternity leave (Baker & French, 2018). The limited part-time job availability poses a significant challenge to women's retention in the construction industry, where full-time job availability is necessary (Baker & French, 2018). Maintaining good physical and mental health is another challenge for women in the construction industry (Rosa et al., 2017). There are a number of reasons for physical or mental health issues, such as being overworked, the stressful nature of the workplace, and the responsibilities of family life (Oo et al., 2021). In addition, there is a need for a better understanding of how gender-related discrimination affects mental health in the construction industry (Nwaogu et al., 2019).

It is a well-known fact that the construction industry culture of gender discrimination perpetuates unfairness towards female professionals (Emond, 2020). Lack of social interaction is another challenge for female employees in the construction sector (Oo et al., 2021). From the recruitment process to career progression and retention, women face different rules and implications than their male counterparts, indicating a biased and discriminatory system (Navarro-Astor et al., 2017). It is high time we recognise and take action to rectify this systemic issue. In addition, Perrenoud et al. (2020) revealed that male executives normally receive more vocational training than female counterparts.

The lack of constructive guidance, such as a lack of role models or mentors, can have a significant impact on an individual's growth and development (Yates, 2001). High-stress levels linked to careers include a lack of recognition and encouragement from supervisors, being asked to do repetitive minor tasks, being undervalued, and having a low potential for career advancement (Loosemore & Waters, 2004). According to Pamidimukkala and Kermanshachi (2023), unfortunately, many construction sites do not provide enough sanitation for female personnel, leading to a range of health issues and difficulties in construction sites. As stated by Jenkins et al. (2018), women often face discrepancies between their perceived societal roles and the construction industry's image. They are subjected to unfair judgment of their training needs, misjudged performance compared with male counterparts, and are often restricted to clerical/administration roles (Dainty et al., 2000). As per this study, it is clear that interventions and strategies are needed to overcome challenges that restrict women's professional advancement in the construction sector.

3.2 SOLUTIONS FOR THE CHALLENGES FACED BY WOMEN IN THE CONSTRUCTION INDUSTRY

Several factors influenced women's career choices, with the most significant ones being the chance to develop new abilities and tackle challenging tasks, the capacity to self-motivate, and interest in the industry (Oo et al., 2020).

It is imperative to provide adequate training programs such as team building, workshops and seminars working with project team members, and communication proficiencies improvement programs for employees in construction industry workplaces to be familiar with workplace culture and develop good communication (Fernando et al., 2014). There is a pressing need for strong collaborations with industries to provide apprenticeship programs that include work experiences that are desirable to women (Simon & Clarke, 2016). Research indicates that mentors and role models play a crucial role in the career and professional growth of women, and female employees benefit from the motivation and emotional support provided by mentors, resulting in beneficial outcomes

(Pamidimukkala & Kermanshachi, 2023). When female mentors are available, students have the opportunity to observe women working in these industries and learn strategies for navigating the male-dominated culture. This is crucial in increasing girls' participation in apprenticeships (Simon & Clarke, 2016). As stated by Azhar and Amos (2014), increased access to training opportunities that facilitate leadership roles and career advancement will likely result in improved levels of job satisfaction among women.

According to Tapia et al. (2020), outreach to female high school students is one effective way to encourage female involvement in the construction industry. The growth of an inclusive culture made the acceptance of a wide range of perspectives and views more accessible, which in turn increased the motivation for women to pursue careers in the industry (Emond, 2020). Moreover, self-adaptation to the working environment through developing new skills to complete challenging tasks, self-derived motivation, and interest in trades is a proper way for women to overcome many challenges within the industry. It is vital to ignore negative gender-based behaviours and to make an effort to "fit in" with the environment to overcome numerous gender-related challenges that are present in the workplace (Agapiou, 2002). Furthermore, positive supervisor support and responsiveness to complaints are needed (Azhar & Amos, 2014). Encouraging women to pursue careers in the construction industry can also be accomplished by granting them equal responsibilities and opportunities for advancement (Gupta, 2023).

As identified by Pamidimukkala and Kermanshachi (2023), numerous construction sites lack adequate sanitation facilities for female workers, resulting in various health problems for these workers. It was discovered that providing adequate sanitary facilities at construction sites would be advantageous in encouraging women to engage in the construction industry and mitigate significant health and safety concerns. Some other solutions for challenges faced by female practitioners in the construction industry are to promote organisational cultures that are flexible, promote effective time management, and establish policies for parental leave (Gupta, 2023).

Women certainly must be resilient and develop their technical, interpersonal, and coping skills to have a successful career in the construction industry (Ghanbaripour et al., 2023). Encouraging more women to join the construction industry requires a comprehensive approach that supports their development of technical, interpersonal, and coping skills (Turner et al., 2021). The findings of a study conducted by Oo et al. (2020) present that recruitment strategies, remuneration, workplace structure, working conditions, incentive systems, and the mentoring and training of entry-level female personnel can enhance the percentage of female employees in the construction industry while simultaneously ensuring that their professional aspirations and job contentment are adequately addressed. Moreover, improved policies and legislation, and support from professional bodies, can lead to a substantial impact on increasing the number of women joining or remaining in the construction industry (Emond, 2020).

Figure 1 illustrates a summary of solutions extracted from reviewed literature within this study.

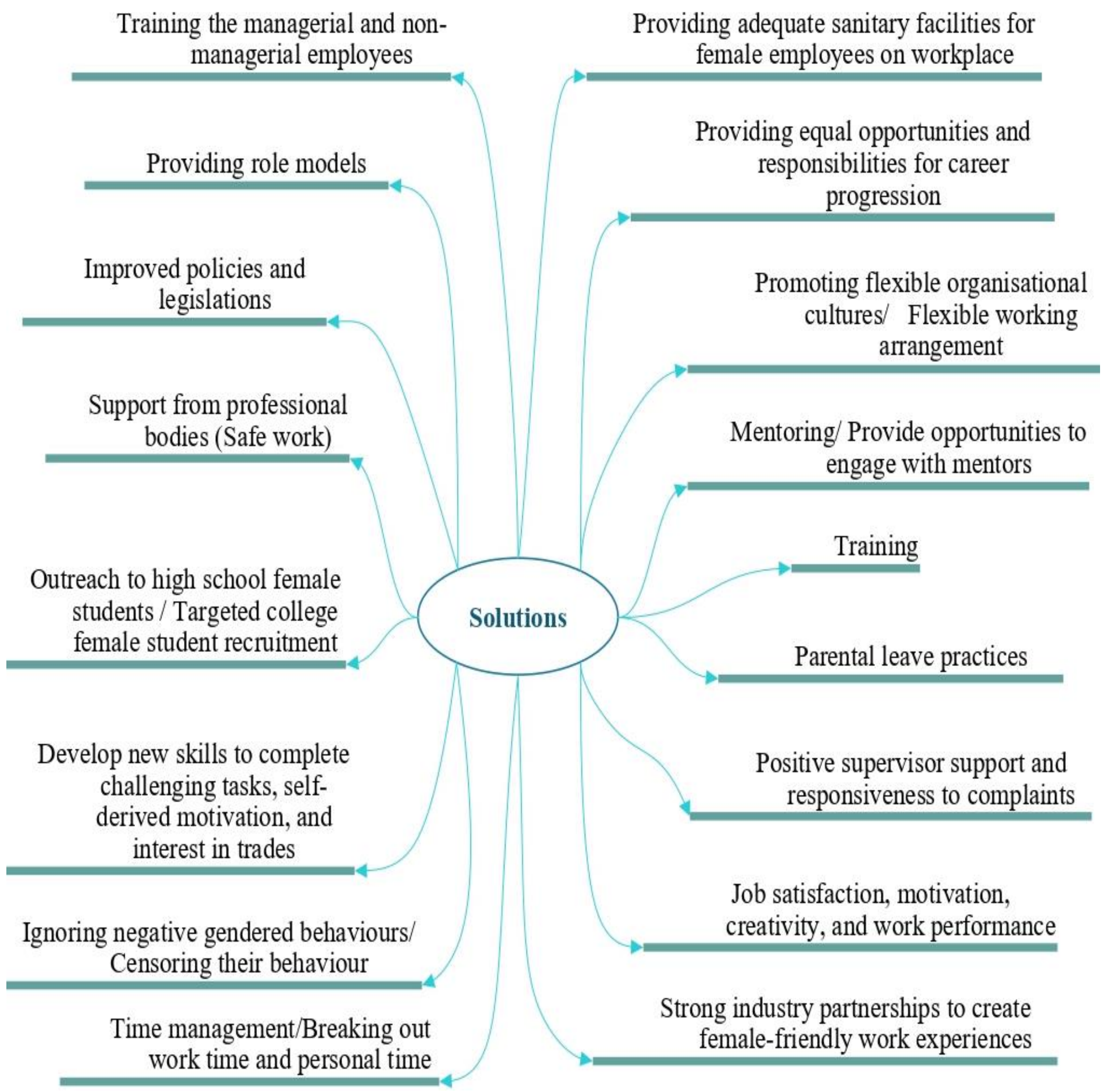


Figure 1: Solutions for the challenges faced by women in the construction industry.

4. CONCLUSIONS AND RECOMMENDATIONS

This study identified challenges faced by women in construction and explores potential solutions to mitigate those challenges through a literature review. Moreover, this study has emphasised research findings demonstrating that women's experiences in various construction roles are significantly impacted not only by the nature of the work but also by gender discrimination and inappropriate conduct in the workplace. As a result, researchers are urging for further research to actively promote wellbeing and address organisational injustices associated with gender inequality and harassment. It also contributes to new insights into gender in construction by exploring how women in the industry are discursively represented.

It is identified that women who pursue careers in construction face several challenges such as struggling to balance work and family life, being unfairly perceived as less capable, experiencing gender discrimination and sexual harassment, working in a male-dominated industry, dealing with mental health issues, and navigating workplace culture. In addition, the construction industry presents numerous challenges to women's career advancement by slow progression, social interaction issues, unfair recruitment practices, lack of appreciation, and socio-cultural issues all contribute to an unfair and unequal workplace. It is essential to address these challenges to create a fair and equitable working environment for women in construction. Unlocking the full potential of talented and capable women is essential for the construction industry to thrive.

To increase the number of women who join and stay in the construction industry, it is necessary to introduce legal and social interventions that address the underlying socioeconomic factors in their favour. It is crucial for all stakeholders, including governments, construction firms, and labour unions, to collaborate and intervene to find a solution. This study suggests solutions for identified challenges as offering individual development programs, training, and flexible work arrangements for female employees can benefit construction employers. The importance of this study lies in enhancing the comprehension of women's career progression and recruitment within the construction sector. The insights gained could aid government bodies and professional organisations in formulating policies and approaches to strengthen women's career advancement in construction.

Women's career development in construction can be achieved through measures such as advocating for flexible work arrangements, ensuring equal opportunities and responsibilities for career advancement, improving access to adequate sanitary facilities, and implementing fair parental leave policies. These initiatives collectively contribute to strengthening women's careers within the construction industry. Encouraging female students to pursue studies in construction is only part of the equation; retaining them throughout their studies and careers is equally crucial to ensure the future vitality of the construction industry.

Furthermore, this paper serves as the initial conceptualisation of an inquiry into the challenges women encounter in the construction industry. The outcomes will aid in formulating a roadmap for implementing policies addressing gender equality and promoting women's participation in the construction sector. This summary outlines a path forward for advancing women's inclusion and empowerment within the construction industry. As a result, there is a call for more extensive research to offer governments and policymakers the necessary insights for designing more effective initiatives. Rather than solely focusing on attraction efforts, the consensus is that women are more likely to stay in the industry if the workplace environment is enhanced by addressing gendered informal norms, thereby creating a more favourable atmosphere for current female employees. This improvement would not only enhance the sector's reputation but also elevate its image, ultimately encouraging more female graduates to pursue occupations in construction. Achieving this goal necessitates academics and policymakers adopting a systemic thinking approach to recognise the characteristics of the system, its causal connections, and points of leverage. This approach would enable the establishment of a framework to aid in developing more efficient strategies and initiatives.

Construction industry practitioners should increase the involvement of women to enhance construction practices. Further research is recommended to explore the feasibility of employing women in construction at different levels of work. To encourage women's participation in construction, they must be supported and encouraged to make unconventional decisions from an early age. Encouraging women's participation in the construction industry is crucial for equal opportunities and diversity. To achieve this, families, communities, educational institutions, and government must support and empower young girls to make unconventional decisions from an early age. Doing so can break down gender stereotypes and create a more inclusive and innovative industry.

5. ACKNOWLEDGEMENTS

The paper acknowledges the funding provided by University of New South Wales (UNSW) as per the collaboration agreement between UNSW and University of Adelaide for the project, 'Women in Construction'.

6. REFERENCES

Afolabi, A., Oyeyipo, O., Ojelabi, R., & Patience, T. (2019). Balancing the female identity in the construction industry. *Journal of Construction in Developing Countries*, *24*(2), 83–104. https://doi.org/10.21315/jcdc2019.24.2.4

Agapiou, A. (2002). Perceptions of gender roles and attitudes toward work among male and female operatives in the Scottish construction industry. *Construction Management and Economics*, *20*(8), 697–705. https://doi.org/10.1080/01446190210000024989

Azhar, S., & Amos, M. K. (2014). *Women in construction: Successes, challenges and opportunities - A USACE case study*. 50th ASC Annual International Conference, 22–25. http://ascpro0.ascweb.org/archives/cd/2014/paper/CPRT249002014.pdf

Baker, M., & French, E. (2018). Female underrepresentation in project-based organizations exposes organizational isomorphism. *Equality, Diversity and Inclusion*, *37*(8), 799–812. https://doi.org/10.1108/EDI-03-2017-0061

Bowen, P., Govender, R., Edwards, P., & Cattell, K. (2017). Work-related contact, work–family conflict, psychological distress and sleep problems experienced by construction professionals: An integrated explanatory model. *Construction Management and Economics*, *36*(3), 153–174. https://doi.org/10.1080/01446193.2017.1341638

Bridges, D., Krivokapic-Skoko, B., Bamberry, L., Jenkins, S., & Wulff, E. (2019). A trade of one's own regional NSW stakeholder findings - The barriers and proposed solutions for women in non-traditional male dominated trades. Charles Sturt University. https://doi.org/10.13140/RG.2.2.14072.39686

Bureau of Labor Statistics. (2022). *Women in the labor force: A databook.* (1097). United States Department of Labor. https://www.bls.gov/opub/reports/womens-databook/2021/home.htm

Carnemolla, P., & Galea, N. (2021). Why Australian female high school students do not choose construction as a career: A qualitative investigation into value beliefs about the construction industry. *Journal of Engineering Education*, *110*(4), 819–839. https://doi.org/10.1002/jee.20428

Dainty, J., Neale, H., & Bagilhole, M. (2000). Comparison of men's and women's careers in U.K. construction industry. *Journal of Professional Issues in Engineering Education and Practice*, *126*(3), 110–115. https://doi.org/10.1061/(ASCE)1052-3928(2000)126:3(110)

Department of Corrections of New Zealand. (2021). *Annual Report 2020/2021*. (61). Minister of Corrections. https://www.pvh.com/-/media/Files/pvh/investor-relations/PVH-Annual-Report-2020.pdf

Emond, O. (2020). *Women in the construction industry.* (Issue April). https://www.randstad.co.uk/women-construction-2020/

Fernando, N. G., Amaratunga, D., & Haigh, R. (2014). The career advancement of the professional women in the UK construction industry: The career success factors. *Journal of Engineering, Design and Technology*, *12*(1), 53–70. https://doi.org/10.1108/JEDT-04-2012-0018

Galea, N. P., Rogan, A., Powell, A. Loosemore., A. M., & Chappell, L. (2018). *Demolishing gender structures*. https://assets.csi.edu.au/assets/research/Demolishing-Gender-Structures-Summary-Report.pdf

Galea, N., Powell, A., Loosemore, M., & Chappell, L. (2015). Designing robust and revisable policies for gender equality: Lessons from the Australian construction industry. *Construction Management and Economics*, *33*(5–6), 375–389. https://doi.org/10.1080/01446193.2015.1042887

Ghanbaripour, A. N., Tumpa, R. J., Sunindijo, R. Y., Zhang, W., Yousefian, P., Camozzi, R. N., Hon, C., Talebian, N., Liu, T., & Hemmati, M. (2023). Retention over attraction: A Review of women's experiences in the Australian construction industry; Challenges and solutions. *Buildings*, *13*(2), 1–19. https://doi.org/10.3390/buildings13020490

Gupta, N. (2023). Women in STEM in India: Understanding challenges through social constructionist perspective. *American Behavioral Scientist*, *67*(9), 1084–1103. https://doi.org/10.1177/00027642221078518

Hasan, A., Ghosh, A., N.M., M., & Thaheem, M. J. (2021). Scientometric review of the twenty-first century research on women in construction. *Journal of Management in Engineering*, *37*(3), 1–16. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000887

Jenkins, S., Bamberry, L., Bridges, D., & Krivokapic-Skoko, B. (2018). Skills for women tradies in regional Australia: a global future. *International Journal of Training Research*, *16*(3), 278–285. https://doi.org/10.1080/14480220.2018.1576329

Loosemore, M., & Waters, T. (2004). Gender differences in occupational stress among professionals in the construction industry. *Journal of Management in Engineering*, *20*(3), 126–132. https://doi.org/10.1061/(asce)0742-597x(2004)20:3(126)

Navarro-Astor, E., Román-Onsalo, M., & Infante-Perea, M. (2017). Women's career development in the construction industry across 15 years: Main barriers. *Journal of Engineering, Design and Technology*, *15*(2), 199–221. https://doi.org/10.1108/JEDT-07-2016-0046

Norberg, C., & Johansson, M. (2021). 'Women and "ideal" women': The representation of women in the construction industry. *Gender Issues*, *38*(1), 1–24. https://doi.org/10.1007/s12147-020-09257-0

Nwaogu, J., Chan, A., Hon, C., & Darko, A. (2019). Review of global mental health research in the construction industry: A science mapping approach. *Engineering Construction & Architectural Management*, *27*(2), 385–410. https://doi.org/10.1108/ECAM-02-2019-0114

Oo, B. L., Lim, B., & Feng, S. (2020). Early career women in construction: Are their career expectations being met? *Construction Economics and Building*, *20*(3), 1–19. https://doi.org/10.5130/AJCEB.v20i3.6867

Oo, B. L., Lim, T. H. B., & Zhang, Y. (2021). Women workforce in construction during the COVID-19 pandemic: Challenges and strategies. *Construction Economics and Building*, *21*(4), 38–59. https://doi.org/10.5130/AJCEB.V21I4.7643

Pamidimukkala, A., & Kermanshachi, S. (2023). Occupational challenges of women in construction industry: Development of overcoming strategies using delphi technique. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *15*(1), 1–8. https://doi.org/10.1061/(asce)la.1943-4170.0000571

Perrenoud, A. J., Bigelow, B. F., & Perkins, E. M. (2020). Advancing women in construction: Gender differences in attraction and retention factors with managers in the electrical construction industry. *Journal of Management in Engineering*, *36*(5), 1–9. https://doi.org/10.1061/(asce)me.1943-5479.0000808

Rosa, J. E., Hon, C. K. H., Xia, B., & Lamari, F. (2017). Challenges, success factors and strategies for women's career development in the Australian construction industry. *Construction Economics and Building*, *17*(3), 27–46. http://epress.lib.uts.edu.au/journals/index.php/AJCEB/article/view/5520/6138

Simon, L., & Clarke, K. (2016). Apprenticeships should work for women too! *Education and Training*, *58*(6), 578–596. https://doi.org/10.1108/ET-02-2016-0022

Sunindijo, R. Y., & Kamardeen, I. (2017). Work stress is a threat to gender diversity in the construction industry. *Journal of Construction Engineering and Management*, *143*(10), 1–36. https://doi.org/10.1061/(asce)co.1943-7862.0001387

Tapia, M., Safapour, E., Kermanshachi, S., & Akhavian, R. (2020). Investigation of the barriers and their overcoming solutions to women's involvement in the U.S. construction industry. *Construction Research Congress*, 1–10. https://doi.org/10.1061/9780784482872.088

Turner, M., Zhang, R. P., Holdsworth, S., & Andamon, M. M. (2021). Taking a broader approach to women's retention in construction: Incorporating the university domain. *Proceedings of the 37th annual ARCOM conference, ARCOM 2021, September*, 188–197.

Yates, J. K. (2001). Retention of non-traditional engineering and construction professionals. *Journal of Management in Engineering*, *17*(1), 41–48. https://doi.org/10.1061/(ASCE)0742-597X(2001)17:1(41)

Zhang, R. P., Holdsworth, S., Turner, M., & Andamon, M. M. (2021). Does gender really matter? A closer look at early career women in construction. *Construction Management and Economics, 39*(8), 669–686. https://doi.org/10.1080/01446193.2021.1948087

Sepalage, K.D., Ranadewa, K.A.T.O., Wijerathna, M.R.D.P., Parameswaran, A. and Weerasooriya, D., 2024. Challenges for commercial management in the construction industry: Case for Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 341-352. DOI: https://doi.org/10.31705/WCS.2024.27. Available from: https://ciobwcs.com/papers/

CHALLENGES FOR COMMERCIAL MANAGEMENT IN THE CONSTRUCTION INDUSTRY: CASE FOR SRI LANKA

K.D. Sepalage[1], K.A.T.O. Ranadewa[2], M.R.D.P. Wijerathna[3], A. Parameswaran[4] and D. Weerasooriya[5]

ABSTRACT

Commercial management significantly contributes to preserving the value of construction projects and sustaining the industry. The fundamental purpose of commercial management is creating and maximising value through informed decision-making and overseeing the project. However, despite its critical importance, there exists a significant research gap regarding the challenges faced in effectively managing the commercial aspects of construction projects. Therefore, this study aims to investigate the challenges of commercial management in construction projects. Quantitative research approach was adopted to fulfil the aim of the study. The questionnaire survey was conducted among professionals in the construction industry which were chosen using the snowball sample method. Accordingly, an online questionnaire form was distributed among the professionals and collected seventy responses. Findings indicate that commercial management plays a pivotal role in project success, with parameters such as cost performance and anticipated profit levels being strongly influenced by effective commercial practices. However, challenges such as poor communication, change management, and external market forces pose significant obstacles. The study underscores the importance of addressing these challenges to enhance project outcomes and advocates for the adoption of innovative approaches to bolster commercial management practices in the construction industry. By shedding light on the unique challenges faced by commercial managers in Sri Lanka, the paper contributes to a deeper understanding of how cultural, regulatory, and economic factors influence commercial management practices in different contexts. This knowledge expansion facilitates cross-contextual comparisons and strengthens the theoretical foundations of commercial management in the construction industry.

Keywords: *Challenges; Commercial Management; Construction Industry.*

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, kawshalya.dilhan98@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, tharushar@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dewminiperera98@gmail.com
[4] PhD Scholar, School of Engineering, Design and Built Environment, Western Sydney University, Australia, aganaparameswaran@gmail.com
[5] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dilanw@uom.lk

1. INTRODUCTION

Many researchers emphasise commercial or business success as a key ingredient of successful construction projects (Moradi & Kähkönen, 2022; Ramlee et al., 2016). Shenhar and Dvir (2007) define commercial or business success as managing the profit margins of a project. Lowe (2013) emphasises the importance of commercial management in safeguarding the profits, minimising the costs, maximising the income and managing the cash flow. Popov et al. (2022) define commercial management as an integral process of management systems that interconnects economics, and financial processes to efficiently utilise resources to produce intended commercial results. Moreover, commercial management is considered the intermediary link between traditional project management and organisational theories centred on business and financial administration (Perera et al., 2016).

The fundamental purpose of commercial management is creating and maximising values through informed decision-making and overseeing the project (Royal Institution of Chartered Surveyors [RICS], 2017). Many researchers have highlighted different techniques and practices that provide successful commercial control of projects. Among them, viewing the big picture, thinking laterally, risk analysing, converting required work into packages, negotiating, and communicating are significant attributes of commercial management (Lowe & Leiringer, 2006). Besides, RICS (2016) identifies estimating, value engineering, supply chain management, valuing work, cost value analysis, cash flow management and commercial decision-making as effective commercial management practices. Thus, commercial management is vital to ensure financial and contractual success while liaising with key project stakeholders (Linkoaho et al., 2020). Moreover, an organisation could exceed expected returns and build improved client relationships with improved commercial control and management (RICS, 2016). However, despite its critical importance, there exists a significant research gap regarding the challenges faced in effectively managing the commercial aspects of construction projects. Therefore, this paper aims to investigate the challenges of commercial management in construction projects in Sri Lanka.

First, a comprehensive literature review on commercial management, the role of commercial management in the construction industry and challenges for commercial management of construction projects is presented. Subsequently, the methodology utilised in this study is presented. Following this, the research findings and their corresponding discussion are outlined, culminating in the presentation of conclusions.

2. LITERATURE REVIEW

2.1 COMMERCIAL MANAGEMENT

The term commercial management is predominantly used in electronic and telecommunication, energy and oil, defence and aerospace, financial services, pharmaceutical and healthcare, engineering and construction sectors (Lowe, 2013). However, Lowe and Leiringer (2006) state that commercial management is ambiguous in its literal interpretation, making it challenging to establish a clear boundary due to its wide practical applicability. Many authors and professional bodies have defined commercial management with different interpretations as shown in Table 1.

Table 1: Definition of commercial management

Definitions	Reference
Commercial management is an integral process of management systems that interconnects economics, and financial processes to efficiently utilise resources to produce intended commercial results.	Popov et al. (2022)
Commercial management is an autonomous discipline which presents organisational theories to bond with conventional project management frameworks in project-based organisations.	Dalcher (2017)
Commercial management encompasses contractual and commercial activities, functions and the entire process from project inception to completion in individual firms and project organisations.	Lowe & Leiringer (2006)
Commercial management is a controlling and administrating process of financial transactions with the prime motive of generating profits.	Lowe et al. (1997)

According to the various interpretations summarised in Table 1, the essence of commercial management is focusing on integrating financial and economic transactions with organisational goals.

2.2 ROLE OF COMMERCIAL MANAGEMENT IN CONSTRUCTION PROJECTS

Commercial management plays a pivotal role in the commercial and financial success of a construction project (RICS, 2017). The unique characteristics of the construction industry including project based and fragmented structure, dynamic nature, elevated level of risks and substantial investments, necessitate the adoption of a distinctive set of commercial management practices (Assaad et al., 2020). Moreover, Lowe and Leiringer (2006) claim that in the construction-related literature, there are two predominant interpretations of commercial management: the first considers commercial management to be a subset of project management about specific projects; and the second interchanges the terms 'quantity surveying' and 'commercial management. Nevertheless, researchers and professional bodies have developed numerous definitions for the commercial management of construction projects as indicated below in Table 2.

Table 2:Definition of commercial management in construction projects

Definition	Reference
Commercial management involves project valuation, change control, financial accounting and controlling and subcontract administration.	Pearson (1996)
Commercial management in construction entails budgeting and forecasting, interim valuation, subcontract administrating, contract management, cost value analysis and teamwork and partnering.	Walker & Wikie (2002)
Commercial management in construction pertains to financial oversight of projects, entailing regular monitoring and reporting of cash flow and profitability. This process involves evaluating and advising financial implications and recommending appropriate management measures.	RICS (2017)

Accordingly, commercial management is a broad field with a variety of responsibilities specific to certain industries, notably in the construction industry, where commercial management is particularly focused on the complexities of project financials and coordination. Pearson (1996) highlights the breadth of commercial management, citing its essential involvement in several project aspects, including project valuation, change control, financial accounting and controlling, and subcontract administration. Walker and Wilkie (2002) offer a more narrowly focused viewpoint that is unique to the construction industry emphasising crucial tasks; forecasting, budgeting, managing subcontracts, and cooperating with others, stressing the significance of financial planning and teamwork in project success. In addition, RICS (2017) goes into further detail about the financial oversight component of commercial management in the construction industry, recognising the need for consistent monitoring, cash flow reporting, and assessing financial implications to guide management choices. Overall, these definitions highlight the complexity of commercial management and how important it is to ensure successful project execution through careful financial planning, strategic coordination, and ongoing monitoring. Perera et al. (2016) visually represent these cost and commercial management practices with reference to RIBA Plan of Work 2013. According to him, the project initiates with the commercial decision of investment. Afterwards during the preconstruction stages cost modelling is undertaken until the pre-tender estimate is formulated, and the post-tender estimate undergoes cost analysis. Subsequently, in the construction stage, project planning, maintaining cash flow, interim valuations, establishing cost control systems, change control, and financial reporting activities are undertaken. Ultimately after the construction stage, final accounts are prepared marking the closeout of the project, and operation and maintenance cost control systems are implemented continuing until the end of the useful lifetime of the project. Hence, commercial management plays a significant role throughout the lifecycle of the project.

2.3 CHALLENGES FOR COMMERCIAL MANAGEMENT OF CONSTRUCTION PROJECTS

The unique characteristics of the construction industry and the management practices in the industry have caused many challenges for commercial management (Chapman, 2016; Navon, 2005). Numerous studies have highlighted various challenges. Table 3 outlines the challenges in the commercial management of construction projects.

Table 3: Challenges of commercial management

Challenges	Definition	Reference
Dynamic, fragmented, and inherently complex characteristics of construction projects	These intrinsic characteristics of the construction industry lead to many problems such as poor communication and coordination, disputes among parties, unpredictable environment and cultural issues. As a result, many commercial problems occur concerning time overruns and delays.	1,2,3
Influence from external market forces	The construction industry is highly sensitive to external market forces - political, economic, environmental, and technological factors, to name a few. Alterations in these factors, such as natural disasters, unforeseeable ground conditions, changes in governmental policies and legislation, demographic shifts affecting labour demand, inflation, and price fluctuation, have a direct effect on commercial transactions, resulting in adjustments to costs and project programs.	4,5
Inefficient administration of data	The construction sector generates a huge amount of data that stakeholders are required to exchange. The administration of this data is necessary to prevent project failure and disputes. Unfortunately, due to the volume and complexity of data, the majority of projects fail to effectively manage it, resulting in ineffective planning, execution, and risk management.	6,7
Change management	Project changes are inevitable in construction projects and possess an unexpected character. These project changes have an impact on several commercial concerns, such as increasing costs and delays in project completion. These kinds of concerns may raise disputes.	8,9
Inefficient tools to analyse the project performances	Existing project performance measurement tools primarily focus on financial aspects like return on investment and profit per unit, but have inadequacies like lagging metrics, lack of strategic focus, and insufficient data on quality, relationships, and environment. Traditional adversarial approaches are being replaced with partnering approaches to achieve win-win results and reduce confrontation.	10,11

[1] (Chapman, 2016) ; [2] (Nasrun et al., 2014) ; [3] (Khan et al., 2016); [4] (Sun & Meng, 2009); [5] (Wu et al., 2004); [6] (Martínez-Rojas et al., 2015); [7] (Tanga et al., 2022); [8] (Rahman et al., 2022); [9] (Chen et al., 2015); [10] (Navon, 2005); [11] (Cheung et al., 2004)

As discussed in Table 3, the commercial management of construction projects encounters significant challenges due to distinct features of construction projects, such as their fragmented and dynamic nature, susceptibility to external forces, and involvement of multiple parties. The combined impact of these challenges can result in financial losses and timely completion of the project, ultimately jeopardising the overall success of construction projects. Researchers have proposed numerous management theories and technological solutions to overcome these issues. Out of those solutions, many studies have identified lean as a better management philosophy based on value-adding for construction management (Koskela, 2020; Li et al., 2020). Further Babalola et al. (2019) emphasise that the adoption of lean practices in construction projects helps to predict costs and manage budgets, ensuring that financial objectives are met with fewer changes and delays. Similarly, commercial management also adds financial value to construction projects to meet the financial objectives of the project. (Lowe & Leiringer, 2006; RICS 2017). Therefore, a thriving need arises to empirically investigate the challenges for commercial management in Sri Lankan construction industry.

3. METHODOLOGY

The study aims to investigate the challenges of commercial management in construction projects. Quantitative research allows data comparability, reproducibility of results, independence from the observer, and analytical simplicity by breaking down the topic into its most basic components (Porte, 2010). Therefore, the study adopts a quantitative approach to fulfil its intended objectives. First, a comprehensive literature review is conducted, analysing the commercial management practices in the construction industry to identify the challenges for commercial management.

A questionnaire is a type of quantitative research that conducts systematic investigations of social issues utilising statistical or numerical data (Lewin, 2005). Hence, this research has used a questionnaire survey through Google Forums since it processes a user-friendly interface which makes it easier for respondents to feed data and offers several data analysing options to achieve the aim of the study. The questionnaire survey was conducted among professionals in the construction industry which were chosen using the snowball sample method. Accordingly, an online questionnaire form was distributed among the professionals and collected 70 responses. Data analysis is the systematic arrangement and classification of data via the use of advanced assessments and interpretations, intending to reveal noteworthy implications, regularities, and motifs within observable and auditory information (Creswell & Creswell, 2005). The quantitative data was analysed using RII to derive a correlation among variables.

4. RESEARCH FINDINGS

The questionnaire survey collects data in the form of close-ended questions with a five point “Likert scale”. Findings of such close-ended questions are analysed and discussed with the aid of Relative Important Index (RII) calculations.

4.1 SIGNIFICANCE OF COMMERCIAL MANAGEMENT FOR PROJECT SUCCESS

The questionnaire survey also explored the pivotal role of commercial management in the success of a construction project concerning a rating scale of 1 to 5. Accordingly, the survey results establish a RII of 0.946, firmly supporting the concept that commercial management is not only a contributing element but a significant determinant for project success. The distributions of the results and the agreement of the opinions among the respondents are further illustrated in the box plot shown in Figure 1.

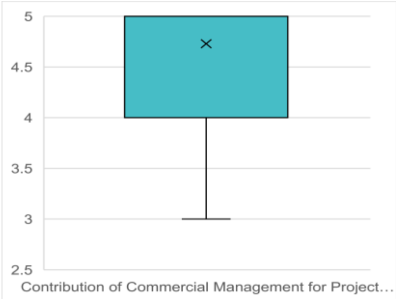


Figure 1: Contribution of commercial management for project success

The box plot in Figure 1 shows that the interquartile range of the distribution is tightly clustered towards the upper end of the scale between 4 and 5. This range is shown by the box part of the figure, which represents the middle 50% of ratings. Additionally, the cross symbol enclosed in the box signifies that the distribution has a mean value of 4.72. Hence, it is evident that commercial management is vital for the success of a construction project. Furthermore, several project parameters are dependent on the success of commercial management. Table 4 illustrates the effects of effective commercial management on anticipated profit levels, cost performance, completion dates, and quality assurance, using the scale percentage of respondent's opinions and the RII value as indicators.

Table 4: Analysis of effective commercial management

Project Parameters	**Scale Percentage (%)**					**RII**	**Rank**
	1	**2**	**3**	**4**	**5**		
Anticipated profit levels	0.03	0.01	0.13	0.51	0.31	0.81	2
Cost performance	0.03	0.00	0.10	0.46	0.41	0.85	1
Completion date	0.03	0.03	0.27	0.40	0.27	0.77	3
Quality assurance	0.04	0.10	0.24	0.43	0.19	0.72	4

According to Table 4, cost performance and anticipated profit levels are ranked first and second, respectively, with RII values over 0.80. Hence, the success of commercial management has a predominant impact on these parameters. Additionally, commercial management significantly impacts the completion date, with an RII of 0.77. On the other hand, quality assurance has the lowest RII of 0.72, indicating that commercial management still has a considerable influence on this parameter. Thus, the table concludes the importance of commercial management for project success and the success of project parameters.

4.2 CHALLENGES TO THE SUCCESS OF COMMERCIAL MANAGEMENT IN CONSTRUCTION PROJECTS

Even though commercial management plays a significant role in project success, many projects fail commercially resulting in loss in anticipated profits and cost performances.

The questionnaire survey identifies reasons for such failures as described in Figure 2 along with their RII values and respondents' opinions.

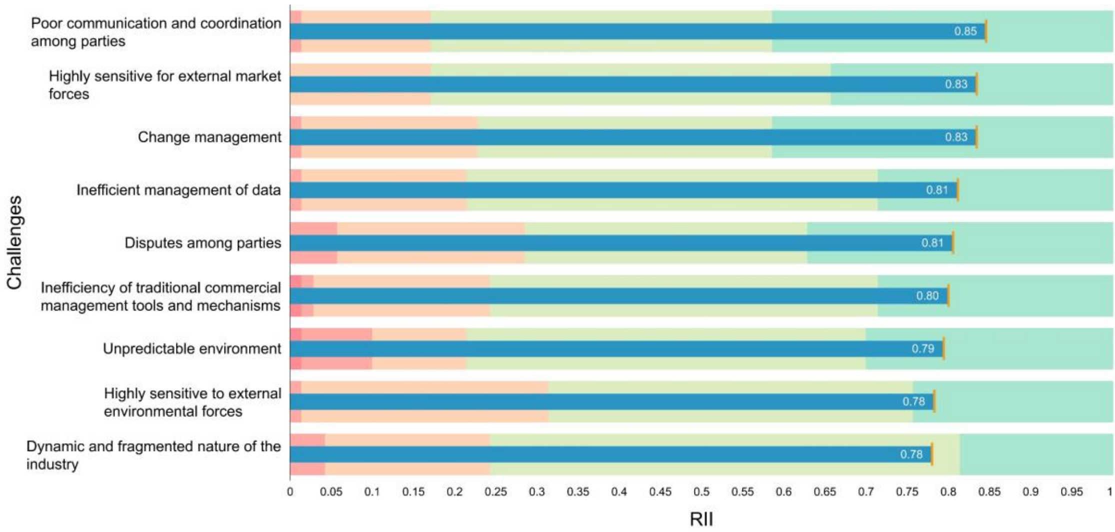


Figure 2: Challenges for the commercial management of construction projects

According to the questionnaire survey, "Poor communication and coordination among parties" stands out as the most cited challenge with an RII of 0.85. This highlights the critical need for effective communication channels and collaborative practices in commercial management. Further "Change management" and "High sensitivity for external market forces" are the second most significant obstacles with RII of 0.83. This reflects the inherently challenging nature of the construction industry due to the turbulent nature of the industry and changes in the project scope. In addition, commercial management faces issues due to "Dispute among parties" and "Inefficient management of data" with a RII of 0.811. Thus, it implies the need for effective dispute resolution methods and dispute avoidance practices for the construction industry. Further, the requirement for a better data management system for establishing a data driven decision making system. Moreover, "Inefficiency of traditional commercial management tools and mechanisms", "Unpredictable environment", "Dynamic and fragmented nature of the industry" and "Highly sensitivity for environmental forces" are also identified as considerable challenges with a RII greater than 0.77. Hence, the questionnaire survey confirms that the issues highlighted in the literature research are present in real-world applications. This is evidenced by all the challenges having a RII greater than 0.70, which indicates that these aspects are significant. Moreover, respondents were asked to identify further challenges in the commercial management of construction projects via an open-ended question. Accordingly, the responses were sorted, and five major challenges were identified as explained in Table 5.

Table 5: Identified other challenges

Challenge	Survey insights
Deficiencies in skill and personnel incompetence	The respondents highlighted that there are significant deficiencies in both technical and soft skills among industry professionals, including inadequate communication abilities and a shortage of competent personnel.
Less adoption of technology	There is a reluctance or a delay in embracing new technologies, along with a greater dependence on obsolete tools such as Excel.

Challenge	Survey insights
Inefficiencies in systems and processes	Survey responses also indicate that due to inefficient systems and processes, it has been unable to effectively maintain cash flow, control costs, and handle material procurement, resulting in cost overruns and project delays.
Influence from external forces	Respondents emphasised that commercial management has been constantly influenced by external forces such as supply chain disruptions, regulatory compliance, and market condition fluctuations.
Malfunctions in management	Respondents identify that middle management lacks comprehension and execution of efficient commercial management practices, which is further exacerbated by a general absence of managerial expertise. A respondent further explained "There is no proper communication between post and pre-contract team particularly when bidding for a project. As a result, the pre-contract team is unaware of the commercial management concerns experienced by the operational team. Further, they are using the old data without updating the cost database based on hands-on experience".

As indicated by Table 5, the construction industry is currently facing significant commercial management challenges. These challenges are intricately interconnected and collectively diminish the effectiveness of commercial management practices. To address these challenges, it is essential to take a comprehensive approach that includes investing in skills development, adopting technological advancements, improving management processes, and promoting a culture of effective communication and leadership. These reforms are crucial for improving operational efficiency and achieving project success. They are also necessary to ensure that industry can adapt and remain resilient in a rapidly changing economic and regulatory environment. This analysis not only enhances understanding of the existing problems but also urges stakeholders in the industry to work together and make significant improvements.

4.3 DEGREE OF DIFFICULTY IN COMMERCIAL MANAGEMENT DISCIPLINES IN CONSTRUCTION PROJECTS

Commercial management is composed of a numerous discipline, each with its own distinct set of issues as identified by the questionnaire survey. Figure 3 presents commercial management functions as identified in the literature review and their level of difficulty in managing them with the aid of RII and the opinions of the respondents.

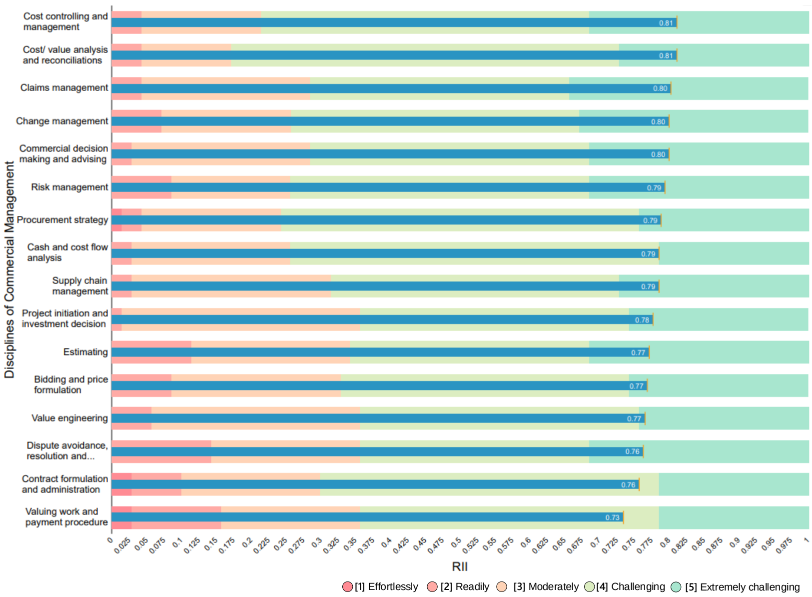


Figure 3:Degree of difficulty in commercial management disciplines

According to Figure 3, "Cost control and management" and "Cost value analysis and reconciliation" have the highest RII of 0.81, showing their challenging and complex nature. Further, "Claims management", "Change management", and "Commercial decision making and advising" are ranked at 3 with a RII of 0.80. Hence, the five most challenging functions process a RII greater than 0.80 highlighting the critical nature of them. Even though "Contract administration" ranked at last, it also has a RII of 0.76 concluding the importance and the degree of difficulty of all the disciplines in the commercial management of construction projects.

As the final question of the questionnaire survey, respondents were asked to propose novel approaches for effective commercial management via an open-ended question. Accordingly, respondents have highlighted four distinct approaches to integrating with commercial management. The majority of the participants recommended integrating digital technologies like BIM and AI into commercial management practices to enhance accuracy in planning and executing commercial management functions. However, a respondent also noted that there are still obstacles to its implementation, especially in regions like Sri Lanka. Furthermore, survey participants suggest utilising lean and agile methodologies for minimising inefficiency and enhancing flexibility to align with the operational procedures that are ever-changing in construction projects. In addition, the respondents also recognised blockchain technology and advanced data analytics for their potential to enhance transparency and facilitate more informed decision-making by utilising real-time data. Finally, respondents emphasised the need to focus more on sustainability and collaborative agreements, improving cooperation among stakeholders. The combination of these approaches demonstrates a comprehensive shift towards more cohesive, effective, and open commercial management in the construction sector, as indicated by the survey participants.

5. DISCUSSION

The challenge of the inefficiency of traditional commercial management tools with an RII greater than 0.77 aligns with Navon (2005) and Cheung et al. (2004), who critique existing performance measurement tools for their narrow focus on financial metrics. Inefficient management of data was noted as a significant issue, with an RII of 0.811. This finding is echoed by Martínez-Rojas et al. (2015) and Tanga et al. (2022), who stress the importance of effective data management in preventing project failures and disputes. The research identified poor communication and coordination among parties as the most cited challenge, with an RII of 0.85. This finding is consistent with the literature, where Chapman (2016) and Nasrun et al. (2014) emphasise that the fragmented nature of construction projects often leads to significant communication issues. Khan et al. (2016) further support this by noting that poor communication exacerbates disputes and delays, affecting overall project performance. This alignment suggests that addressing communication breakdowns through enhanced collaborative practices and communication channels is crucial for improving commercial management.

Further, change management was identified as a significant obstacle with an RII of 0.83, reflecting its critical impact on project costs and timelines. Literature by Rahman et al. (2022) and Chen et al. (2015) highlight that changes in project scope or design are inevitable and can lead to substantial commercial concerns, including increased costs and delays. Effective change management practices, therefore, are essential for mitigating these impacts and ensuring smoother project execution. Both the study and the literature underscore the importance of addressing communication and coordination issues, managing changes effectively, adapting to external market forces, improving data management, and using efficient tools and methods. The alignment between the research findings and the literature validates the study's conclusions and recommendations.

Figure 4: Word cloud for challenges for commercial management in construction projects

Further insight into the challenges of commercial management in the construction industry is provided through Figure 4 have highlighted "Disruptions" as a significant challenge in commercial management in construction as illustrated.

6. CONCLUSIONS

The study underscores the significance of commercial management within the construction sector and underscores the challenges to its successful implementations. Challenges identified in the study highlight issues such as poor communication, change management, sensitivity to external market forces etc. These challenges highlight the importance of having effective communication strategies, change management and adaptation to external influences. Furthermore, the study reveals other obstacles such as conflict between parties and poor data management, highlighting the complexity of real-world marketing strategy issues. To improve project performance and operational efficiency, the study emphasises how important it is to address these issues. Furthermore, the innovative approaches suggested by the respondents such as utilising digital technologies, implementing lean and agile methodologies, and giving priority to collaborative agreements and sustainability indicate a general movement in the direction of more integrated and successful commercial management practices in the construction.

This paper unveils the specific challenges faced by commercial management in the construction industry in Sri Lanka, providing industry stakeholders with a comprehensive understanding of the factors that hinder effective commercial management practices. By highlighting these challenges, the research offers valuable insights to industry practitioners, enabling them to make informed decisions regarding commercial management strategies and practices. Understanding these challenges allows stakeholders to develop targeted solutions to address issues and improve project performance. Moreover, the paper contributes to theoretical frameworks and existing literature by providing evidence-based support for the identified challenges, enriching theoretical discourse and enhancing the understanding of commercial management dynamics in the construction sector. Additionally, by focusing on the Sri Lankan context, the paper expands the body of knowledge on how cultural, regulatory, and economic factors influence commercial management practices, facilitating cross-contextual comparisons and strengthening theoretical foundations.

Research has significantly enhanced our understanding of commercial management functions in construction projects and their crucial role in ensuring project success. It has identified current issues within commercial management, offering a foundation for practical improvements. The findings of this study guide industry practitioners to adopt effective management approaches with the following recommendations: employ the research findings to delineate the necessary commercial management functions for each phase of construction, which will facilitate effective organisation and management of commercial aspects while enhancing project value; and use the research findings as a guideline to identify the most suitable lean tools for optimising commercial management processes. However, it is important to note that the study's focus was limited to the current state of commercial management practices.

7. REFERENCES

Assaad, R., Asce, S. M., El-Adaway, I. H., & Asce, F. (2020). Enhancing the knowledge of construction business failure: A social network analysis approach. *Journal of Construction Engineering and Management*, *146*(6). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001831

Babalola, O., Ibem, E. O., & Ezema, I. C. (2019). Implementation of lean practices in the construction industry: A systematic review. *Building and Environment*, *148*, 34–43. https://doi.org/10.1016/j.buildenv.2018.10.051

Chapman, R. J. (2016). A framework for examining the dimensions and characteristics of complexity inherent within rail megaprojects. *International Journal of Project Management*, *34*(6), 937–956. https://doi.org/10.1016/j.ijproman.2016.05.001

Chen, C. S., Tsui, Y. K., Dzeng, R. J., & Wang, W. C. (2015). Application of project-based change management in construction: A case study. *Journal of Civil Engineering and Management*, *21*(1), 107–118. https://doi.org/10.3846/13923730.2013.802712

Chen, Z. (2019). Grand challenges in construction management. *Frontiers in Built Environment*, 5. https://doi.org/10.3389/fbuil.2019.00031

Cheung, S. O., Suen, H. C. H., & Cheung, K. K. W. (2004). PPMS: A Web-based construction Project Performance Monitoring System. *Automation in Construction*, *13*(3), 361–376. https://doi.org/10.1016/j.autcon.2003.12.001

Creswell, J. W., & Creswell, J. D. (2005). *Mixed methods research: Developments, debates, and dilemma*. Berrett-Koehler Publishers Oakland, CA.

Dalcher, D. (2017) *Managing Projects in a World of People, Strategy and Change: Commercial management and projects, a long overdue match?* (1st ed.). Routledge.

Khan, K. I. A., Flanagan, R., & Lu, S. L. (2016). Managing information complexity using system dynamics on construction projects. *Construction Management and Economics*, *34*(3), 192–204. https://doi.org/10.1080/01446193.2016.1190026

Koskela, L. (2020). *Theory of lean construction: Lean Construction: Core Concepts and New Frontiers* (1st ed.). Routledge.

Lewin, C. (2005). Elementary quantitative methods. In B. Somekh & C. Lewin (Eds.), In S. Bridget & C. Lewin (Eds.), *Research methods in the social sciences* (1st ed., pp. 215–225). SAGE Publications.

Li, X. K., Wang, X. M., & Lei, L. (2020). The application of an ANP-Fuzzy comprehensive evaluation model to assess lean construction management performance. *Engineering, Construction and Architectural Management*, *27*(2), 356–384. https://doi.org/10.1108/ECAM-01-2019-0020

Linkoaho, O. M., Koschnick, J., & Rantaharju, M. B. A. M. (2020). *Commercial Management of Projects*.

Lowe, D. J. (2013). *Commercial management : theory and practice*. Blackwell Publishing Ltd.

Lowe, D., & Leiringer, R. (2006). *Commercial management of projects: defining the discipline*. Blackwell Publishing Ltd.

Lowe, D., Peter, F., & Sarah, R. (1997). Commercial management: An investigation into the role of the commercial manager within the UK construction industry. *CIOB Papers*, *81*, 1–8. https://www.thenbs.com/PublicationIndex/documents/details?Pub=CIOB&DocID=246868

Lowe, David., & Leiringer, Roine. (2006). *Commercial management of projects: defining the discipline*. Blackwell Pub.

Martínez-Rojas, M., Marín, N. & Vila, M. A. (2015). *The Role of Information Technologies to Address Data Handling in Construction Project Management*, *30*(4), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000538

Moradi, S., & Kähkönen, K. (2022). Success in collaborative construction through the lens of project delivery elements. *Built Environment Project and Asset Management*, *12*(6), 973–991. https://doi.org/10.1108/BEPAM-09-2021-0118

Nasrun, M., Nawi, M., Baluch, N., & Bahauddin, A. Y. (2014). Impact of fragmentation issue in construction industry: An overview; *MATEC Web of Conferences*, *15*(2), https://doi.org/10.1051/matecconf/20141501009

Navon, R. (2005). Automated project performance control of construction projects. *Automation in Construction*, *14*(4), 467–476. https://doi.org/10.1016/j.autcon.2004.09.006

Pearson, D. (1996). Contractor's QS or financial manager: what's in a name. *Construction Manager*, *2*(7), 13–13.

Perera, S., Zhou, L., Udeala, C., Victoria, M., & Chen, Q. (2016). *A comparative study of construction cost and commercial management services in the UK and China*. Royal Institute of Chartered Surveyors (RICS). www.rics.org

Popov, A., Lapteva, E., & Kuzmicheva, A. (2022). Methodological foundations for managing commercial activities of small businesses. *Proceedings of the international scientific-practical conference "ensuring the stability and security of socio-economic systems: overcoming the threats of the crisis space"* (pp. 241–245). https://doi.org/10.5220/0010697800003169

Porte, G. K. (2010). *Appraising research in second language learning: A practical approach to critical analysis of quantitative research*. John Benjamins Publishing Company

Rahman, I. A., Al Ameri, A. E. S., Memon, A. H., Al-Emad, N., & Alhammadi, A. S. A. M. (2022). Structural Relationship of Causes and Effects of Construction Changes: Case of UAE Construction. *Sustainability (Switzerland)*, *14*(2), 596. https://doi.org/10.3390/su14020596

Ramlee, N., Tammy, N. J., Raja Mohd Noor, R. N. H., Ainun Musir, A., Abdul Karim, N., Chan, H. B., & Mohd Nasir, S. R. (2016). Critical success factors for construction projects. *AIP Conference Proceedings*, *14(*5), *1774*. https://doi.org/10.1063/1.4965067

Royal Institution of Chartered Surveyors. (2017). *The role of the commercial manager in infrastructure.* RICS Infrastructure Professional Group. https://www.rics.org/content/dam/ricsglobal/documents/standards/the_role_of_the_commercial_manager_in_infrastructure_1st_edition_rics.pdf

Royal Institution of Chartered Surveyors (RICS). (2016). *Commercial management of construction* (1st edition). Royal Institution of Chartered Surveyors (RICS). www.rics.org

Shenhar, A. J., & Dvir, D. (2007). *Reinventing project management: the diamond approach to successful growth and innovation*. Harvard Business Review Press.

Sun, M., & Meng, X. (2009). Taxonomy for change causes and effects in construction projects. *International Journal of Project Management*, *27*(6), 560–572. https://doi.org/10.1016/j.ijproman.2008.10.005

Tanga, O., Akinradewo, O., Aigbavboa, C., Oke, A., & Adekunle, S. (2022). Data Management Risks: A Bane of Construction Project Performance. *Sustainability (Switzerland)*, *14*(19).

Walker, I., & Wikie, R. (2002). *Commercial management in construction*. Wiley-Blackwell.

Wu, C. H., Hsieh, T. Y., Cheng, W. L., & Lu, S. T. (2004). Grey relation analysis of causes for change orders in highway construction. *Construction Management and Economics*, *22*(5), 509–520. https://doi.org/10.1080/0144619042000202735

Kavinda, S.A.C. and Gallage, S.D., 2024. Challenges for project selection and execution of Public-Private Partnership projects in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 353-364. DOI: https://doi.org/10.31705/WCS.2024.28. Available from: https://ciobwcs.com/papers/

CHALLENGES FOR PROJECT SELECTION AND EXECUTION OF PUBLIC-PRIVATE PARTNERSHIP PROJECTS IN SRI LANKA

S.A.C. Kavinda[1] and S.D. Gallage[2]

ABSTRACT

Public-Private Partnerships (PPP) have grown in popularity in developing countries as a means of engaging the private sector in the building of public infrastructure. Determining the most suitable PPP model for construction projects in Sri Lanka is challenging due to the unique economic, social, and political context of the country. To identify these challenges, the research adopted a mixed approach, with questionnaire surveys, and expert interviews utilised to obtain data. Six expert interviews with experts who have more than 15 years of expertise in the field were selected for the preliminary survey, and forty-three project managers, engineers, quantity surveyors, and procurement specialists who were involved with PPP projects were subsequently selected for the questionnaire survey. Manual content analysis was used to examine the interview results. Relative Importance Index (RII) and manual content analysis were both applied to evaluate the questionnaires. The results disclosed that selecting a PPP project depends on several factors. Those Selection factors were categorised under economical, technical, legal, financial, and environmental considerations. Additionally, ten challenges were identified with the selection and execution of PPP projects to implement a selection criterion for PPP projects. Overall, a comprehensive assessment of the project's economic, technical, legal, financial, and environmental implications should serve as the foundation for the selection criteria as the recommendation. These findings will aid industry professionals in selecting a PPP project that will promote long-term economic growth in Sri Lanka.

Keywords: *Project Evaluation; Project Selection Criteria; Public-Private Partnership (PPP) Projects.*

1. INTRODUCTION

The popularity of PPPs in construction has grown, with PPPs recognised as innovative procurement strategies that offer promising prospects for the global construction industry (Osei-Kyei & Chan, 2017). PPPs are seen as effective institutional mechanisms for addressing market failures by fostering equity and accountability between public and private entities (Sandhu et al., 2018). In Sri Lanka, PPP guidelines were introduced in 1992 (Fernando, 2019). While PPPs have been effective in delivering assets including hospitals and schools, they are considered a valuable method for achieving the best value for money in public infrastructure projects (Bing et al., 2005). However, various PPP models such as BOT, BOOT, and DBOT have different approaches to incorporating

[1] Quantity Surveyor, All Stop Fire Systems, Sri Lanka, chamarakavinda1997@gmail.com
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sasankag@uom.lk

private sector involvement in traditional public services (Al-sharif & Kaka, 2004). Many developing countries, including Malaysia, have faced challenges in attracting private investment, with obstacles such as lengthy negotiations, lack of clear government guidelines, higher costs for users, political delays, and unclear evaluation criteria (Wang et al., 2019). The top factors affecting PPP project selection include market conditions, financial resources, project environments, time delays, and budget overruns (Issa et al., 2020).

Governments in both developing and developed countries are increasingly turning to the PPP procurement method to fill critical infrastructure gaps rather than building construction (Gunnigan & Rajput, 2010). Furthermore, there are past research studies which prove the importance of the PPP to infra-structure projects (Bing et al., 2005; Cui et al., 2018; Zheng et al., 2018). However, there is a lack of research regarding PPP project selection. According to Appuhami et al. (2016), PPP projects were not initiated, especially in the road, telecommunication, and power sectors, even though there was a necessity to develop the infrastructure facilities as a developing country. Therefore, the selection of the project for PPP in a proper way is essential. Hence, considering the above-mentioned industrial need and the literature gap, it is essential to research the project selection criteria for PPP projects in Sri Lankan context. This study aims to identify suitable project selection criteria for PPP Projects in the Sri Lanka with the established five objectives including reviewing the characteristics of the PPP, and the PPP arrangements/ types, investigating the factors affecting the selection of existing PPP projects in Global Context, recognising challenges with the selection and execution of PPP projects.

2. LITERATURE REVIEW

2.1 CONSTRUCTION PROCUREMENT

Construction procurement involves acquiring goods and services essential for project execution and smooth commercial operations (Masterm et al., 2002). It includes direct and indirect procurement, covering the acquisition of labour and materials necessary for construction (Watermeyer & Director, 2012). The procurement process consists of several steps: creating a procurement management plan, conducting the procurement process, awarding contracts, monitoring construction, and closing contracts (Gunawardhane & Karunasena, 2014). Effective procurement is vital for timely project completion and delivery (Molavi & Barral, 2016).

Procurement systems in construction are categorised into traditional and non-traditional systems (Rameezdeen & de Silva, 2002). Traditional systems including package deals and turnkey projects, involve separate management of design and construction tasks. Non-traditional systems include integrated approaches, such as design and build, where design and construction responsibilities are consolidated, and management-oriented methods that involve a contractor managing subcontractors and design consultants (Utama et al., 2022). The choice of procurement system affects project outcomes: traditional systems may lead to fragmented communication, integrated systems streamline processes yet limit client control, and management-oriented systems offer strong project management hence require extensive contractor coordination (Utama et al., 2022).

2.2 SIGNIFICANCE OF PPP OVER OTHER PROCUREMENT SYSTEMS

PPPs are diverse contractual arrangements enabling collaboration between the public and private sectors. Although no single global definition exists, PPPs generally involve agreements where a government agency or public organisation partners with a private sector entity to provide public assets and services. These arrangements include substantial risk-sharing and performance-linked payments to the private sector (Dabarera et al., 2019; Reeves et al., 2014).

PPPs offer mutual benefits: the private sector's technology and innovation can enhance public service efficiency, while the public sector provides incentives to ensure projects are completed on time and within budget. PPPs are increasingly used to finance large infrastructure projects, offering higher private-sector involvement compared to traditional procurement methods. This approach aims to improve project efficiency and effectiveness throughout its lifecycle and allows for cost distribution over a longer period. Consequently, it helps free public funds for other investments and contributes to a country's economic stability (Liu & Wilkinson, 2011).

2.3 USAGES OF PPP

PPPs are gaining recognition for their potential to improve health systems by combining the strengths of both sectors to enhance effectiveness, quality, and innovation (Sovacool, 2013). Governments are increasingly using PPPs to reduce healthcare costs and boost investment. Successful examples include Brazil, where private operators increased patient treatment by 30% in new government-built hospitals, and St. Goran's Hospital in Sweden (Zhou et al., 2013). PPPs are applied in sectors including energy and infrastructure, leveraging private sector resources and expertise to enhance public services and asset management (Sovacool, 2013).

Since the late 1990s, Sri Lanka has promoted PPPs for infrastructure development to enhance funding, management, and cost efficiency. Despite early efforts, the results were disappointing. In the past 15 years, Sri Lanka has executed 15 PPP projects with a $1.65 billion investment, falling behind India, Pakistan, and Bangladesh in both investment and project count (Weththasinghe et al., 2016). The Colombo Port City Project (CPCP), a major PPP with China Harbour Engineering Corporation, is the largest and most ambitious project in Sri Lanka. However, it faced delays and controversy due to alleged mismanagement (Thoradeniya, 2016).

2.4 DIFFERENT PROCUREMENT MODELS IN PPP

Many different models can be made for public-private partnerships. Recognising that effective risk sharing, or transfer is essential for a PPP model's success is crucial (Lee & Choi, 2015). There are six models, ranging from low to high levels of privatisation: BT, DBFO, BOOT, BTO, BOT, and BOO. According to various contract agreements, BOT, in this sense, includes DBFO, BOOT, and BTO. The Canadian PPP Committee ordered the sequence of the five PPP modes from low to high, resembling a ladder, based on the extent of private sector participation and risk (Hu et al., 2010). Table 1 provides a summary of the PPP types, and detailed descriptions, enabling a clearer understanding of their respective roles and characteristics.

Table 1: Different types of procurement models in PPP

Type	Description
Build Transfer (BT) [1]	Design and Build (DB) involves the public sector contracting a private partner for design and construction while managing operations and maintenance.
Build Transfer Operate (BTO) [2]	Design Build Operate (DBO) involves a private partner designing, building, and operating a facility, while the public sector retains ownership.
Build Operate Transfer (BOT) [1]	Design Build Operate Maintain (DBOM) involves a private partner handling design, construction, operation, and maintenance, with asset ownership transferring after the contract.
Build Own Operate Transfer (BOOT) [2,3]	Private partners will be awarded grants for designing and building the facility. The private sector will own the asset and operate it. The asset will transfer ownership once the contract period is completed.
Build Own Operate (BOO) [2]	A private entity designs, builds, operates, and maintains the facility with ownership retained, similar to BOT but without transfer obligation.
Design Build Finance Operate/Maintain (DBFO) [4]	The private partner is responsible for designing, constructing, operating, and maintaining the facility. This is considered as a long-term agreement. The asset will transfer ownership once the contract period is completed.

Source: [1; (Opawole & Jagboro, 2018), 2; (Akomea-Frimpong et al., 2020), 3; (Almeile et al., 2024), 4; (Dabarera et al., 2019)

2.5 EXISTING PROJECT SELECTION FACTORS IN GLOBAL CONTEXT

The general project selection criteria are divided into two categories by Mohanty (2014): intrinsic and extrinsic. Okpala (2012) conducted a study on the Nigerian selection criteria and identified ten factors that have an impact on project selection. Table 2 illustrates factors for project selection in different types of projects.

Table 2: Factors for project selection in different types of projects

General Project Selection (Mohanty, 2014)	**Construction Project Selection** (Okpala, 2012)	**Infrastructure Project Selection** (World Bank Group 2022)
Intrinsic Factors 1. Project-identification ability 2. Resources requirements and availabilities 3. Past experiences of the organization in managing projects 4. Management attitudes 5. The time horizon of the project **Extrinsic Factors** 1. The risk/return ratio 2. The market environment 3. Government policies and regulations 4. The socio-economic climate 5. Legal and technological implications	1. Availability of capital 2. Economic situation 3. Profitability 4. Political situation 5. Benefit 6. Management 7. Competitive activities 8. Viability 9. Uncertainty and risk level 10. Project competitiveness	1. Project development objective 2. Strategic context 3. Project description 4. Project rationale 5. Project analysis 6. Sustainability and risks 7. Main conditions 8. Readiness for implementation 9. Compliance with bank policies

Furthermore, other selection factors were discovered after academic and institutional literature reviews were conducted to develop relevant standards for assessing PPP project selection (Osei-Kyei et al., 2020). Table 3 illustrates the list of selection factors for PPP projects.

Table 3: List of selection factors for PPP projects

Selection factors for PPP projects	Sources / Authors
Conformity of proposal with sector/national policy	Hodges & Dellacha (2007); PPIAF (2024);
Whole life value for money	
Outstanding creativity and innovative technological solutions	PPIAF (2024); World Bank Group (2022)
Affordability of user tariffs	
Appropriateness of risk-sharing mechanism	PPIAF (2024)
Financial capabilities of private sector proponent	Hodges & Dellacha (2007)
Environmental safety of proposed solutions	
Cost-effectiveness of service delivery mechanism	PPIAF (2024); World Bank Group (2022)
Climate change and sustainability impacts of proposal	

2.6 APPLICABILITY OF PPP TO SRI LANKAN CONTEXT

When there is no systematic or practical method available to choose the procurement system appropriate for a building project, Ratnasabapathy and Rameezdeen (2007) state that in the Sri Lankan context, the identification of procurement selection factors and development of a model appropriate for a realistic selection process are essential to the effectiveness and success of the project (Dabarera et al., 2019).

The novelty of this research lies in its focus on developing specific project selection criteria tailored for PPP projects in Sri Lanka, a topic with limited exploration in both local and global contexts. While previous studies (Gunnigan & Rajput, 2010; Bing et al., 2005; Cui et al., 2018; Osei-Kyei & Chan, 2017) have highlighted the general importance of PPPs in infrastructure, this research addresses a critical gap by examining the unique factors influencing project selection and execution in the Sri Lankan setting. By reviewing existing PPP characteristics, arrangements, and global selection factors, the study aims to identify and propose criteria that can improve the effectiveness and success rates of PPP projects in Sri Lanka, particularly in sectors like road, telecommunication, and power (Appuhami et al., 2016; Fernando, 2019; Weththasinghe et al., 2016).

3. RESEARCH METHOD

The study utilised a mixed approach, integrating qualitative and quantitative methods to thoroughly investigate the challenges in project selection and execution of PPP projects in Sri Lanka. Expert interviews with PPP professionals with over 15 years of experience were conducted to gather in-depth insights, as suggested by Prescott and Conger (1995) and Johnson and Onwuegbuzie (2004). The manual content analysis of these interviews provided qualitative data. Additionally, a questionnaire survey, based on Roopa and Rani (2012), was employed to collect quantitative data, using purposive sampling (Mishra & Alok, 2017). Table 4 illustrates the respondents of expert interviews.

Table 4: Details of expert interviews

Interviewee	Type of Organisation	Respondent Details
R1	Consultant	Senior Legal Advisor - 18 years of work experience
R2	Consultant	Lawyer - 16 years of work experience

Interviewee	Type of Organisation	Respondent Details
R3	Contractor	Claim Consultant - 17 years of work experience
R4	Contractor	Senior Quantity Surveyor - 25 years of work experience
R5	Consultant	Contract & Claims Engineer - 22 years of work experience
R6	Consultant	Chief Quantity Surveyor - 16 years of work experience

Six interviewers with more than 15 years of experience participated in the expert interviews. The interviewees were all highly qualified, successful in the Sri Lankan and international construction industries, and knowledgeable about different project selection criteria and PPP in Sri Lanka. The questionnaire survey was structured using the outcomes of expert interviews. During the questionnaire study, 65 questionnaires were issued to industry professionals in the construction sector, and 43 of those professionals responded and they were asked to rank the findings in expert interviews. Table 5 summarises the details of the questionnaire participants.

Table 5: Questionnaire participants

	Project Managers	Engineers	Quantity Surveyors	Procurement Specialists	Contract Managers	Total
0-5 Years	-	-	2	-	-	2
6-10 Years	-	1	8	-	-	9
11-15 Years	2	3	8	3	2	18
16-20 Years	2	3	2	2	1	10
> 20 Years	1	1	2	-	-	4
Total	5	8	22	5	3	43

The project selection factors for PPP projects are ranked according to their specific consideration using the Relative Importance Index (RII). RII is computed by multiplying the highest weighting by the total number of respondents and dividing the sum of weightings.

$$Relative\ Important\ Index\ (RII) = \frac{\Sigma(Wn)}{A \times N} \qquad (Eq.\ 01)$$

Where; RII= Relative Importance Index, W=Weighting given to each factor by the respondents, n=Frequency of responses, A=Highest weight, and N=Total number of respondents

4. FINDINGS

4.1 CHARACTERISTICS OF THE PPP, AND THE PPP ARRANGEMENTS/TYPES

Compared to traditional procured projects, PPP projects are a special type of project. The public sector invites the private sector to finance its own money to build the project. The operational and managing rights are transferred to the private sector to recover the cost-plus profit. However, this question is examined the opinion of each respondent whether they agree or disagree with the special characteristics which were identified from literature compared to traditional procured projects. Table 6 illustrates opinions on the special characteristics of PPP projects compared to traditional procured projects.

Table 6: Characteristics of the PPP

Characteristic	Special Characteristics of PPP ([A]gree / [D]isagree)					
	R1	R2	R3	R4	R5	R6
Private sector participation	A	A	A	A	A	A
Value for Money	D	A	D	A	A	A
Certainty of Outcomes	D	A	A	A	A	A
Innovation	A	D	D	A	A	D
Work Planning and Organizing	D	D	D	D	D	D
Optimization of Life Cycle cost	D	A	D	A	A	D
Risk sharing	A	A	A	A	A	A
Responsibility sharing	A	A	A	A	A	A
Resource sharing	A	A	A	A	A	A
Improve level of Delivery	D	D	A	A	A	A
Transparency	A	D	D	A	A	A
Long term projects	A	D	D	A	A	A
Viability Gap Funding	D	A	D	A	A	A

According to Table 7, all of the respondents agreed that private sector participation, risk sharing, responsibility sharing, and resource sharing can be identified as special characteristics of PPP projects compared to traditional procured projects.

4.2 Factors Affecting the Selection of PPP Projects

The questionnaire was conducted to determine the importance of selection factors regarding economic, technical, legal, financial and environmental considerations for PPP projects.

4.2.1 Economical Consideration

According to the findings of the questionnaire survey, as indicated in Table 7, favourable inflation, exchange, and interest rates have the highest RII value (0.888) as a PPP project selection factor regarding economic consideration. Favourable exchange, inflation, and interest rates may favourably affect PPP projects' economic concerns. Better financial returns, higher profitability, and fewer costs are all possible outcomes.

Table 7: RII values for selection factors regarding economic consideration

PPP Project Selection Factors: Economical Consideration	RII	Rank
Socio economic climate	0.700	6
Project scale and amount of investment relative to GDP	0.775	3
Appropriate risk sharing mechanism	0.738	4
Affordability of user tariff	0.656	9
Saving operational costs	0.663	8
Avoiding delays and cost overruns	0.244	10
Favourable inflation, exchange, and interest rates	0.888	1
Early completion of projects	0.700	6
Preconstruction risks	0.713	5
Value for money assessment	0.788	2

4.2.2 Technical Consideration

According to Table 8, Innovation in technology, management, operation, and maintenance in the public and private sectors has the highest RII value (0.788) as a PPP project selection factor regarding technical consideration. In general, choosing PPP projects that make use of cutting-edge technology, management strategies, and practices for operation and maintenance can offer significant technological advantages.

Table 8: RII values for selection factors regarding technical consideration

PPP project selection factors regarding technical consideration	RII	Rank
Management attitudes	0.256	5
Innovation in technology, management, operation and maintenance in public and private sector	0.788	1
Project design and construction complexity	0.744	2
Integration of design/construction and operation	0.675	4
Facility performance criteria	0.744	2

4.2.3 Legal Consideration

As indicated in Table 9, the stable politics and government system has the highest RII value (0.881) as a PPP project selection factor regarding Legal consideration. Political instability or an untrustworthy government can result in a lack of legal protections and uncertainty for private sector investment, making political and governmental stability an essential legal factor. A stable political and governmental structure increases the likelihood that PPP project-related contracts and agreements will be upheld.

Table 9: RII values for selection factors regarding legal consideration

PPP Project Selection Factors regarding Legal Consideration	RII	Rank
Government policies and Legal regulations	0.775	2
Stable politics and government system	0.881	1
Saving capital costs	0.713	7
Getting private financing	0.750	4
Commitment of partners	0.763	3
Insurance requirement for disaster risk	0.713	7
Early termination conditions	0.244	10
Public and political approvals	0.725	6
Dispute resolution process	0.738	5
Land acquisition procedure	0.644	9

4.2.4 Financial Consideration

According to Table 10, the financial capabilities of the private sector proponent have the highest RII value (0.881) as a PPP project selection factor regarding financial consideration. PPP initiatives require substantial monetary investments, and the private partner must possess the financial capacity to complete the project and manage the risks involved. It is crucial to consider several aspects, including a private sector proponent's financial capacity, creditworthiness, track record, and financial plan.

Table 10: RII values for selection factors regarding financial consideration

PPP Project Selection Factors: Financial Consideration	RII	Rank
Availability of capital and other resources	0.800	2
Financial capabilities of private sector proponent	0.881	1
Asset valuation, tariff demand and revenue risks	0.656	4
Currency volatility risk	0.319	5
Risk/Return ratio	0.756	3

4.2.5 Environmental Consideration

As indicated in Table 11, Environmental impact assessment has the highest RII value (0.744) as a PPP project selection factor regarding environmental Consideration. An EIA is a procedure that assesses a project's possible environmental effects and identifies steps to lessen such consequences. When choosing a PPP project, an EIA is crucial since it aids in identifying potential environmental risks and countermeasures.

Table 11: RII values for selection factors regarding environmental consideration

PPP project selection factors: Environmental consideration	RII	Rank
Business/external environment	0.619	3
Environmental impact assessment	0.744	1
Disaster risk management	0.575	4
Climate change commitments in PPP guidelines	0.206	5
Sustainable use of land and other resources	0.638	2

4.2.6 Challenges with the Selection and Execution of PPP Projects

According to Table 12, the biggest challenge in PPP projects is improper analysis of proposals, with a high RII value of 0.806, which can lead to poor outcomes, financial losses, and legal issues. In contrast, short-term government policies, with a low RII value of 0.263, are less impactful but still problematic by creating uncertainty for private partners. Consistent and predictable policies are essential to support successful long-term PPP initiatives.

Table 12: RII values for challenges

Challenges	RII	Rank
Lack of knowledge and prior experience in the selection and execution of PPP	0.744	3
Poor Commitment and unwillingness to work on projects from the public sector	0.694	7
Improper analysis of project proposals before selection of PPP	0.806	1
Economic and political instability	0.725	5
Less focus on architectural design development	0.694	7
Short-term government policies	0.263	10
Weaknesses of legal and regulatory framework	0.781	2
Over-reliance on unsolicited proposals	0.738	4
Land valuation and acquisition issues	0.681	9
Multiple agencies with overlapping functions	0.700	6

5. CONCLUSIONS

The research identifies five critical factors for selecting PPP projects in Sri Lanka: economic, technical, legal, financial, and environmental. Prioritising these factors using the RII is essential to develop effective project selection criteria. The study highlights that past unsuccessful PPP projects and ineffective unsolicited proposals have hindered the adoption of PPP procurement methods in Sri Lanka. Current PPP guidelines are insufficient in addressing infrastructure and construction gaps comprehensively. To overcome these challenges, the research recommends developing detailed PPP guidelines incorporating the five key considerations and using the RII methodology for prioritisation. Strengthening the legal and regulatory framework is crucial for ensuring transparency and accountability, which are vital for building stakeholder trust. Enhancing stakeholder engagement, including private sector partners and public representatives, is important for gathering diverse perspectives and fostering collaboration. Improving the evaluation of unsolicited proposals through a systematic approach ensures they meet selection criteria and offer value for money. Implementing a competitive bidding process can further enhance transparency and fairness. Additionally, investing in capacity building and continuous professional development for public sector officials is crucial to improving their understanding of PPP procurement and management. The study emphasises the importance of clear plans for sustainable operations, performance monitoring, and evaluation mechanisms to track progress and make necessary adjustments. Encouraging innovation and technology adoption can enhance efficiency, reduce costs, and improve project outcomes, supporting research and development to advance PPP practices.

6. REFERENCE

Akomea-Frimpong, I., Jin, X., & Osei-Kyei, R. (2020). A holistic review of research studies on financial risk management in public–private partnership projects. *Engineering, Construction and Architectural Management, 28*(9), 2549–2569. https://doi.org/10.1108/ECAM-02-2020-0103.

Almeile, A. M., Chipulu, M., Ojiako, U., Vahidi, R., & Marshall, A. (2024). The impact of economic and political imperatives on the successful use of public-private partnership (PPP) in projects. *Production Planning & Control*, *35*(6), 559–579. https://doi.org/10.1080/09537287.2022.2110171.

Al-sharif, F., & Kaka, A. (2004). PFI / PPP topic coverage in construction. In: Khosrowshahi, F (Eds.), *20th Annual ARCOM Conference, Edinburgh, 1-3 September 2004* (pp.711-719). Retrieved from https://www.arcom.ac.uk/-docs/proceedings/ar2004-0711-0719_Al-Sharif_and_Kaka.pdf

Appuhami, R., & Perera, S. (2016). Management controls for minimising risk in public-private partnerships in a developing country: Evidence from Sri Lanka. *Journal of Accounting & Organizational Change*, *12*(3), 408–431. https://doi.org/10.1108/JAOC-10-2013-0075

Bing, L., Akintoye, A., Edwards, P. J., & Hardcastle, C. (2005). The allocation of risk in PPP/PFI construction projects in the UK. *International Journal of Project Management*, *23*(1), 25–35. https://doi.org/10.1016/j.ijproman.2004.04.006.

Cui, C., Liu, Y., Hope, A., & Wang, J. (2018). Review of studies on the public–private partnerships (PPP) for infrastructure projects. *International Journal of Project Management*, *36*(5), 773–794. https://doi.org/10.1016/j.ijproman.2018.03.004.

Dabarera, G. K. M., Perera, B. A. K. S., & Rodrigo, M. N. N. (2019). Suitability of public-private-partnership procurement method for road projects in Sri Lanka. *Built Environment Project and Asset Management*, *9*(2), 199–213. https://doi.org/10.1108/BEPAM-01-2018-0007/FULL/XML

Fernando, S. N. (2019). A review of challenges to attract public private partnership (PPP) investments to power generation infrastructure in Sri Lanka (SL). *Sri Lanka Journal of Marketing*, *5*(1), 1-17. https://doi.org/10.4038/sljmuok.v5i1.24.

Gunawardhane, K. A. P., & Karunasena, G. (2014). Sustainability concerning to public procurement process in construction: Literature Review. In *The 3rd World Construction Symposium 2014: Sustainability and Development in Built Environment, 20 – 22 June 2014, Colombo, Sri Lanka* (pp. 525-533). University of Moratuwa. Retrieved from https://www.researchgate.net /Gayani-Karunasena/publication/324496634.pdf

Gunnigan, L., & Rajput, R. (2010, May 10). *Comparison of Indian PPP construction industry and European PPP construction industry: Process, thresholds and implementation*. In Proceedings of CIB world congress 2010. Salford, United Kingdom. https://doi.org/10.21427/2gjg-2y54.

Hodges, J. T., & Dellacha, G. (2007). *Unsolicited infrastructure proposals: How some countries introduce competition and transparency*. World Bank. http://documents.worldbank.org/curated/en/895161468313861433/Unsolicited-infrastructure-proposals-how-some-countries-introduce-competition-and-transparency

Hu, Z., Li, Q., Liu, T., Wang, L., & Cheng, Z. (2020). Government equity investment, effective communication and public private partnership (PPP) performance: Evidence from China. *Engineering, Construction and Architectural Management*, *28*(9), 2811–2827. https://doi.org/10.1108/ECAM-02-2020-0138.

Issa, U. H., Mosaad, S. A. A., & Salah Hassan, M. (2020). Evaluation and selection of construction projects based on risk analysis. *Structures*, *27*, 361–370. https://doi.org/10.1016/j.istruc.2020.05.049.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, *33*(7), 14–26. https://doi.org/10.3102/0013189X033007014.

Lee, S., & Choi, J. (2015). Wastewater treatment transfer-operate-transfer (TOT) projects in China: The case of Hefei Wangxiaoying Wastewater treatment TOT project. *KSCE Journal of Civil Engineering*, *19*(4), 831–840. https://doi.org/10.1007/s12205-013-0095-5.

Liu, T., & Wilkinson, S. (2011). Adopting innovative procurement techniques: Obstacles and drivers for adopting public private partnerships in New Zealand. *Construction Innovation*, *11*(4), 452–469. https://doi.org/10.1108/14714171111175918/FULL/PDF.

Masterm, J. W., Taylor, F., Group LONDON, F., & York, N. (2002). *An introduction to building procurement systems* (2nd ed.). Routledge.

Mishra, A. S. B., & Alok, A. S. (2017). *Handbook of research methodology English*. Educreation Publishing.

Mohanty, A. (2014). Evolving paradigms in Odisha state finance: An empirical analysis. *Odisha Review, June*. *70*(6), 15-24. Retrieved from https://magazines.odisha.gov.in/Orissareview/2014/Jan/engpdf/january_or_2014.pdf

Molavi, J., & Barral, D. L. (2016). A construction procurement method to achieve sustainability in modular construction. *Procedia Engineering*, *145*, 1362–1369. https://doi.org/10.1016/J.PROENG.2016.04.201.

Okpala, K. E. (2012). Adoption of IFRS and financial statements effects: The perceived implications on FDI and Nigeria economy. *Australian Journal of Business and Management Research*, *2*(5), 76-83. http://dx.doi.org/10.52283/NSWRCA.AJBMR.20120205A10.

Opawole, A., Jagboro, G. O., Kajimo-Shakantu, K., & Olojede, B. O. (2018). Critical performance factors of public sector organizations in concession-based public-private partnership projects. *Property Management*, *37*(1), 17–37. https://doi.org/10.1108/PM-09-2017-0052.

Osei-Kyei, R., & Chan, A. P. C. (2017). Implementing public–private partnership (PPP) policy for public construction projects in Ghana: Critical success factors and policy implications. *International Journal of Construction Management*, *17*(2), 113–123. https://doi.org/10.1080/15623599.2016.1207865.

Prescott, M. B., & Conger, S. A. (1995). Information technology innovations: A classification by IT locus of impact and research approach. *SIGMIS Database*, *26*(2–3), 20–41. https://doi.org/10.1145/217278.217284.

Public-Private Infrastructure Advisory Facility (PPIAF) Annual Report (2024). *World Bank*. http://documents1.worldbank.org/curated/en/099433011162311647/pdf/IDU002e5d5a10eb5e047280aaf2088a5c6f0f2f4.pdf

Rameezdeen, R., & de Silva, S. (2002). Trends in construction procurement systems in Sri Lanka. *Built-Environment Sri Lanka*, *2*(2), 2-9. https://doi.org/10.4038/besl.v2i2.7631.

Ratnasabapathy, S., & Rameezdeen, R. (2007). Influence of clients' requirements on procurement selection in construction industry. *Proceedings of International Conference on Business Management*, *4*. https://journals.sjp.ac.lk/index.php/icbm/article/view/817

Reeves, E., Palcic, D., & Flannery, D. (2014). PPP procurement in Ireland: An analysis of tendering periods. *Local Government Studies*, *41*(3), 379–400. https://doi.org/10.1080/03003930.2014.982108.

Roopa, S., & Rani, M. (2012). Questionnaire designing for a survey. *Journal of Indian Orthodontic Society*, *46*(4), 273–277. https://doi.org/10.5005/jp-journals-10021-1104

Sandhu, M. A., Shamsuzzoha, A., & Helo, P. (2018). Does outsourcing always work? A critical evaluation for project business success. *Benchmarking: An International Journal*, *25*(7), 2198–2215. https://doi.org/10.1108/BIJ-06-2017-0146.

Sovacool, B. K. (2013). Expanding renewable energy access with pro-poor public private partnerships in the developing world. *Energy Strategy Reviews*, *1*(3), 181–192. https://doi.org/10.1016/j.esr.2012.11.003.

Thoradeniya, D.L. (2016) *Public-private partnerships: the case study of the Colombo Port City* [Doctoral dissertation, University of Moratuwa]. University of Moratuwa.http://dl.lib.uom.lk/bitstream/handle/123/12784/pre-text.pdf?sequence=1

Utama, D. M., Santoso, I., Hendrawan, Y., & Dania, W. A. P. (2022). Integrated procurement-production inventory model in supply chain: A systematic review. *Operations Research Perspectives*, 9, 100221. https://doi.org/10.1016/J.ORP.2022.100221.

Wang, H., Liu, Y., Xiong, W., & Zhu, D. (2019). Government support programs and private investments in PPP markets. *International Public Management Journal*, *22*(3), 499–523. https://doi.org/10.1080/10967494.2018.1538025.

Watermeyer, R. B., & Director, F. (2012). A framework for developing construction procurement strategy. Proceedings of the institution of civil engineers-management, *Procurement and Law*, *165*(4), 223–237. http://dx.doi.org/10.1680/mpal.11.00014.

Weththasinghe, K., Gajendran, T., & Brewer, G. (2016). Barriers in proper implementation of public private partnerships (PPP) in Sri Lanka. In N. Singhaputtangkul (Eds.), *Radical Innovation in Built Environment*, (pp. 858 – 869). Central Queensland University. https://espace.library.uq.edu.au/view/UQ:396629/UQ396629_frontmatter.pdf

World Bank Group (2022). *Project appraisal document (pad)*. World Bank Group. http://documents.worldbank.org/curated/en/099620009232294776/P50010ab1b2dd4112c

Zheng, S., Xu, K., He, Q., Fang, S., & Zhang, L. (2018). Investigating the sustainability performance of PPP-type infrastructure projects: A case of China. *Sustainability*, *10*(11), 4162. https://doi.org/10.3390/su10114162

Zhou, L., Xianglai, T., Jiaojiao, K., Perera, S., & Udeaja, C. (2013). PPP infrastructure development in China: Challenges and future trends. *PPP13: PPP International conference in Preston* (pp. 391-397), University of Central Lancashire (UCLan), UK. https://nrl.northumbria.ac.uk/id/eprint/17192/

Pathiraja, G.A.P.C.S.M., Piyumra, R.A.D. and Disaratna, P.A.P.V.D.S., 2024. Challenges in chemical anchoring carried out in the Sri Lankan context. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 365-378. DOI: https://doi.org/10.31705/WCS.2024.29. Available from: https://ciobwcs.com/papers/

CHALLENGES IN CHEMICAL ANCHORING CARRIED OUT IN THE SRI LANKAN CONTEXT

G.A.P.C.S.M. Pathiraja[1], R.A. Dinithi Piyumra[2], and P.A.P.V.D.S. Disaratna[3]

ABSTRACT

Adhesive anchoring has achieved rapid growth in the construction industry, due to the numerous advantages that it offers over conventional joining methods. Particularly, in Sri Lanka, the adhesive or Chemical Anchoring technique is widely used in the field of construction. This research investigated potential challenges that can be faced in Chemical Anchoring and carrying out strength tests in the Sri Lankan context to overcome those challenges while getting maximum output to the construction. Following the qualitative approach, eleven semi-structured expert interviews were carried out to collect the data while adopting manual content analysis as the analytical tool. According to the findings of expert interviews, poor workmanship is the basic challenge identified in Chemical Anchoring in the Sri Lankan context. It is the ground for most of the other challenges. Hence, proper supervision, adherence to manufacturers' recommendations, and the product manual designed for the Sri Lankan context will be the best approach to overcome them. With the use of designing software for Chemical Anchoring, under-design, and over-design which are the common errors in industry, that can be mitigated. The research study proposed solutions to issues in Chemical Anchoring process to enhance the performance in the construction sector.

Keywords: *Anchor Application; Challenges; Chemical Anchoring; Construction; Sri Lanka.*

1. INTRODUCTION

Cast-in-place anchors and post-installed anchors are the two main types of anchors used to provide connections between concrete and structural parts (Mazumder et al., 2020). According to the same source, chemically bonded anchors have become increasingly popular in Turkey for retrofit applications since the 1999 Kocaeli Earthquake. Chemical anchoring refers to the process of installing a new element, such as brick or concrete, to an existing structural element using a chemical mixture or highly reactive resins (Çalışkan et al., 2022). When strengthening and repairing older structures with inadequate seismic performance, chemical anchors are commonly used (Mazumder et al., 2020). The adaptability of the new structure depends on the bonding between the reinforcement of

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, chathuripathiraja791@gmail.com
[2] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, radinithipiyumra@gmail.com
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, vijithad@uom.lk

the structure and the reactive resins and the base material (Cook, 1993). Hence, choosing the proper materials helps to ensure the full bonding of the chemical anchor (Çalışkan et al., 2022). According to Mazumder et al. (2020), Chemical Anchoring is widely used for post-installed reinforcement because of its cost-effectiveness and efficiency in application. Moreover, Müsevitoğlu et al. (2020) revealed that the primary reason of why chemical anchors is preferred is that they are greatly convenient to the user in the design, application and planning process. In addition to that, Chemical Anchoring has the potential to deal with most of the issues that occur in mechanical anchors and reacting mixture or reactive resins used in boreholes while having the opportunity to make slight adjustments to the stud's alignment (Çalışkan et al., 2022). The durability and strength of chemical anchors can be influenced by several factors, including curing, the chemical composition of the reactive resins, drilling depth, cleanliness of the borehole, the method of injecting chemicals into the hole, and the technique for inserting the steel rod into the drilled hole (Mazumder et al., 2020). To ensure the strength of the chemical anchors, various strength tests such as bench impact tests and pull-out tests are employed in the industry to measure the strength of these chemical anchors (Titov et al., 2022).

In the Sri Lankan context, Chemical Anchoring is widely used in road construction building construction and dam construction (Thienoosan et al., 2023). Nevertheless, practical anchoring applications encounter various issues. As to Bayraktar et al. (2016) and Karakotas et al. (2005), the primary issue is the poor quality of the concrete in the current construction that is intended to be reinforced (Müsevitoğlu et al., 2020). Therefore, it is imperative to conduct an in-depth study to identify the potential challenges associated with the Chemical Anchoring process in the Sri Lankan construction sector to ameliorate the efficacy and quality of the Chemical Anchoring process. Apart from that, previous research studies primarily focused on the tensile behaviour of Chemical Anchors (Kim et al., 2013; Müsevitoğlu et al., 2020), developing codes for Chemical Anchoring (Stierschneider et al., 2022), shear capacities (Yilmaz et al., 2013). On the other hand, numerous studies have been carried out on current chemical anchor systems in construction elaborating on the basic concept of bonded anchor systems (Kim et al., 2013; Yılmaz et al., 2013). Their design, load-bearing capacities, load-bearing behaviour and chemical compositions of highly reactive resins that are used to bond the anchor and base materials have been intensively studied over the past years (Eligehausen et al., 2006). Nevertheless, neither research study has deeply investigated the challenges associated with the Chemical Anchoring process, which is evident that there is a prevailing research gap regarding this matter. Therefore, to fulfil both the industrial need and perceived research gap this study aims to investigate the challenges that can be encountered in Chemical Anchoring. The following objectives were achieved; to study the concept of Chemical Anchoring, to identify the application of Chemical Anchoring, to investigate the challenges encountered during Chemical Anchoring and to propose possible solutions to overcome them.

2. LITERATURE REVIEW

2.1 CHEMICAL ANCHORING

Sabatini et al. (1999) have identified anchors as structural elements installed in soil or rock, or other base material that is used to transmit an applied tensile load into the ground or other structures. Xanthakos (1991) states that the purpose of anchors is to act as load-carrying elements, consisting essentially of a steel tendon inserted into a suitable formation or structure in almost any direction.

2.1.1 Bonded Anchors

Connections to concrete include both cast-in-place and post-installed anchors. Post-installed anchors are either mechanical or bonded anchors (Cook et al. 2007). According to Eligehausen et al. (2006), bonded anchor systems can be identified as anchors bonded into concrete with the aid of chemical and non-chemical components. A bonded anchor comprises a threaded rod, a washer and hexagon nut, and a resin motor. Cattaneo and Muciaccia (2015) stated that bonded anchors are even very popular because of their flexibility. Moreover, as Sakla (2005) declared bonded anchors are increasingly employed as structural fastenings to hardened concrete. Types of the bonded anchor systems are identified in Figure 1.

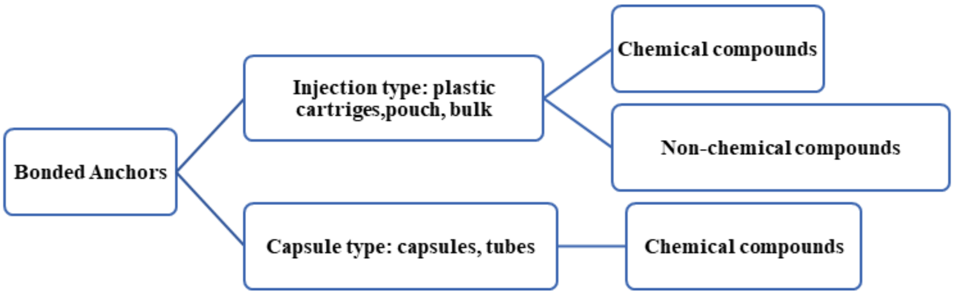


Figure 1: Types of bonded anchor systems in concrete

Sakla (2005) has stated that an adhesive anchor is installed using a reinforcing bar or threaded rod inserted in a drilled hole in hardened concrete using a polymer-based bonding agent including epoxies, vinyl esters, and polyesters. Collins et al. (1989). AI-Mansouri et al. (2019) have investigated two advantages of these adhesive anchors i.e. (i) ease of implantation, and (ii) their high load-bearing capacity at ambient temperature for deep embedment depths.

2.1.2 Application of Chemical Anchoring

According to the Ramset anchoring resource book (2009), the principal applications of chemical anchors in construction have been identified as structural beams and columns, batten fixing, installing signs, handrails, balustrades, and gates, racking, safety barriers, stadium seating and machinery holds down. In addition, chemical anchors are ideal for high-stress applications, such as seismic zones or high-wind locations, and for safety-critical situations where exceptionally high loads must be supported. This is because they form an excellent bond between the anchor and the substrate (Budhai, n.d.). Cook et al. (2007) have revealed that the nature of the drilled hole, concrete compressive strength, type of aggregate, curing period of adhesive, method of hole drilling, and temperature effects are the governing factors of bond strength of chemical anchors.

2.1.3 Process of Chemical Anchoring

The correct installation technique must be employed to ensure a stable anchor that meets load-bearing requirements and withstands the test of time (Budhai, n.d.). According to the Ramset anchoring resource book (2009), the installation of a chemical anchor has been described step by step as shown in Figure 2.

<u>Capsule Method</u>

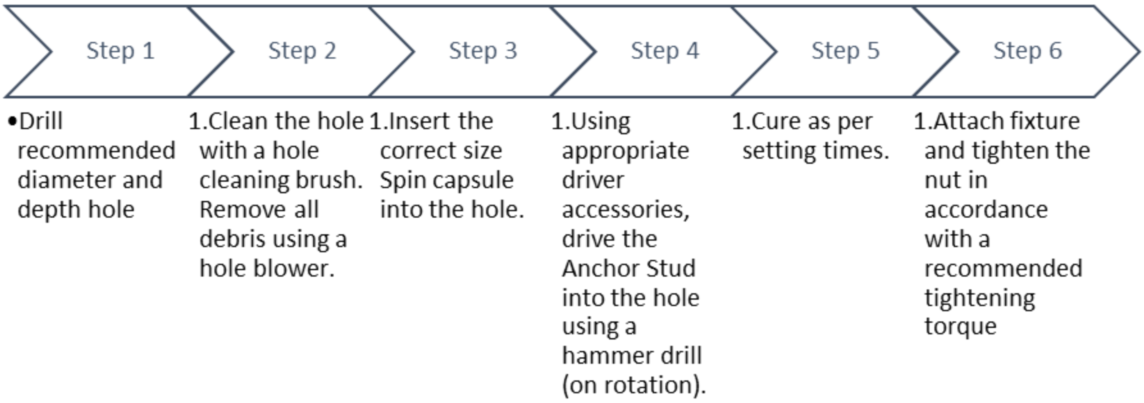


Figure 2: Capsule method

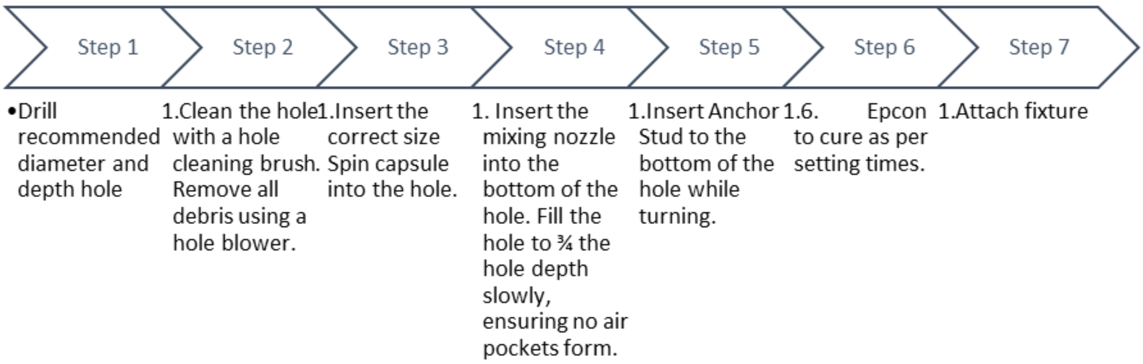


Figure 3: Inserting method with gun

3. RESEARCH METHODOLOGY

To study the challenges associated with chemical anchoring applications, a qualitative research approach was adopted, as it allows for a deeper understanding of the issues from the experts' perspectives (Ospina, 2004). Moreover, due to its exploratory nature, the qualitative research approach is a beneficial strategy when researching a phenomenon for which there is limited accessible information (Taherdoost, 2022). Expert interviews provide rich and detailed information on the research topic from the perspectives of individuals with specialised knowledge or experience (MacDonald & Headlam, 2011). Because it enables researchers to obtain comprehensive data and supporting documentation from respondents while taking the study's topic into account, the semi-structured interview holds greater significance in qualitative research than another interview format (Belina, 2023). Moreover, as this approach offers greater flexibility with appropriate guidance for the researcher (Munianday et al., 2022), eleven semi-structured interviews were conducted to collect the data. Each interview was conducted either face-to-face or online and lasted approximately 30 to 40 minutes. The experts were selected using a purposive sampling technique, which allows for gathering information to ensure maximum diversity within the sample (Weerasooriya et al., 2024). The experts were selected based on the pre-determined criteria as delineated in Table 01.

Table 1: Profile details of the interviewees

Code	Compulsory Requirement (Satisfy all)		Additional Qualification (satisfy at least two)		
	10+ years' experience in the Construction Industry	5+ years' experience in Chemical Anchoring	Having bachelor's degree related to the built environment	Having post-graduate degree related to the built environment	Interest in sustainability practices
E1	✓	✓	✓	✓	✓
E2	✓	✓	✓	x	✓
E3	✓	✓	✓	✓	✓
E4	✓	✓	✓	✓	x
E5	✓	✓	✓	x	✓
E6	✓	✓	✓	✓	✓
E7	✓	✓	✓	✓	✓
E8	✓	✓	✓	x	✓
E9	✓	✓	✓	✓	✓
E10	✓	✓	✓	✓	x
E11	✓	✓	✓	✓	x

Under compulsory requirements, all the interviewees must have more than ten years of experience in the construction sector and more than five years of experience in Chemical Anchoring. The primary purpose of "compulsory criteria" is to ensure that, the selected experts have the specific industrial knowledge of the Chemical Anchoring process to give more accurate and practical answers to the interview questions. Under, additional qualifications, each interviewee shall fulfil at least two conditions, having a bachelor's degree related to the built environment, having post-graduate degree related to the built environment and interest in sustainability practices. The purpose of additional qualification criteria is to ensure that interviewed experts have sound academic backgrounds in built environment practices.

According to Hsieh and Shanon (2005), content analysis is the main data analysis technique used for qualitative research. It involves systematically categorising and interpreting the content of a set of data, such as interview transcripts, documents, or images, to identify patterns, themes, or meanings (Leedy & Ormrod, 2015). Therefore, adopting manual content analysis the collected data were analysed accordingly to meet the defined objectives of the study.

4. RESEARCH FINDINGS

4.1 CHEMICAL ANCHORING APPLICATIONS USED IN THE SRI LANKAN CONTEXT

According to the literature findings, post-installed chemical anchors are easy to install and cost-effective. As a result, their applications are increasingly gaining popularity in practice. Many applications can be found internationally; however, in the Sri Lankan context, they are not very popular. Table 2 summarises the chemical anchor applications in the Sri Lankan context.

Table 2: Chemical anchoring applications

Applications	Literature	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Structural beams and columns	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Installing signs, handrails, balustrades, and gates	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
To maintain column position		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Base plate application		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Joints between precast concrete units	✓	✓		✓		✓	✓		✓			✓
Fixing in stone							✓	✓	✓		✓	
Safety barriers	✓	✓					✓					
Batten fixing	✓						✓					
Racking	✓						✓					
Starter rebars for staircase							✓		✓			
Missed rebar in pile caps							✓		✓			
To extend existing slab part									✓		✓	

All the interviewees have experienced Chemical Anchoring in structural beams and columns and in installing signs, handrails, balustrades, and gates. E1 stated that "*most of the time for structural beams and columns, Chemical Anchoring is done to install missed rebars*". Further, E3 mentioned that "*keeping start-up for handrails and balustrades when concreting is sometimes difficult because they are not usually aligned, So, contractors prefer to go with Chemical Anchoring to install them*". E1 added another application which is maintaining column position as a common application in the Sri Lankan context. E8 introduced Chemical Anchoring as the best method to extend the existing slab part. Further, he said "*But it is not in use most of the time. People always try to go with a conventional method like chipping or breaking concrete until reinforcement appears and then bind them with new steel bars and concrete again*". Those are the applications of Chemical Anchoring that can be found in Sri Lankan practice.

4.2 CHALLENGES ENCOUNTERED IN CHEMICAL ANCHORING AND POSSIBLE SOLUTIONS TO OVERCOME THEM

4.2.1 Challenges Faced During Selecting a Chemical Anchoring Method and Proposed Solutions

The expert interview guidelines focused on studying potential challenges that might be encountered at the stage of selecting the Chemical Anchoring method. Accordingly, it was revealed that eight obstacles and proposed possible solutions to overcome the identified barriers. Table 3 delineates the findings.

Apart from the challenges, the study focused on proposing potential solutions to overcome the identified obstacle. However, the interviewees failed to suggest solutions for all the challenges. Accordingly, Table 3 showcases both challenges and proposed solutions.

Table 3: Challenges faced during selecting a chemical anchoring method and proposed solutions

Challenge											**Solution**										
Monopoly for one company											Give opportunities for new service providers										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✓		✓			✓	✓	✓	✓	✓	✓				✓						✓	
Not having proper knowledge of chemical types and their characteristics											Workshop for engineers and professionals who are engaged in the design process. Training programs for labourers										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
	✓		✓		✓	✓	✓			✓		✓	✓			✓	✓	✓	✓	✓	✓
Overdesign											Use software when designing. Get designs from industry experts										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
		✓		✓	✓			✓	✓						✓						
Having only one method to do Chemical Anchoring																					
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
	✓	✓	✓		✓				✓												
Under design											Get designs from industry experts. Use software when designing										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
		✓			✓			✓							✓	✓					
The high price of some specific chemical types											Minimize chemical wastage when applying										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✓				✓	✓										✓				✓		
Poor adoption of new technologies											Workshop for engineers and professionals who engage in the design process										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
				✓				✓							✓				✓		
Not having service providers in the rural area																					
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
		✓																			

According to E2, E3, and E6, not having proper knowledge of chemical types and their characteristics is another challenge that can be faced in Sri Lanka. Engineers tend to use the same chemical products for all applications. Further E2 mentioned that:

"*Usually, to cure the chemical it takes five or seven hours under normal conditions and until that time passed, the load should not be applied on rebar. if the contractor wants to cure the chemical and load it within a few hours under any condition, some chemicals have their own characteristics. But both contractors and engineers are not aware of them".*

According to E3, they advise the contractor to cure chemical anchors for 24 hrs because climatic conditions and other site conditions can be changed. E8 mentioned that "because of wet surfaces and water, it takes more time to cure for normal chemicals but there are some chemicals, those conditions do not affect. But they are not in use because engineers don't know about them*".* Further E2 mentioned that *"*when selecting chemicals for anchoring for green concept projects, engineers should be aware of VOC (Volatile Organic Compounds) level of the chemical. Otherwise, the green certificate cannot be gained for the project*".* As stated by E5, E6, E9, and E10, usually, chemical anchors are overdesigned in Sri Lanka, resulting in additional cost and time.

Moving onto solutions, most of the interviewees suggested workshops to educate industry professionals who are engaged in the design process of the chemical anchors about the chemical types, their characteristics, and new technologies used. According to E2, training sessions for labourers are most important, to educate them on standard operating steps and maintain that equipment. It helps to minimise chemical wastage.

E5 mentioned that "s*oftware can be used to design chemical anchors now. It avoids over design and under designs*". Getting designs from industry professionals and having contact and checking the design with the support of the technical team of the service providers also helps to overcome this challenge. Those are solutions interviewees suggested for the challenges identified.

4.2.2 Challenges During Installation of Chemical Anchors and Potential Solutions Against the Challenges

The interviewees were asked to give their opinions on what type of challenges would be faced by the professionals during the phase of installation of chemical anchors following the above, possible solutions were suggested by the experts as outlined in Table 4.

Table 4: Challenges during installation of chemical anchors and potential solutions against the challenges

<table>
<tr><th colspan="11">Challenge</th><th colspan="11">Solution</th></tr>
<tr><td colspan="11">Poor Workmanship</td><td colspan="11">Proper supervision
Use new technologies</td></tr>
<tr><td>E1</td><td>E2</td><td>E3</td><td>E4</td><td>E5</td><td>E6</td><td>E7</td><td>E8</td><td>E9</td><td>E10</td><td>E11</td><td>E1</td><td>E2</td><td>E3</td><td>E4</td><td>E5</td><td>E6</td><td>E7</td><td>E8</td><td>E9</td><td>E10</td><td>E11</td></tr>
<tr><td>✔</td><td>✔</td><td>✔</td><td></td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td></td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td><td>✔</td></tr>
<tr><td colspan="11">Drilling reinforced concrete</td><td colspan="11">Break or chip the clear cover
Scan the element to identify the formation of reinforcement</td></tr>
</table>

Challenge											**Solution**										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔	✔		✔		✔	✔	✔	✔	✔	✔					✔						
Have to minimize the chemical wastage											Proper supervision Follow standards and use the correct consumption chart for chemicals.										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔				✔	✔	✔	✔	✔	✔	✔	✔	✔		✔		✔	✔	✔			
Not having proper knowledge and experience											Workshops or training sessions										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔	✔			✔		✔	✔	✔		✔	✔	✔			✔		✔	✔	✔		✔
Not having the required instrument											Getting service done by a reputed company										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔	✔			✔		✔	✔	✔		✔					✔		✔	✔	✔	✔	✔
Having difficulties reaching the exact location											Identify client requirements properly at the design stage Avoid design and construction errors or mistakes										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
	✔		✔			✔		✔		✔				✔			✔		✔		
No proper storage facilities for chemicals											A separate place to store chemicals under required conditions										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	E11
				✔	✔			✔	✔	✔					✔	✔			✔	✔	✔
Pure epoxy getting cured in the nozzle											Proper cleaning before use										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
					✔	✔		✔	✔	✔						✔	✔		✔	✔	✔
Hazardous chemicals											Wear gloves and eye protectors										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
	✔			✔	✔	✔				✔		✔			✔	✔	✔				✔

Accordingly, nine challenges were identified and propose one or two solutions for each identified barrier.

Poor workmanship is the main challenge in the Sri Lankan context. Labourers do not follow the standard process when installing chemical anchors. E2 mentioned, "n*o proper cleaning is the main challenge we face in Chemical Anchoring. Bond strength is reduced because of the dust in the holes*". The reason for this is chemicals tend to bond with the dust but not with the concrete. Further E2 described "n*ot setting required parameters like depth, holes diameter, drill cut size according to bar size is another challenge*". According to E6 and E8, drilling the hole perpendicularly is important to get the required load strength to the anchors. When reinforcement appears during drilling, labourers tend to stop the drilling or try to deflect the hole. Further E7 mentioned that "*when applying chemicals to the hole, if air bubbles remain inside the holes, required bond strength can't be gained. Also, those air bubbles can be exposed making injuries to the workers*".

For most of the challenges identified in this stage, proper supervision is the possible solution that can be taken. Apart from that, awareness programs and workshops are another possible solution for some challenges. According to E5, using new technologies avoids poor workmanship. Further for cleaning instead of a brush, using water is more effective to remove dust, and E6 mentioned that "*we must educate the respective persons in the supply chain to store the goods properly*". Following standard safety procedures is more effective than doing treatment for the injuries. E2 mentioned that *"wearing eye protectors, gloves and safety belt is more important to avoid accidents in site"*. Those are the possible solutions identified in the installation stage.

4.2.3 Challenges Faced after Installing Chemical Anchors and Proposed Solutions

According to literature findings, rebar should be inserted into chemicals while turning. During the gelling period, rebar can be adjusted. This is the main advantage of Chemical Anchoring when compared with mechanical anchoring. But after gelling time, rebar should not be disturbed. Otherwise, bond quality will be reduced. Table 5 summarises all challenges respondents identified after installing Chemical Anchoring.

Table 5: Challenges that can be faced after installing chemical anchors and proposed solutions

Challenge											Solution										
Tackle the construction program											Identify critical paths and work that can be done simultaneously and redevelop the construction program										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔		✔		✔		✔	✔	✔	✔				✔		✔	✔		✔	✔	✔	✔
Pure epoxy resins have a high curing time											Use hybrid resins which have relatively less curing time										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔					✔	✔	✔	✔	✔	✔	✔		✔		✔			✔	✔	✔	
Corrosion of rebar											Use Certified adhesives which resist corrosion										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
				✔			✔	✔	✔			✔	✔		✔	✔		✔			✔
Shear failures											Design chemical anchors where shear is not critical Carry out the shear test before attaching the fixture to the anchor										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔		✔					✔			✔	✔			✔			✔		✔	✔	
Reduce structural integrity											Minimize chemical anchor applications for structural parts										

Challenge											Solution										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
✔		✔		✔			✔			✔	✔	✔		✔					✔		✔
Change curing period due to temperature and site condition											Utilize a product manual designed for the Sri Lankan context Use resins that have relatively less curing time and less sensitivity to the temperature										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
	✔					✔			✔				✔			✔	✔				
The actual applied load is not provided which results in using larger diameter rebars or high embedment depths											The structural design team should involve the manufacturer from the beginning to have the optimal design										
E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*
					✔		✔					✔			✔			✔			

Most of the interviewees identified that pure epoxy resins have high curing time as a challenge, though the product manual mentions curing time as five or six hours, which changes according to the climate and site condition. E2 mentioned that "if the surface is not dry or wet, it takes much time to harden". According to E7, when temperature drops, curing time is high. Further E7 mentioned that "in Nuwaraeliya, chemicals have higher cure time than other districts". According to E1 and E7, most of the time engineers recommend curing the chemical anchor around 24 hours or day. This is the challenge faced by the contractors. If Chemical Anchoring was included during the design stage, it is not a problem because the construction program is developed considering those facts. But most of the time chemical anchors are done for sudden design changes or to install missed rebars. In such a situation curing for a day is a huge time waste and difficult to tackle the construction program.

Further E5 described that "c*hemicals not up to the standard level let the rebar corrode inside the chemical*", which leads to happen failure in the structure. According to E1, shear failure can happen because usually chemical anchors are not designed for shear, and they are designed where shear is not critical. Yet sometimes after the actual load is applied, shear will be critical for some areas. Those are the challenges identified after installing chemical anchors by interviewees.

5. DISCUSSION

Chemical anchors are perfect for applications requiring high loads since the load they support is nearly always greater than the initial substrate material. There is no pre-loading tension applied to the substrate, unlike with expansive mechanical anchors, because the system is based on chemical and mechanical compounds (Sika Group, n.d.). Chemical anchors are, therefore, perfect for group anchoring and fixing near edges. Nevertheless, the research study revealed a set of challenges faced by Sri Lankan professionals throughout the application of Chemical Anchoring. Eight challenges were identified in the design phase of chemical anchors, with experts proposing solutions for each challenge.

One significant challenge is purchasing materials, as the monopoly market in Sri Lanka limits the availability of Chemical Anchoring materials to just one firm. As a result of the monopoly market, it has been difficult to manage the price of materials (Dai & Guo, 2020). In addition to that, Sri Lanka lags in the application of novel technologies, and the lack of knowledge among professionals has led to both under-design and over-design of chemical anchors. To address these issues, it is crucial to conduct training and workshops and to involve experts in the field of anchoring during the design phase. Experienced workmanship is critical during the installation of chemical anchors. Many anchors fail due to poor workmanship, failure to find the correct depth, limited chemical availability, and a lack of advanced tools and materials. Proper supervision, adopting new technologies, and implementing proper designs are the primary solutions suggested by the interviewees. In Chemical Anchoring, the anchor hole must be cleaned well, as chemicals can be damaged when mixed with debris in the holes. After the installation process, to address the challenge of maintaining the construction schedule, most interviewees recommended identifying critical paths. Corrosion is another issue practitioners face after Chemical Anchoring, and it was recommended to use adhesives to resist corrosion. Taking longer curing times can be managed by replacing pure epoxy resins with hybrid resins. Moreover, utilising product manuals designed for the site conditions can manage the changing curing times resulting from temperature differences and site conditions.

6. CONCLUSIONS AND RECOMMENDATIONS

According to the study, adhesive anchors mainly find their use for repairing, strengthening, and reinforcing existing structures, connecting two similar or dissimilar materials, and resisting mechanical and environmental loads. The applications of Chemical Anchoring are discussed in the literature review. Expert interviews revealed the potential challenges that could be encountered during the design stage, installation and after installation of chemical anchors and proposed solutions. Newly added challenges which arise due to the pandemic situation and economic crisis can be identified as significant increases in chemical prices, lack of chemicals in the stores and supervision. As solutions, designing software can be introduced to overcome under-design, cover design and other mistakes in designing. Moreover, proposer supervision, adopting new technologies, and following proper standards are solutions for the identified challenges.

This research contributes to the industry by identifying potential challenges in Chemical Anchoring and proposing solutions. Further, the study contributes to the theory by addressing the prevailing research gap of none of the studies carried out focusing on Chemical Anchoring within the Sri Lankan context. The research study is limited to the post-installed chemical anchors where the base material is concrete and bricks. Rock anchoring, mechanical anchoring, and grouted anchoring are not considered when carrying out this research.

7. REFERENCES

Al-Mansouri, O., Mège, R., Pinoteau, N., Guillet, T., & Remond, S. (2019). Influence of testing conditions on thermal distribution and resulting load-bearing capacity of bonded anchors under fire. *Engineering Structures*, 192, 190–204. https://doi.org/10.1016/j.engstruct.2019.04.099

Askar, M. K., Hassan, A. F., & Al-Kamaki, Y. S. (2022). Flexural and shear strengthening of reinforced concrete beams using FRP composites: A state of the art. *Case Studies in Construction Materials*, 17, e01189. https://doi.org/10.1016/j.cscm.2022.e01189

Bayraktar, A., Altunışık, A. C., & Muvafık, M. (2016). Field investigation of the performance of masonry buildings during the October 23 and November 9, 2011, Van earthquakes in Turkey. *Journal of Performance of Constructed Facilities*, *30*(2), 1–10. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000383

Belina, A. (2023). Semi-structured interviewing as a tool for understanding informal civil society. *Voluntary Sector Review*, *14*(2), 331–347. https://doi.org/10.1332/204080522x16454629995872

Budhai, N. (n.d.). *Anchor and chemical installation tips with Nikhiel Budhai*. Retrieved June 10, 2024, from https://upat.co.za/chemical-anchors-explanation-uses/

Çalişkan, Ö., Karakurt, C., Aras, M., & Kaya, T. (2022, April 21). *Behaviors of chemical anchors installed in different types of concrete | Research square*. https://www.researchsquare.com/article/rs-1570263/v1

Cattaneo, S. and Muciaccia, G. (2015) 'Adhesive anchors in high performance concrete,' *Materials and Structures*, 49(7), pp. 2689–2700. https://doi.org/10.1617/s11527-015-0677-4.

Collins, D. M., Klingner, R. E., & Polyzois, D. (1989). *Load-deflection behavior of cast-in-place and retrofit concrete anchors subjected to static, fatigue, and impact tensile loads*. https://library.ctr.utexas.edu/digitized/texasarchive/phase2/1126-1.pdf

Cook, R. A. (1993). Behavior of chemically bonded anchors. *Journal of Structural Engineering*, *119*(9), 2744–2762. https://doi.org/10.1061/(asce)0733-9445(1993)119:9(2744)

Cook, R.A., Eligehausen, R. and Appl, J.J. (2007) 'Overview: Behavior of adhesive bonded anchors,' *Beton-Und Stahlbetonbau*, 102(S1), 16–21. https://doi.org/10.1002/best.200710107.

Dai, Z., & Guo, L. (2020). Market competition and corporate performance: Empirical evidence from China listed banks with financial monopoly aspect. *Applied Economics*, *52*(44), 4822–4833. https://doi.org/10.1080/00036846.2020.1745749

Eligehausen, R., Cook, R. A., & Appl, J. (2006). Behavior and design of adhesive bonded anchors. *ACI Structural Journal*, *103*(6), 822–831. https://www.researchgate.net/publication/280039038_Behavior_and_design_of_adhesive_bonded_anchors

Hsieh, H., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research*, *15*(9), 1277–1288. https://doi.org/10.1177/1049732305276687

Karakostas, C., Lekidis, V., Makarios, T., Salonikios, T., Sous, I., & Demosthenous, M. (2005). Seismic response of structures and infrastructure facilities during the Lefkada, Greece earthquake of 14/8/2003. *Engineering Structures/Engineering Structures (Online)*, *27*(2), 213–227. https://doi.org/10.1016/j.engstruct.2004.09.009

Kim, J., Jung, W., Kwon, M., & Ju, B. (2013). Performance evaluation of the post-installed anchor for sign structure in South Korea. *Construction & Building Materials*, *44*, 496–506. https://doi.org/10.1016/j.conbuildmat.2013.03.015

Leedy, P. D., & Ormrod, J. E. (2015). *Practical research: Planning and design* (11th ed.). Pearson.

MacDonald, S., & Headlam, N. (2011). *Research methods handbook: Introductory guide to research methods for social research*. Centre for Local Economic Strategies.

Mazumder, M., Miah, M. K., Amin, A., & Riyad, R. H. (2020). Comparison of pull-out strength behavior for chemical adhesive anchors installed in concrete. *American Academic Scientific Research Journal for Engineering, Technology, and Sciences*, 72(1), 81–89. https://asrjetsjournal.org/index.php/American_Scientific_Journal/article/download/6204/2236

Munianday, P., Radzi, A. R., Esa, M., & Rahman, R. A. (2022). Optimal strategies for improving organizational BIM capabilities: PLS-SEM approach. J*ournal of Management in Engineering*, 38(3). https://doi.org/10.1061/(asce)me.1943-5479.0001038

Müsevitoğlu, A., Arslan, M. H., Aksoylu, C., & Özkış, A. (2020). Experimental and analytical investigation of chemical anchors's behaviour under axial tensile. *Measurement*, *158*, 107689. https://doi.org/10.1016/j.measurement.2020.107689

Ospina, S. (2004). Qualitative research. In G. R. Goethals, G. J. Sorenson, & J. M. Burns (Eds.), *Encyclopedia of leadership* (Vol. 1, pp. 1279–1284). Sage.

Ramset. (2009). *Mechanical anchoring*. Ramset. https://www.scribd.com/document/234529143/Ramset-Anchors

Sabatini, P. J., Pass, D. G., & Bachus, R. C. (1999). *Geotechnical engineering circular no. 4: Ground anchors and anchored systems* (Publication No. FHWA-IF-99-015). United States Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/712

Sakla, S. S. S., & Ashour, A. F. (2005). Prediction of tensile capacity of single adhesive anchors using neural networks. *Computers & Structures*, *83*(21–22), 1792–1803. https://doi.org/10.1016/j.compstruc.2005.02.008

Sika Group. (n.d.). *Chemical resin anchors offer distinct advantages over mechanical anchors*. Retrieved June 10, 2024, from https://www.sika.com/en/construction/anchoring.html

Stierschneider, E., Zeman, O., & Bergmeister, K. (2022). Freeze-thaw behaviour of post-installed bonded anchors under changing climate conditions. *CivilEng*, *3*(2), 332–346. https://doi.org/10.3390/civileng3020020

Taherdoost, H. (2022). What are different research approaches? comprehensive review of qualitative, quantitative, and mixed method research, their applications, types, and limitations. *Journal of Management Science & Engineering Research*, *5*(1), 53–63. https://doi.org/10.30564/jmser.v5i1.4538

Thienoosan, S., Goonewardena, D. J. C. Y., & Tharmarajah, G. (2023). Physical and mechanical characteristics of lime-based cementitious grout. *Proceedings of the SLIIT international conference on engineering and technology, Colombo*, 234–244. https://doi.org/https://doi.org/10.54389/HDST9141

Titov, O. V., Nadezhdin, V. S., Gruzdev, A. S., & Kuprin, A. V. (2021). On the strength of chemical anchors. *IOP Conference Series. Materials Science and Engineering*, *1129*(1), 012023. https://doi.org/10.1088/1757-899x/1129/1/012023

Weerasooriya, D., Ranadewa, K.A.T.O., & Perera, B.A.K.S. (2024). Facilitating the role of quantity surveyors through integration of cyber-physical systems. *Journal of Engineering, Design and Technology*. https://doi.org/10.1108/jedt-03-2023-0126

Yılmaz, S., Özen, M. A., & Yardım, Y. (2013). Tensile behavior of post-installed chemical anchors embedded to low strength concrete. *Construction and Building Materials*, 47, 861–866. https://doi.org/10.1016/j.conbuildmat.2013.05.032

Xanthakos, P. P. (1991). *Ground anchors and anchored structures*. Wiley. https://doi.org/10.1002/9780470172780

Dilaksha, S., Ranadewa, K.A.T.O., Weerasooriya, D., Parameswaran, A. and Weerakoon, P., 2024. Comparative analysis of challenges in manual and automated construction progress monitoring in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 379-394. DOI: https://doi.org/10.31705/WCS.2024.30. Available from: https://ciobwcs.com/papers/

COMPARATIVE ANALYSIS OF CHALLENGES IN MANUAL AND AUTOMATED CONSTRUCTION PROGRESS MONITORING IN SRI LANKA

S. Dilaksha[1], K.A.T.O. Ranadewa[2], D. Weerasooriya[3], Agana Parameswaran[4], and Panchali Weerakoon[5]

ABSTRACT

Construction Progress Monitoring (CPM) plays a pivotal role in ensuring the timely and cost-effective completion of construction projects. Previous research has classified CPM techniques into manual and automated methods. While traditional manual CPM has been prevalent in the Sri Lankan construction industry, it suffers from several limitations that can impede project success. Despite the significance of CPM, both manual and automated techniques face challenges in implementation. Therefore, the research aims to explore the challenges associated with CPM in the Sri Lankan construction industry. A comprehensive literature review was conducted to establish a theoretical framework. A quantitative research approach was employed, utilising a questionnaire survey with a heterogeneous purposive sampling method, involving 68 respondents. Data analysis was performed using IBM SPSS software. The study revealed different challenges in manual CPM and automated CPM specifically within the Sri Lankan context. One of the key takeaways of this study is that the challenges in manual CPM outweigh those in automated techniques. However, statistical analysis indicated that both manual and automated CPM face significant challenges, as evidenced by a negative skewness in survey data. Automated CPM heavily relies on computer vision technologies, with issues primarily arising from reality-capturing technologies. This study significantly contributes to the existing body of knowledge by identifying and categorising challenges in both manual and automated CPM within the Sri Lankan construction industry. The findings provide a platform for future research endeavours to devise strategies and solutions to address these challenges, ultimately enhancing the efficiency and effectiveness of construction progress monitoring in the industry.

Keywords: *Automated Progress Monitoring; Challenges; Construction Progress Monitoring (CPM); Manual Progress Monitoring; Sri Lanka.*

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, dilakshasamarasingha@gmail.com

[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, tharushar@uom.lk

[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dilanw@uom.lk

[4] PhD Scholar, School of Engineering, Design and Built Environment, Western Sydney University, Australia, aganaparameswaran@gmail.com

[5] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, panchaliweerakoon@gmail.com

1. INTRODUCTION

The construction industry plays a vital role in contributing to the economy of the nation (Parameswaran & Ranadewa, 2024). However, the construction industry is plagued by project delivery delays, and cost overruns (Amri & Marey-Pérez, 2020; Parameswaran et al., 2024). Han et al. (2018) stated that, although project managers allocate a considerable priority to project schedule and budget adherence, due to the failure to effectively capture construction progress more than 66% of projects are cost overrunning, and 53% of projects are getting delayed. In addition, Alizadehsalehi and Yitmen (2019) stated that time, cost, and quality are the key indicators in the progress of a construction project which can impact the project during the construction period. Most researchers have identified that CPM can influence a project's time, cost, and quality aspects (Ingle & Mahesh, 2022). Khairadeen Ali et al. (2021) stated that CPM can be used to overcome scheduled delays and budget overruns. Ekanayake et al. (2021) mentioned that CPM is critical for determining progress discrepancies between as-planned and as-built status and for taking corrective actions on time. In compliance with these statements, the CPM can be considered an essential aspect of project control that supports making timely decisions to ensure successful project delivery (Rehman et al., 2022). Therefore, it is vital to monitor the progress on construction sites during the construction period as CPM benefits the project by cost savings, time shortening, and quality improvement (Fobiri et al., 2022). To achieve the benefits, different CPM techniques have been followed by the industry people for instance computer vision techniques (Rehman et al., 2022), visual and virtual techniques (Lin & Golparvar-Fard, 2020), reality capturing techniques (Jacob-Loyola et al., 2021). Therefore, both automated and manual CPM techniques can be identified in the construction industry.

Automated CPM is defined as the process of using technology and data analysis to monitor construction projects in real time, with less labour involvement (Kopsida et al., 2015; Perera et al., 2023). Manual CPM is considered where the whole process of monitoring will be done with human involvement and primitive technology will be adopted and based on labour (Qureshi et al., 2022). In addition to that, manual techniques are time-consuming (Silva et al., 2015) and less accurate (Wang et al., 2015). Despite the importance of CPM, there are several challenges in manual progress monitoring methods (Dasović et al., 2020; Reja et al., 2022) and automated CPM techniques (Christou et al., 2021; Qureshi et al., 2022; Rodríguez et al., 2022). Thus, there is a need to investigate the challenges of manual and automated CPM. Therefore, the research aims to investigate the challenges in CPM in the Sri Lankan construction industry. The objectives of the research are to identify the challenges of manual and automated CPM. This paper commences with a literature review on challenges in manual CPM and challenges in automated CPM techniques. Thereafter, the research methodology adopted is presented. The next section presents an analysis of empirical data in terms of challenges in manual CPM and automated CPM techniques, and the overall mean comparison to challenges between manual and automated CPM techniques.

2. LITERATURE REVIEW

2.1 CHALLENGES IN MANUAL CPM

Despite the importance of CPM, manual progress monitoring methods can be difficult. Table 1 emphasises the major challenges that are faced by the project managers by incorporating manual CPM methods. The following categorisations have been done with the level of human involvement for each technique.

Table 1: Challenges in manual CPM

Method		No	Challenges	References
Commercial Software	MS Project and Primavera P6 software.	1	Both software does not allow for drawings and visualization of construction. Therefore, the client is unable to understand.	[1]; [20]
		2	In MS Project software, displaying multiple Baseline bars is difficult.	[2]; [22]
		3	Lack of multi-project control in MS Project.	[19]
		4	Less interoperability between P6 and Microsoft Word.	[2]
		5	Require manual data updating, which is time-consuming and error-prone for both software.	[7], [21]
		6	Both these software programs are quite expensive.	[13],[14],[15]
		7	Primavera tools are not arranged properly. Hence, difficult to navigate within the software.	[16]
		8	PDF reports are not supported by Primavera P6.	[17]
		9	Both software does not support real-time (Automated) updates without integration.	[18]
	4D Modelling Software.	10	Determining who will oversee entering BIM data into the model and ensuring its accuracy and consistency is a risk.	[23]
		11	Require manual data updating, which is time-consuming and error-prone.	[24],[25],[26]
		12	Limited adoption of progress monitoring tools.	[27]
Earned Value Management.		13	Hugely influenced by material prices and labour rates.	[11]
		14	Lump-sum price breakdown is necessary to calculate the BCWP value.	[5]
		15	Measures only 'amount of work performed', but time deviations are not considered.	[6]
Physical Measurement Techniques.		16	Labour incentives, involve paperwork and are time-consuming.	[7]
		17	Manual, lengthy drafting and updating process.	[15]
		18	Manual data collection makes the process inaccurate.	[9],[10],[11]
		19	Reliance on the supervisor's determination and integration of cost with time, and scope of work into progress measurement is difficult.	[9],[12],[27]

[1] - (Reja et al., 2022) , [2] - (Phophalia & Basu, 2018), [3] - (Puri & Turkan, 2020),[4] - (Christensen, 1998), [5] - (Bhosekar & Vyas, 2012), [6] - (Ballesteros-Pérez & Elamrousy, 2018), [7] - (Zaher et al., 2018), [8] - (Xu et al., 2021), [9]- (Danku et al., 2020),[10]- (Ibrahim et al., 2009), [11] - (Ergen et al., 2007), [12]- (Ibrahim et al., 2009), [13] - (Alaidaros et al., 2019), [14] - (Azhaman et al., 2021), [15]- (Nyandongo & Lubisi, 2019), [16] -(Pankaj et al., 2020), [17] –(Khairadeen Ali et al. 2021), [18] – (Perera et al., 2023) , [19] -(Wali & Othman, 2019), [20]- (Noaman & Al-Taie, 2020), [21] - (Dasović et al., 2020), [22] - (Deshmukh et al., 2019), [23] - (Ahmadi & Arashpour, 2020) , [24] -(Kropp et al., 2012), [25] -(Kim & Lee, 2019), [26] - (Silvestre & Ţîrcă, 2019), [27] - (Álvares & Costa, 2019)

According to Table 1, most of the researchers have emphasised that the MS Project and Primavera P6 software are quite expensive. In addition to that, researchers have identified that manual data updating is demanded by this software which can be prone to errors. Importantly, several researchers express that progress understanding is quite hard when visualisation is not supported by this software. Besides, most researchers indicated that 4D modelling software also demands manual data updating when automated technologies are not integrated for data capturing. A major challenge in Earned Value Management (EVM) is that it is only used for financial progress measurement purposes while a separate technique should be followed for physical progress. When considering the physical measurement techniques, their results are subjective because they depend on the supervisor's decisions. Besides Omar et al. (2018) stated that these manual CPM processes are extremely slow, as updating the construction activities requires approximately 20-30% of the feeders' daily efforts. Therefore these, manual progress monitoring methods are currently unable to keep up with the industry's rapid development (Sidani et al., 2021).

Omar et al. (2018) further stated that manual CPM is outdated due to the various challenges faced by the progress inspectors. Pan and Zhang (2021) highlighted that manual progress-tracking methods have limitations in studying project progress precisely. Therefore, Puri and Turkan (2020) highlighted that the challenges in manual progress-measuring approaches emphasise the importance of implementing modern technologies for CPM. As a recent trend, automated CPM is trying to find answers to these issues (Shamsollahi et al., 2022)

2.2 CHALLENGES IN AUTOMATED CPM TECHNIQUES

Researchers have reviewed that computer vision is not still a regression as it is improving (Wang et al., 2021), yet it has faced challenges that have prevented it from being widely adopted in the construction industry. Despite the success of computer vision technology, automated CPM is still quite a challenge due to many challenges in the use of various data-collecting methods (Pučko et al., 2018). These challenges are listed in Table 2.

Table 2: Challenges in existing CPM

Method	Technology	No	Description	Reference
Point cloud and 4D BIM-based technologies.	3D laser scanning	1	High expensive equipment, mixed pixel restoration, need for sensor calibrations regularly, greater warm-up time.	[1];[2];[3]; [4];[5]
		2	Operation requires high technical knowledge.	[6]
		3	The accuracy of the data acquisition using laser scanning might be affected due to occlusions and shadows in the site.	[7]; [8]
	Light detection and ranging scanning (LiDAR).	4	LiDAR data processing refers to the use of algorithms due to unorganized point clouds occurring by dynamic scanning.	[9]
		5	Require expert operators when the sensor platform flies through narrow pathways.	[10]
		6	Large empty voxels may cause the loss of information, which will reduce the accuracy of data processing.	[11]
	Photogrammetry	7	Differences in lighting conditions may affect the resolution.	[12];[13]
		8	Object edge detection may be affected. Moreover, shadows, occlusions, and noisy images will affect the accuracy of progress estimation.	[14];[15]
		9	Noisier point clouds than LiDAR.	[16]
		10	The accuracy level in point cloud models depends on the number of photographs.	[17];[18]
		11	Photogrammetry scanning is a lengthy process that needs a lot of software knowledge.	[19]
		12	Large-scale construction projects may become exceedingly labour-intensive and error-prone.	[20]
	Videogrammetry	13	Highly get affected by occlusions.	[21]

Method	Technology	No	Description	Reference
	Time Lapse Camera	14	Adjacent buildings or elements (temporary or permanent) affect the visual quality of photographs. Varying lighting, shadows, weather, and site conditions complicate image analysis. Display only what is in the range and view field.	[22]
	CCTV Camera	15	Fixed cameras increase the number of cameras required. Less field of view can be caused by data clashes.	[23]
Sensor-based technologies.	Quick response or QR codes.	16	Might be damaged by environmental conditions.	[24]
		17	Object tracking is difficult for some materials, which are not easily accessible.	[25]
	Radio Frequency Identification or RFID tags.	18	RFID tags are usually developed with a fixed single sensor or, multiple built-in sensors which results in limited flexibility.	[26]
		19	Blind spots may occur when the RFID tag is not in the coverage area of the receiver.	[27]
		20	Due to sensors, transceivers, and various devices, energy consumption is high.	[28]
Geospatial technologies.	Geographic Information System (GIS)	21	The main challenge is difficulty in handling in indoor environments. Therefore, most suitable for outdoor progress monitoring.	[29]
		22	Need system developers.	[30]

[1]-(Moon et al., 2019), [2]- (Nguyen et al., 2020) , [3] -(Alshawabkeh et al., 2021), [4]- (Dreier et al., 2021), [5] - (Lassiter et al., 2021), [6] - (Qureshi et al., 2022) , [7] - (Phophalia & Basu, 2018), [8] - (Mwangangi et al., 2022) , [9] - (Paiva et al., 2023) , [10] - (Weinmann et al., 2021), [11] -(Gharineiat et al., 2022), [12] - (Ventura et al., 2021), [13] -(Peng et al., 2021), [14] - (Reja et al., 2022), [15] – (Barbero-García et al., 2021) [16]- (Latella et al., 2022), [17] - (Rodríguez et al., 2022), [18]- (Štroner et al., 2021), [19] - (Omar et al., 2018), [20] - (Rahimian et al., 2020), [21]- (Alaloul et al., 2021), [22]-(Golparvar-Fard et al., 2009), [23] -(Reja et al., 2022), [24] -(Wang et al., 2021), [25] -(Zhai et al., 2019), [26] -(Landaluce et al., 2020), [27]-(Shirehjini & Shirmohammadi, 2020), [28]- (Cui et al., 2019), [29] -(Thellakula et al., 2021), [30]- (Christou et al., 2021)

In compliance with Table 2, field data-capturing technologies are undermining the existing automated CPM techniques to some extent. Commonly, all these point cloud techniques are used to re-model real-world objects through reality capturing, therefore, all researchers have mentioned that each technique is lighting sensitive. According to Table 2, most researchers have addressed that 3D laser scanning techniques are having many challenges rather to the other techniques. Comparatively, challenges in Photogrammetry techniques were also highly reviewed by the researchers that emphasise the difficulties in that technology. However, this literature review identified that still automated reality-capturing techniques can be used for CPM due to fewer references to the challenges in other technologies except for several techniques. Nevertheless, researchers further emphasised that reality-capturing technologies in the CPM are still connected with BIM (Alaloul et al., 2021; Arif & Khan, 2021; Kavaliauskas et al., 2022). Therefore, it is important to review the research findings regarding the challenges in BIM. Szeliski (2022) stated that engineers face difficulties while managing complex 3D models. Besides, (Li et al., 2022) mentioned that BIM modelling demands high-performance servers for rendering, and it takes a long time to complete the rendering procedure. Johansson and Roupé (2019) expressed that BIM applications are constantly improving, but there are issues with the user interface, and extracting information and taking correct measurements directly from the model is difficult. For this reason, information transfer from the design office to the construction site is delayed. Because of these difficulties, most of the BIM-integrated CPM techniques have become a challenge. In this case, researchers have identified the optimum use of XR technologies and BIM-integrated computer vision-based CPM techniques. Together these technologies successfully visualise the progress deviations by superimposing BIM models to the construction images over a 3D model (Ekanayake et al., 2021).

Exploring the critical significance of CPM, both manual and automated approaches encounter various challenges. Hence, there is a need to investigate the challenges of both manual and automated CPM. Therefore, the research aims to investigate the challenges in CPM in Sri Lankan construction.

3. RESEARCH METHODOLOGY

The study started with a comprehensive literature review. Questionnaires are frequently utilised in survey methodologies since they offer an approach to collecting responses from a large sample, ensuring uniformity in questioning, and enabling effective quantitative analysis (Saunders et al., 2009). Therefore, a questionnaire survey was used to collect the data. Accordingly, challenges to existing CPM techniques were identified through a questionnaire survey. The selected population for the questionnaire survey was the professionals who have addressed the CPM in local and international level project delivery. The heterogeneous purposive sampling technique was used for quantitative approaches to select a representative sample from the population as it assisted in selecting a sample that is relevant to a range of experiences, perspectives, and characteristics (Mweshi & Sakyi, 2020). In this study, a heterogenous sampling technique was adopted since it allows to choice of professionals know about automated and manual CPM techniques. The sample population was limited to 68 people who are engaged in CPM techniques in the industry representing different educational levels, professions and experiences within the construction industry. Furthermore, a questionnaire survey was conducted through the Google Forms platform, requesting ratings on the challenges to CPM that were identified. Majorly, the questionnaire survey requested to rate the challenges related to both automated and manual CPM techniques for a given scale. The scale for the ratings was a five-point “Likert scale” that was requested to rate the level of significance of each challenge in both CPM techniques, where 1 meant "Strongly disagree" and 5 meant "Strongly Agree (Parameswaran & Ranadewa, 2022).

3.1 PROFILE OF THE SURVEY RESPONDENTS

Figure 1 presents the details of the respondents.

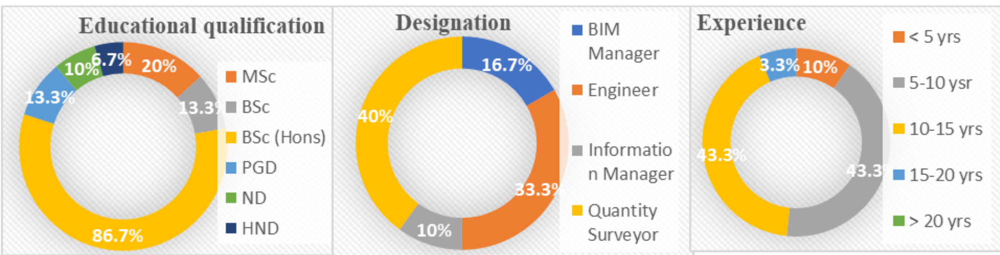


Figure 1: Details of the respondents

The selected sample necessarily had experience in CPM and before sharing the questionnaire a verification was done to ensure the respondent had adequate experience in terms of CPM in both manual and automated techniques. Most of the respondents had experience in the local context except a few respondents who had experience overseas. According to Figure 1, 86.7 % portion of respondents completed BSc (Hons) level educational qualifications. 20% of them completed the MSc. An equal number of BSc degree and Post Graduate Diploma holders represent Figure 1. Higher national diploma holders account for 10% of the chart. The remaining 6.7 % belonged to the National Diploma holders. Figure 1 indicates the designation of each respondent who answered the questionnaire survey. Accordingly, 40% of the respondents were Quantity Surveyors and 33.3% were Engineers.

Importantly, several BIM experts were able to attend the questionnaire. Among them, 16.7% of respondents were BIM Managers while 10% of them were Information Managers. Figure 1 shows the distribution of experience of the respondents among 30 respondents of the questionnaire survey. Similarly, 43.3% of the respondents had experience of 5-10 years and 10-15 years. However, 10% of the sample had less than five years' experience. The remaining 3.3% of the chart is taken by the respondents who had experience for 15-20 years. Challenges in the literature findings related to both manual and automated CPM techniques had to be analysed. Thus, IBM SPSS software was used as a supportive tool that assists the statistical measures of survey data. Accordingly, the central tendency parameters have been considered to determine the suitability to use such parameters to analyse the survey data. The analysis is further discussed by using the statistical parameters on the responses such as Mean, Median, and Mode Standard Deviation and Variance (Ali & Bhaskar, 2016).

4. RESEARCH FINDINGS

4.1 ANALYSIS OF CHALLENGES IN MANUAL CPM

Challenges to manual CPM techniques were identified in the literature review through Table 1, the questionnaire survey was designed to scale the level of significance of each challenge. Thus, Table 3 indicates the statistical parameters on the level of significance.

Table 3: Statistical parameters on challenges of manual CPM

Challenge *No.*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Mean	4.5263	4.5263	4.2368	4.5263	4.1053	4.0526	3.6579	3.7105	4.5789	3.8684	3.4211	3.5000	3.2632	3.9737	4.1316	4.2895	4.7895	4.1842	3.8158
Median	5.0000	5.0000	4.0000	5.0000	4.0000	4.0000	4.0000	4.0000	5.0000	4.0000	3.0000	3.0000	3.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000
Mode	5.00	5.00	4.00	5.00	4.00	4.00	4.00	4.00	5.00	4.00	3.00a	3.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Std. Deviation	.79651	.82975	.71411	.86170	.89411	.76925	.93798	.89768	.79293	.52869	1.05604	.95153	1.00497	.54460	.47483	.73182	.89411	.60873	.98242
Variance	.634	.688	.510	.743	.799	.592	.880	.806	.629	.280	1.115	.905	1.010	.297	.225	.536	.799	.371	.965

The results of the questionnaire survey on the challenges to manual CPM techniques have shown the central tendency parameters concerning the Likert scale. The Median and the

Mode of the challenges varied between four and five except for challenges 11, 12, and 13. Therefore, it is decided that most respondents agreed with the identified challenges while others have not decided whether to agree or not. Moreover, in Table 3, it is shown that the distribution of scores was relatively narrow in challenges 1, 2, 8, 9, 10, 14, and 19 because the mean score was slightly lower than the median and mode. When the mean is lower than the median and mode, it implies that there are a few lower scores that are bringing the mean down. Therefore, there is a small number of extremely low ratings because of that it is decided most of the respondents did not rate these challenges under the disagreed level.

Besides, when the Mean value is higher than the Median and Mode, it indicates that there are a smaller number of high ratings on the challenges. The challenges number 11 and 13 show greater Standard deviation on the Mean which cannot be decided on the level of significance using the central tendency parameters. The data set was negatively skewed as emphasised earlier; therefore, the Mean is not suitable for analysing the level of significance of the given data set. However, the Median can be used to analyse the data set as it does not have a greater impact on the skewness. Accordingly, challenges 1, 2, 4, and 9, indicate a higher tendency to the "Strongly agree" statement. However, challenge number 12 remained in the "Undecided yet" category while the rest of the challenges have been rated as "Agreed" level.

4.2 ANALYSIS OF CHALLENGES IN AUTOMATED CPM

Table 4 indicates the statistical parameters for the findings of the questionnaire survey. Accordingly, an analysis of the challenges to the automated CPM that was listed in Table 2 is further discussed herein.

Table 4: Statistical parameters on challenges of automated CPM

Challenge *No.*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Mean	4.5263	4.2222	3.7568	3.7297	3.9189	3.5946	3.5946	3.5405	3.5135	3.5946	3.6486	3.6486	3.5946	3.7297	3.8378	3.7568	3.8889	3.6486	3.6111	3.7297	3.7838	4.0541
Median	5.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	3.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000
Mode	5.00	5.00	4.00	4.00	4.00a	3.00	4.00	3.00a	3.00	4.00	3.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Std. Deviation	.72548	.76012	.64141	.73214	.92431	.64375	.59905	.55750	.60652	.49774	.67562	.63317	.59905	.50819	.55345	.49472	.74748	.58766	.59894	.60776	.58382	.77981
Variance	.526	.578	.411	.536	.854	.414	.359	.311	.368	.248	.456	.401	.359	.258	.306	.245	.559	.345	.359	.369	.341	.608

In this case, the Mean score has been lowered than the Median and Mode in many challenges such as challenges number 1, 3, 4, 5, 7, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21. Accordingly, the data set describes the challenges to the automated CPM that have been rated at higher levels of the scale by the respondents. However, the range of the Mean value varied between 3.5135 and 4.5263, while challenge number 9 indicates the lowest Mean and challenge number 1 indicates the highest Mean. Accordingly, respondents may have stated that the most significant challenge is from the 3D laser scanning technique. However, importantly, this data set indicates that overall survey results varied between "Agreed" and "Undecided yet" levels. Because the Mean value of the results varied between 3.5135 and 4.5263 and Standard Deviations remained lower level. The reason could be that most of the automated CPM techniques are not practised in the industry as mentioned in the literature review (Pučko et al., 2018). The Mean has exceeded the Median and Mode in challenge numbers 9 and 22 when it comes to the challenges in automated CPM techniques. According to that result, those are the lower-rated challenges when it comes to the challenges in automated CPM techniques. As mentioned before this data set was negatively skewed, therefore, the Mode has been selected as the comparison parameter. In compliance with that, challenges number 1 and 2 have been highly rated under the "Strongly agreed" while challenge number 9 appears to "Undecided yet" level of significance. Moreover, remain challenges were rated under the "Agreed" level. Compliance with the overall analysis of each CPM technique, the results, showed that there are high negative ratings on the manual CPM techniques. On the other hand, automated CPM techniques that have been discussed in the literature review were significantly unrated by the professionals.

4.3 THE OVERALL MEAN COMPARISON TO CHALLENGES BETWEEN MANUAL AND AUTOMATED CPM TECHNIQUES

The overall Mean in a data set is a statistical measure that represents the average value of all the observations in the data set (Datta & Datta, 2003). It is calculated by summing up all the observations and then dividing by the total number of observations (Barnett, 2004). Comparing the overall Means of two data sets can be useful in many research fields (Demšar, 2006). Therefore, to compare the manual and automated CPM techniques overall Mean of each data set was used. Considering that two data sets following linear graph were developed in Figure 2.

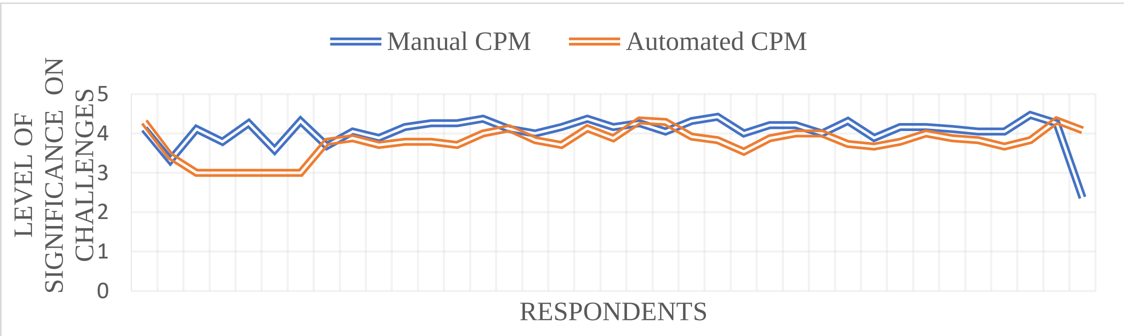


Figure 2: Overall Mean comparison

Figure 2 presents the analysed data on the overall Mean of each manual and automated CPM technique. As shown by Figure 2, manual and automated CPM techniques show a greater deviation from each other because the level of significance on challenges to manual CPM techniques is shown higher significance while the automated CPM techniques are comparatively less. Importantly, the overall Mean has taken a place at an upper level of moderate level of significance which expresses that the literature findings on most of the challenges are truly experienced by the CPM up until now. As appeared in Figure 2, one of the few challenges of both CPM techniques is showing the same overall level of significance as the graphs overlap each other. Finally, the overall analysis of manual and automated CPM techniques has emphasised the importance of an automated CPM technique which can eliminate the challenges in automated CPM techniques that have been analysed in this chapter.

5. DISCUSSION

Azhaman et al. (2021), Danku et al. (2020) and Kim and Lee (2019) pointed out that both software solutions such as MS Project and Primavera P6 software are costly and necessitate manual data updates, leading to time-consuming and error-prone processes and manual data collection introduces inaccuracies, are posing significant challenges in Manual CPM. However, the finding underscored that neither software facilitates drawings and construction visualisation, hampering client comprehension; MS Project struggles with displaying multiple baseline bars, and there's limited interoperability between P6 and Microsoft Word. Furthermore, both platforms lack support for real-time updates without integration, which were highlighted as major challenges. These challenges were strongly acknowledged by respondents in the Sri Lankan construction industry's manual CPM practices, with a high level of agreement observed under the identified 19 challenges. On the other hand, when examining the obstacles within existing automated CPM techniques, Alshawabkeh et al. (2021) and Nguyen et al. (2020) emphasised significant challenges such as the high cost of equipment, issues with mixed pixel restoration, the necessity for frequent sensor calibrations, and longer warm-up times. These challenges were widely acknowledged among respondents, with a notable emphasis on the high expense of equipment, mixed pixel restoration, regular sensor calibrations, and the requirement for extensive technical expertise. Moreover, the challenge relating to noisier point clouds compared to LiDAR was met with uncertainty, indicating a lower level of agreement among respondents. These findings depict that the Sri Lankan construction industry lacks a proper CPM technique which can overcome the identified challenges and obstacles in both manual and automated techniques which are currently available in the construction sector.

6. CONCLUSIONS

The findings of this study provide valuable insights into the challenges faced in both manual and automated CPM techniques. The statistical parameters of this study clearly show the perceived significance of each challenge, allowing for a comprehensive analysis of the responses. In the manual CPM techniques, challenges such as: requiring manual data updating, which is time-consuming and error-prone, limited adoption of progress monitoring tools and is hugely influenced by material prices and labour rates, however, exhibit a certain level of indecision among respondents, suggesting a lack of consensus on these issues. The narrow distribution of scores in challenges includes highly expensive equipment, mixed pixel restoration, the need for sensor calibrations regularly, and greater warm-up time; the operation requires high technical knowledge; object edge detection may be affected. Moreover, shadows, occlusions, and noisy images will affect the accuracy of progress estimation, the accuracy level in point cloud models depends on the number of photographs; adjacent buildings or elements (temporary or permanent) affect the visual quality of photographs. Varying lighting, shadows, weather, and site conditions complicate image analysis. Display only what is in the range and view field; blind spots may occur when the RFID tag is not in the coverage area of the receiver, implying that while most respondents agreed with these challenges, a few lower scores were bringing down the mean.

Moving on to the automated CPM techniques, the mean scores range from 3.5135 to 4.5263, indicating that respondents rated these challenges at higher levels on the Likert scale. The data set suggests an overall agreement or indecision, with mean values falling between "Agreed" and "Undecided yet" levels. Comparing the challenges between manual and automated CPM techniques, the overall mean comparison in Figure 2 reveals a notable deviation. Challenges to manual CPM techniques show higher significance, reflecting the more pressing concerns faced in this traditional approach. Conversely, challenges in automated CPM techniques are comparatively less significant, possibly due to limited industry adoption, as mentioned in the literature review. The overall analysis emphasises the importance of automated CPM techniques in mitigating the challenges faced by manual methods. The Overall Mean Comparison graph in Figure 2 indicates a substantial difference in the level of significance between the two techniques, with automated CPM techniques offering a potential solution to the identified challenges. Finally, the findings of this research highlighted that challenges to manual CPM have a higher level of significance compared to automated CPM techniques. However, the statistical survey results indicated that identified challenges have taken a higher level of significance in both manual and automated CPM as the survey data showed a negative skewness. Automated CPM relies on computer vision technologies. Many issues related to automated CPM techniques have arisen due to the use of reality-capturing technologies.

This paper provides a comprehensive analysis of the challenges encountered in both manual and automated construction progress monitoring in Sri Lanka. By systematically comparing these challenges, the paper offers valuable insights to industry practitioners, enabling them to understand the limitations and obstacles associated with different monitoring approaches. Through the detailed examination of empirical data, this paper offers practical guidance to stakeholders involved in construction progress monitoring in Sri Lanka. By understanding the specific challenges inherent in manual and automated monitoring methods, practitioners can make informed decisions regarding the selection and implementation of monitoring techniques, ultimately improving project efficiency and performance. By empirically validating the challenges in manual and automated construction progress monitoring, this paper contributes to theoretical frameworks and existing literature. The findings of this research provide empirical evidence to support the identified challenges, enriching theoretical discourse and advancing the understanding of construction progress monitoring dynamics in the Sri Lankan context and will support the stakeholders in choosing a project monitoring technique. By shedding light on the unique challenges faced in this setting, the paper contributes to a deeper understanding of how cultural, regulatory, and technological factors influence monitoring practices. This knowledge expansion facilitates cross-contextual comparisons and strengthens the theoretical foundations of construction progress monitoring. Further, future researchers can use the findings of this study to introduce an innovative CPM technique that can overcome the identified challenges and obstacles.

7. REFERENCES

Ahmadi, P., & Arashpour, M. (2020). An analysis of 4D-BIM construction planning: Advantages, risks and challenges.*37th International Symposium on Automation and Robotics in Construction ISARC 2020.* https://doi.org/10.22260/ISARC2020/0025

Alaidaros, H., Omar, M., Romli, R., & Hussein, A. (2019). *The development and evaluation of a progress monitoring prototype tool for software project management.* 2019 First International Conference of Intelligent Computing and Engineering (ICOICE). https://doi.org/10.1109/ICOICE48418.2019.9035146

Alaloul, W. S., Qureshi, A. H., Musarat, M. A., & Saad, S. (2021). Evolution of close-range detection and data acquisition technologies towards automation in construction progress monitoring. *Journal of Building Engineering*, *43*, 102877. https://doi.org/10.1016/j.jobe.2021.102877

Ali, Z., & Bhaskar, S. (2016). Basic statistical tools in research and data analysis. *Indian Journal of Anaesthesia*, *60*(9), 662. https://doi.org/10.4103/0019-5049.190623

Alizadehsalehi, S., & Yitmen, I. (2019). A concept for automated construction progress monitoring: Technologies adoption for benchmarking project performance control. *Arabian Journal for Science and Engineering*, *44*(5), 4993–5008. https://doi.org/10.1007/s13369-018-3669-1

Alshawabkeh, Y., Baik, A., & Miky, Y. (2021). Integration of laser scanner and photogrammetry for heritage BIM enhancement. *ISPRS International Journal of Geo-Information*, *10*(5), 316. https://doi.org/10.3390/ijgi10050316

Álvares, J. S., & Costa, D. B. (2019). *Construction progress monitoring using unmanned aerial system and 4D BIM*. 27th Annual Conference of the International Group for Lean Construction (IGLC). 1445–1456. https://doi.org/10.24928/2019/0165

Amri, T. Al, & Marey-Pérez, M. (2020). Towards a sustainable construction industry: Delays and cost overrun causes in construction projects of Oman. *Journal of Project Management*, 87–102. https://doi.org/10.5267/j.jpm.2020.1.001

Arif, F., & Khan, W. A. (2021). Smart progress monitoring framework for building construction elements using videography–MATLAB–BIM integration. *International Journal of Civil Engineering*, *19*(6), 717–732. https://doi.org/10.1007/s40999-021-00601-3

Azhaman, I., Petryshchenko, N., Hronska, M., Pandas, A., & Pushchina, N. (2021). Project management software in Ukraine. *IOP Conference Series: Materials Science and Engineering*, *1141*(1), 012012. https://doi.org/10.1088/1757-899X/1141/1/012012

Ballesteros-Pérez, P., & Elamrousy, K. M. (2018). On the limitations of the earned value management technique to anticipate project delays. *Proceedings of International Structural Engineering and Construction*, *5*(1). https://doi.org/10.14455/ISEC.res.2018.43

Barbero-García, I., Pierdicca, R., Paolanti, M., Felicetti, A., & Lerma, J. L. (2021). Combining machine learning and close-range photogrammetry for infant's head 3D measurement: A smartphone-based solution. *Measurement*, *182*, 109686. https://doi.org/10.1016/j.measurement.2021.109686

Barnett, A. G. (2004). Regression to the mean: What it is and how to deal with it. *International Journal of Epidemiology*, *34*(1), 215–220. https://doi.org/10.1093/ije/dyh299

Bhosekar, S. K., & Vyas, G. (2012). Cost controlling using earned value analysis in construction industries. *International Journal of Engineering and Innovative Technology (IJEIT)*, *1*(4), 2277–3754.

Christensen, D. S. (1998). The costs and benefits of the earned value management process. *Journal of Parametrics*, *18*(2), 1–16. https://doi.org/10.1080/10157891.1998.10462568

Christou, G., Georgiou, A., Christodoulou, E., Tziakouri, M., Christodoulou, C., Kasinopoulou, S., Panayiotou, C. G., & Savva, A. (2021). Design and development of a GIS-based platform using open source components for monitoring, maintenance and management of road network: The case study of cyprus. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVI-4/W2-*, 37–42. https://doi.org/10.5194/isprs-archives-XLVI-4-W2-2021-37-2021

Cui, L., Zhang, Z., Gao, N., Meng, Z., & Li, Z. (2019). Radio frequency identification and sensing techniques and their applications: A review of the state-of-the-art. *Sensors*, *19*(18), 4012. https://doi.org/10.3390/s19184012

Danku, J. C., Agyekum, K., & Asare, F. T. (2020). Professionals' perceptions on construction progress measurement methods used in Ghana. *World Journal of Engineering and Technology*, *08*(02), 145–158. https://doi.org/10.4236/wjet.2020.82012

Dasović, B., Galić, M., & Klanšek, U. (2020). A survey on integration of optimization and project management tools for sustainable construction scheduling. *Sustainability*, *12*(8), 3405. https://doi.org/10.3390/su12083405

Datta, S., & Datta, S. (2003). Comparisons and validation of statistical clustering techniques for microarray gene expression data. *Bioinformatics*, *19*(4), 459–466. https://doi.org/10.1093/bioinformatics/btg025

Demšar, J. (2006). Statistical comparisons of classifiers over multiple data sets. *Journal of Machine Learning Research*, *7*, 1–30.

Deshmukh, S. P., Sagale, A. V, & Bais, M. M. (2019). Study of scheduling in microsoft project software. *International Journal of Scientific Research & Engineering Trends*, *5*(2), 419–428.

Dreier, A., Janßen, J., Kuhlmann, H., & Klingbeil, L. (2021). Quality analysis of direct georeferencing in aspects of absolute accuracy and precision for a UAV-based laser scanning system. *Remote Sensing*, *13*(18), 3564. https://doi.org/10.3390/rs13183564

Ekanayake, B., Wong, J. K.-W., Fini, A. A. F., & Smith, P. (2021). Computer vision-based interior construction progress monitoring: A literature review and future research directions. *Automation in Construction*, *127*, 103705. https://doi.org/10.1016/j.autcon.2021.103705

Ergen, E., Akinci, B., & Sacks, R. (2007). Life-cycle data management of engineered-to-order components using radio frequency identification. *Advanced Engineering Informatics*, *21*(4), 356–366. https://doi.org/10.1016/j.aei.2006.09.004

Fobiri, G., Musonda, I., & Muleya, F. (2022). Reality capture in construction project management: A review of opportunities and challenges. *Buildings*, *12*(9), 1381. https://doi.org/10.3390/buildings12091381

Gharineiat, Z., Tarsha Kurdi, F., & Campbell, G. (2022). Review of automatic processing of topography and surface feature identification LiDAR data using machine learning techniques. *Remote Sensing*, *14*(19), 4685. https://doi.org/10.3390/rs14194685

Golparvar-Fard, M., Peña-Mora, F., Arboleda, C. A., & Lee, S. (2009). Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. *Journal of Computing in Civil Engineering*, *23*(6), 391–404. https://doi.org/10.1061/(ASCE)0887-3801(2009)23:6(391)

Han, K., Degol, J., & Golparvar-Fard, M. (2018). Geometry- and appearance-based reasoning of construction progress monitoring. *Journal of Construction Engineering and Management*, *144*(2). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001428

Ibrahim, Y. M., Lukins, T. C., Zhang, X., Trucco, E., & Kaka, A. P. (2009). Towards automated progress assessment of workpackage components in construction projects using computer vision. *Advanced Engineering Informatics*, *23*(1), 93–103. https://doi.org/10.1016/j.aei.2008.07.002

Ingle, P. V., & Mahesh, G. (2022). Construction project performance areas for Indian construction projects. *International Journal of Construction Management*, *22*(8), 1443–1454. https://doi.org/10.1080/15623599.2020.1721177

Jacob-Loyola, N., Muñoz-La Rivera, F., Herrera, R. F., & Atencio, E. (2021). Unmanned Aerial Vehicles (UAVs) for physical progress monitoring of construction. *Sensors*, *21*(12), 4227. https://doi.org/10.3390/s21124227

Johansson, M., & Roupé, M. (2019). *BIM and Virtual Reality (VR) at the construction site*. 19th International Conference on Construction Applications of Virtual Reality, November, 1–10.

Kavaliauskas, P., Fernandez, J. B., McGuinness, K., & Jurelionis, A. (2022). Automation of construction progress monitoring by integrating 3D point cloud data with an IFC-based BIM model. *Buildings*, *12*(10), 1754. https://doi.org/10.3390/buildings12101754

Khairadeen Ali, A., Lee, O. J., Lee, D., & Park, C. (2021). Remote indoor construction progress monitoring using extended reality. *Sustainability*, *13*(4), 2290. https://doi.org/10.3390/su13042290

Kim, K., & Lee, Y.-C. (2019). Automated generation of daily evacuation paths in 4D BIM. *Applied Sciences*, *9*(9), 1789. https://doi.org/10.3390/app9091789

Kopsida, M., Brilakis, I., & Vela, P. (2015). *A review of automated construction progress and inspection methods.* Proceedings of the 32nd CIB W78 Conference on Construction IT, January, 421–431.

Kropp, C., Koch, C., König, M., & Brilakis, I. (2012). *A framework for automated delay prediction of finishing works using video data and BIM-based construction simulation*. Proceedings of the 14th International Conference on Computing in Civil and Building Engineering, January, 10–12.

Landaluce, H., Arjona, L., Perallos, A., Falcone, F., Angulo, I., & Muralter, F. (2020). A review of IoT sensing applications and challenges using RFID and wireless sensor networks. *Sensors*, *20*(9), 2495. https://doi.org/10.3390/s20092495

Lassiter, H. A., Wilkinson, B., Perez, A. G., & Kelly, C. (2021). Absolute 3D accuracy assessment of uas LiDAR surveying. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *44*(M–3), 105–111. https://doi.org/10.5194/isprs-archives-XLIV-M-3-2021-105-2021

Latella, M., Raimondo, T., Belcore, E., Salerno, L., & Camporeale, C. (2022). On the integration of LiDAR and field data for riparian biomass estimation. *Journal of Environmental Management*, *322*, 116046. https://doi.org/10.1016/j.jenvman.2022.116046

Li, K., Zhao, H., Zhang, Q., & Jia, J. (2022). CEBOW: A Cloud-Edge-Browser Online Web3D approach for visualizing large BIM scenes. *Computer Animation and Virtual Worlds*, *33*(2). https://doi.org/10.1002/cav.2039

Lin, J. J., & Golparvar-Fard, M. (2020). Construction progress monitoring using cyber-physical systems. In *Cyber-Physical Systems in the Built Environment*, *Springer International Publishing*. https://doi.org/10.1007/978-3-030-41560-0_5

Moon, D., Chung, S., Kwon, S., Seo, J., & Shin, J. (2019). Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning. *Automation in Construction*, *98*, 322–331. https://doi.org/10.1016/j.autcon.2018.07.020

Mwangangi, K. K., Mc'Okeyo, P. O., Oude Elberink, S. J., & Nex, F. (2022). Exploring the potentials of uav photogrammetric point clouds in façade detection and 3D reconstruction of buildings. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIII-B2-2*, 433–440. https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-433-2022

Mweshi, G. K., & Sakyi, K. (2020). Application of sampling methods for the research design. *Archives of Business Research*, *8*(11), 180–193. https://doi.org/10.14738/abr.811.9042

Nguyen, T. A., Nguyen, P. T., & Do, S. T. (2020). Application of BIM and 3D laser scanning for quantity management in construction projects. *Advances in Civil Engineering*, *2020*, 1–10. https://doi.org/10.1155/2020/8839923

Noaman, M. A. A. A., & Al-Taie, E. T. (2020). Resource optimization for sustainable construction development in Iraq using primavera P6. *Journal of Green Engineering*, *10*(7), 4006–4020.

Nyandongo, K. M., & Lubisi, J. (2019). Assessing the use of project management information systems and its impact on project outcome. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, *July*, 1501–1512.

Omar, H., Mahdjoubi, L., & Kheder, G. (2018). Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities. *Computers in Industry*, *98*, 172–182. https://doi.org/10.1016/j.compind.2018.03.012

Paiva, P. V. V., Dezen-Kempter, E., & Carvalho, M. (2023). Morphological operations on unorganized point clouds using octree graphs. *Journal on Computing and Cultural Heritage*, *16*(1), 1–6. https://doi.org/10.1145/3534930

Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction*, *122*, 103517. https://doi.org/10.1016/j.autcon.2020.103517

Pankaj, V., Pitroda, J., & Bhavsar, A. N. (2020). Effective scheduling and control of construction project using Primavera P6 : A Review. *UGC Care Journal*, *40*(50).

Parameswaran, A., & Ranadewa, K. A. T. O. (2022). *Construction industry on the brink: The COVID-19 impact.* Proceedings of 10th World Construction Symposium 2022, 220–235. https://doi.org/10.31705/WCS.2022.19

Parameswaran, A., & Ranadewa, K. A. T. O. (2024). Learning-to-learn sand cone model integrated lean learning framework for construction industry. *Smart and Sustainable Built Environment*, *13*(4), 856–882. https://doi.org/10.1108/SASBE-10-2022-0234

Parameswaran, A., Ranadewa, K. A. T. O., & Rathnasinghe, A. P. (2024). Roles of lean learners for successful lean implementation in the construction industry: A force-directed graph. *International*

Journal of Productivity and Performance Management. https://doi.org/10.1108/IJPPM-07-2023-0346

Peng, M., Di, K., Wang, Y., Wan, W., Liu, Z., Wang, J., & Li, L. (2021). A Photogrammetric-Photometric Stereo method for High-Resolution Lunar Topographic Mapping using Yutu-2 Rover images. *Remote Sensing*, *13*(15), 2975. https://doi.org/10.3390/rs13152975

Perera, W. S. D., Ranadewa, K. A. T. O., Parameswaran, A., & Weerasooriya, D. (2023). Status QUO of digitalisation in the Sri Lankan construction industry. *11th World Construction Symposium - 2023*, 944–959. https://doi.org/10.31705/WCS.2023.76

Phophalia, K., & Basu, R. (2018). Evaluation of Microsoft project and Primavera P6 as construction project management software in India. 5(3), 78–88. https://msp-vs-p6.questionpro.com

Pučko, Z., Šuman, N., & Rebolj, D. (2018). Automated continuous construction progress monitoring using multiple workplace real time 3D scans. *Advanced Engineering Informatics*, *38*, 27–40. https://doi.org/10.1016/j.aei.2018.06.001

Puri, N., & Turkan, Y. (2020). Bridge construction progress monitoring using lidar and 4D design models. *Automation in Construction*, *109*, 102961. https://doi.org/10.1016/j.autcon.2019.102961

Qureshi, A., Alaloul, W. S., Wing, W. K., Saad, S., Ammad, S., & Musarat, M. A. (2022). Factors impacting the implementation process of automated construction progress monitoring. *Ain Shams Engineering Journal*, *13*(6), 101808. https://doi.org/10.1016/j.asej.2022.101808

Rahimian, F., Seyedzadeh, S., Oliver, S., Rodriguez, S., & Dawood, N. (2020). On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Automation in Construction*, *110*, 103012. https://doi.org/10.1016/j.autcon.2019.103012

Rehman, M., Shafiq, M. T., & Ullah, F. (2022). Automated computer vision-based construction progress monitoring: A systematic review. *Buildings*, *12*(7), 1037. https://doi.org/10.3390/buildings12071037

Reja, V. K., Varghese, K., & Ha, Q. P. (2022). Computer vision-based construction progress monitoring. *Automation in Construction*, *138*, 104245. https://doi.org/10.1016/j.autcon.2022.104245

Rodríguez, R., Ponte, M., Bento, R., & Cardoso, R. (2022). Potential of mobile application based on Structure from Motion (SfM) photogrammetry to monitor slope fast erosion by runoff water. *CATENA*, *216*, 106359. https://doi.org/10.1016/j.catena.2022.106359

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*. Pearson education.

Shamsollahi, D., Moselhi, O., & Khorasani, K. (2022). *Construction progress monitoring and reporting using computer vision techniques: A review*. Proceedings of the International Symposium on Automation and Robotics in Construction, 2022-July(Isarc), 467–474.

Shirehjini, A. A., & Shirmohammadi, S. (2020). Improving accuracy and robustness in HF-RFID-based indoor positioning with Kalman filtering and Tukey smoothing. *IEEE Transactions on Instrumentation and Measurement*, *69*(11), 9190–9202. https://doi.org/10.1109/TIM.2020.2995281

Sidani, A., Dinis, F. M., Sanhudo, L., Duarte, J., Santos Baptista, J., Poças Martins, J., & Soeiro, A. (2021). Recent tools and techniques of BIM-based virtual reality: A systematic review. *Archives of Computational Methods in Engineering*, *28*(2), 449–462. https://doi.org/10.1007/s11831-019-09386-0

Silva, G. A., Warnakulasooriya, B. N. F., & Arachchige, B. (2015). Critical success factors for construction projects: A literature review. *SSRN Electronic Journal*, *7(3)* , 27-37, https://doi.org/10.2139/ssrn.2699890

Silvestre, B. S., & Ţîrcă, D. M. (2019). Innovations for sustainable development: Moving toward a sustainable future. *Journal of Cleaner Production*, *208*, 325–332. https://doi.org/10.1016/j.jclepro.2018.09.244

Štroner, M., Urban, R., Seidl, J., Reindl, T., & Brouček, J. (2021). Photogrammetry using UAV-mounted GNSS RTK: Georeferencing strategies without GCPs. *Remote Sensing*, *13*(7), 1336. https://doi.org/10.3390/rs13071336

Szeliski, R. (2022). *Computer Vision*. Springer International Publishing. https://doi.org/10.1007/978-3-030-34372-9

Thellakula, V., Reja, V. K., & Varghese, K. (2021). *A web-based GIS tool for progress monitoring of linear construction projects.* Proceedings of the International Symposium on Automation and Robotics in Construction, 2021-Novem(Isarc), 33–40. https://doi.org/10.22260/isarc2021/0007

Ventura, D., Dubois, S. F., Bonifazi, A., Jona Lasinio, G., Seminara, M., Gravina, M. F., & Ardizzone, G. (2021). Integration of close-range underwater photogrammetry with inspection and mesh processing software: A novel approach for quantifying ecological dynamics of temperate biogenic reefs. *Remote Sensing in Ecology and Conservation*, *7*(2), 169–186. https://doi.org/10.1002/rse2.178

Wali, K. I., & Othman, S. A. (2019). Comparison and assessment of using Primavera and Microsoft Project in construction projects in Erbil City. *Zanco Journal of Pure and Applied Sciences*, *31*(s3). http://dx.doi.org/10.21271/ZJPAS.31.s3.39

Wang, J., Sun, W., Shou, W., Wang, X., Wu, C., Chong, H.-Y., Liu, Y., & Sun, C. (2015). Integrating BIM and LiDAR for real-time construction quality control. *Journal of Intelligent & Robotic Systems*, *79*(3–4), 417–432. https://doi.org/10.1007/s10846-014-0116-8

Wang, Z., She, Q., & Ward, T. E. (2021). Generative adversarial networks in computer vision: A survey and taxonomy. *ACM Computing Surveys*, *54*(2), 1–41. https://doi.org/10.1145/3439723

Weinmann, M., Wursthorn, S., Weinmann, M., & Hübner, P. (2021). Efficient 3D mapping and modelling of indoor scenes with the Microsoft HoloLens: A Survey. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, *89*(4), 319–333. https://doi.org/10.1007/s41064-021-00163-y

Xu, S., Wang, J., Shou, W., Ngo, T., Sadick, A.-M., & Wang, X. (2021). Computer vision techniques in construction: A critical review. *Archives of Computational Methods in Engineering*, *28*(5), 3383–3397. https://doi.org/10.1007/s11831-020-09504-3

Zaher, M., Greenwood, D., & Marzouk, M. (2018). Mobile augmented reality applications for construction projects. *Construction Innovation*, *18*(2), 152–166. https://doi.org/10.1108/CI-02-2017-0013

Zhai, Y., Chen, K., Zhou, J. X., Cao, J., Lyu, Z., Jin, X., Shen, G. Q. P., Lu, W., & Huang, G. Q. (2019). An Internet of Things-enabled BIM platform for modular integrated construction: A case study in Hong Kong. *Advanced Engineering Informatics*, *42*, 100997. https://doi.org/10.1016/j.aei.2019.100997

Hewagarusinghe, S.H. and Sridarran, P., 2024. Compare VR vs. Conventional training for construction workers' safety awareness. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 395-409. DOI: https://doi.org/10.31705/WCS.2024.31. Available from: https://ciobwcs.com/papers/

COMPARE VR VS. CONVENTIONAL TRAINING FOR CONSTRUCTION WORKERS' SAFETY AWARENESS

S.H. Hewagarusinghe[1] and P. Sridarran[2]

ABSTRACT

In recent years, Sri Lanka's construction industry has seen a troubling increase in both fatal and non-fatal accidents, largely attributed to insufficient safety knowledge among workers and deficiencies in the health and safety system. To mitigate these accidents, effective occupational health and safety training is imperative. However, the efficacy of traditional safety training methods has been questioned due to their limited impact on workers' ability to identify and assess risks critically. The lack of experiential training is the primary cause of accidents that could have been easily avoided at construction sites in Sri Lanka. Addressing this gap, there is growing interest in utilising Virtual Reality (VR) as a powerful tool for experiential safety training in the construction sector. VR offer a realistic and safe environment where workers can engage with various scenarios and procedures, enhancing their understanding and awareness of safety protocols. This research explores the effectiveness of VR tools in enhancing safety knowledge and awareness among construction workers through a simulation safety training platform, using VR and PowerPoint methods for data collection. An experiment was conducted with VR and PowerPoint safety training methods as a data collection method. A questionnaire survey was conducted to compare conventional training methods with the VR solution. The results indicate that workers trained in VR environments had better retention of critical information, highlighting the efficiency of VR in providing a safe yet realistic training experience. This research emphasises the potential advantages of the suggested VR safety training methods in improving construction safety knowledge and awareness of construction workers.

Keywords: *Construction Safety, Safety Training, Virtual Reality (VR), Construction Accidents*

1. INTRODUCTION

The construction industry is one of the significant industries subjected to massive health and safety problems which is linked to a dangerous work environment that causes many work-related hazardous, injuries, and diseases for the employees compared with other industries (Kumarasinghe & Dilan, 2022; Risath & Alm, 2017). When considering the Sri Lankan construction industry has reported a higher number of fatalities and injury rates, which is ranked as the 3rd worst among industry groups in Sri Lanka (Risath & Alm, 2017). Every year 2500 to 3,000 accidents are reported to the Industrial Safety

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, hewagarusinghesh.19@uom.lk
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, psridarran@gmail.com

Division of the Labour Department in Sri Lanka (Ministry of Labour, 2021). Out of those accidents, 40% to 60% were fatal and 30% were construction accidents (Delpachitra & Allis, 2022). As it is clear from much research data, the accident still happens with great frequency and severity and the unsafe working environment in the construction industry of Sri Lanka is still an unsolved problem.

Several reasons can cause safety hazards to construction workers in Sri Lanka. One of the major reasons for that kind of injury is the lack of strong health and safety practices (Kumarasinghe & Dilan, 2022). Shamsuddin et al. (2015) highlighted most of the building construction projects in Sri Lanka experience weak health and safety practices. Shamsuddin et al (2015) described that the inefficiency of current safety training practices is the most influencing factor in causing unsafe work conditions in the building construction industry in Sri Lanka. Further, it highlighted that providing well-structured and highly engaging training for construction employees is essential. The workforce in Sri Lanka can be categorised into management and technical, skilled, semi-skilled, and unskilled, with all workers at risk of injury, death, or illness (Risath et al., 2017). The lack of safety training and awareness among skilled and unskilled workers is a serious issue that needs to be addressed to enhance the occupational health and safety of the construction industry (Vitharana et al., 2015). Although there are various safety training programs implemented in the construction industry, the current safety training has not resulted in an improvement in accident rates in the construction industry (Yoo et al., 2023). Unfortunately, traditional safety training methods such as lectures, pamphlets, presentations, videos, and seminars can be problematic as they often lead to learners being passive and not actively engaging with the material (Elrifaee, 2023). Adami et al. (2021) state that complex tasks using specialised equipment may pose unjustifiable risks to trainees' safety, limiting their exposure to complex situations on site, and the costs associated with acquiring the necessary equipment and materials for the training may be too high. Further identified that On-site training may create unsafe conditions for trainees, a lack of real-time experience, and Training with low engagement such as lectures, presentations and lack of chance to engage with materials (Sacks et al., 2013; Yoo et al., 2023). Even in Sri Lanka, traditional methods have not led to improvements in accident rates and unsafe working behaviours.

New technological tools such as augmented reality, virtual reality, Building Information Modelling, and robots have been used globally for construction safety training (Darda et al., 2023). Many researchers have indicated that construction safety training practices using new technology have been introduced to avoid the unfavourable conditions caused by traditional methods. Xu and Zheng (2021) describe how to develop an immersive and interactive multiplayer-based training platform that incorporates Virtual Reality (VR) technology to improve the safety awareness of workers. Hence, VR-based training can indeed be used to train construction workers effectively to gain the necessary knowledge, skills, and safety behaviour in construction works. Besides, it is the best tool for accident reconstruction, training, and hazard identification by immersing the trainee in an environment as close to the real world as possible (Babalola et al., 2023; Yoo et al., 2023). However, there is a possibility of providing safety training to construction workers using VR technology in the construction industry of Sri Lanka, but there are still no research reports that have been done regarding the initiatives of using these technologies for safety training in the construction industry of Sri Lanka. Therefore, using this new technology for health and safety training in the construction sector of Sri Lanka can be used as an efficient training method that can be used to enhance the safety knowledge and awareness of construction workers. Moreover, it is crucial to train both skilled and unskilled workers to safely and effectively interact with these new technologies such as VR safety training. Accordingly, this research aims to evaluate the effectiveness of VR tools to enhance the safety knowledge and awareness of construction workers.

2. LITERATURE REVIEW

2.1 HAZARDS IN THE CONSTRUCTION INDUSTRY

The construction industry has created huge employment for workers and makes significant economic contributions yearly (Li, 2018). The construction industry workers are involved in several complex activities while doing construction works on sites. These complexities make the construction industry one of the most dangerous industries that cause several work-related injuries and fatalities across all industries, which makes safety a critical aspect of this industry (Adami et al., 2021; Rokooei et al., 2023). For instance, according to the Korea Occupational Safety and Health Agency (KOSHA), industrial accident status and analysis from 2009 to 2017 showed that fall accidents in the construction industry accounted for 47.7% to 52.1% of fatalities annually (Bao et al., 2022), and also Li (2018) mention that 30% to 40% of fatal industrial accidents in Japan and 50% in Ireland involve construction-related fatalities. Further, Delpachitra and Allis (2022) state that 40% to 60% of were fatal and 30% were construction accidents among those accidents in Sri Lanka. Several factors influence those hazards in the construction sites in Sri Lanka. Those accidents can happen through slipping and stripping at the site, falling from heights, using machines and falling objects from upper floors, lifting and carrying, during machinery works, electrocution, elevator accidents, fire, and explosion (Elrifaee, 2023; Halwathura, 2012; Risath & Alm, 2017). Hence, the construction industry is required to implement proper health and safety practices and enhance the safety knowledge and awareness of construction workers' consideration (Delpachitra & Allis, 2022).

2.2 OCCUPATIONAL HEALTH AND SAFETY TRAINING IN THE CONSTRUCTION INDUSTRY

Construction safety is an important concern that must be considered in the construction industry. Based on the findings of many researchers, the best way to mitigate accidents in construction sites is through better education and safety training of construction workers (Halwathura, 2012; Rita Yi Man Li, 2018; Rokooei et al., 2023; Yoo, 2023). Therefore, conducting proper occupational health and safety programs in the construction industry is an essential area that needs to identify worksite hazards and mitigate the risk of accidents occurring in the construction industry (Chellappa et al., 2022). Construction workers have a significant influence on their safety by deciding to either embrace or avoid risks through their actions. Through proper safety training, construction workers can improve their skills in the ability to identify risks and their subjective analysis of the magnitude of those risks (Sacks et al., 2013). Therefore, it is important to ensure that safety training is interactive and engaging because those strategies can ensure that employees are paying attention to the information and improve their awareness of the subjects being discussed (Elrifaee, 2023).

2.2.1 Role of Training for Construction Safety

According to Yoo et al. (2023), the main role of safety training is to introduce hazards in construction sites and ways to prevent accidents from happening therein. Traditional and computer-based methods are used to enhance employee behaviour and knowledge acquisition. Participatory safety training, which involves active participation and dialogue, is more effective than passive approaches including lectures, presentations, and videos (Burke et al., 2011). Nonetheless, both strategies have been linked to enhanced worker behaviour in terms of safety and health, while more engaging training methods have shown correlations with increased knowledge acquisition and decreased instances of reported accidents and injuries (Burke et al., 2006). These methods can lead to increased knowledge acquisition and decreased accidents and injuries (Nykänen et al., 2020). Hence, effective and efficient Safety training improves individuals' ability to assess hazards and associated risks (Sacks et al., 2013).

2.2.2 Safety Training Methods and their Effectiveness

There are different methods for safety and health training, varying from less engaging to more engaging methods. Burke et al. (2006) found that both engaging (Active strategies), and non-engaging training (Passive strategies) methods improved trainees' behavioural performance. However, active participation in engaging training led to improved knowledge acquisition and reduced accidents. Robson et al. (2015) found that highly engaging training was more effective when the severity of hazardous events was high.

Table 1: Safety training methods
Source: (Burke et al., 2006; Gao et al., 2019; Goh et al., 2015)

Less engaging training method	More engaging training method
Videos	Behavioural modelling
Manuals without exercises	Augmented reality training (AR)
Lectures with minimal interaction	Virtual reality training (VR)
Computer instruction with no interaction	Hands-on training
Feedback and discussion	
Pamphlets	

One of the most effective training methods is participatory training, which has been widely accepted, as adult learners are identified as 'problem-centred' and 'solution-driven'. Nevertheless, the majority of training programs in use currently are inadequate at fulfilling these requirements effectively. According to Burke et al. (2006), they lack engagement and might not optimise the acquisition and retention of knowledge. Many research studies have shown that improving occupational health and safety training appropriately is an important phase (Cha et al., 2012; Huang et al., 2011; Manca et al., 2013; Read et al., 2012). The best way to train is to simulate real tasks and obtain experience (Goldenhar et al., 2001). which illustrates a hierarchy of teaching styles and their effectiveness for trainees. It indicates that Real-life tasks and representative simulations (VR-powered training) are the most effective learning styles. In contrast to passive learning methods, which are less effective, particularly for adult learners, active and participatory training frequently possess a higher level of comprehension activities (Kowalski & Vaught, 2002). Participatory training brings a realistic aspect to safety training that helps trainees relate to conditions and regulations in real-life situations. They learn how to react to life-or-death situations in an 'it can happen to you' scenario.

Accordingly, many pieces of research have shown that the more engaging a method of training, the greater the effects of safety and health training on knowledge acquisition and retention (Adami et al., 2021).

2.3 CURRENT SAFETY PRACTICES IN SRI LANKA

Sri Lanka's construction sector has grown significantly, yet ensuring health and safety remains a major concern, particularly in the building construction segment (Shang et al., 2012). Many researchers found that failure to safety rules, lack of adequate safety procedures and precautions, insufficient safety awareness, lack of communication (Bandara & Perera, 2022), insufficient safety knowledge regarding the handling of machinery, and equipment and neglect to work with simple procedures on the construction site are the higher average causes of occupational accidents occurring in the construction industry in Sri Lanka (Kumarasinghe & Dilan, 2022; Perera et al., 2017). In addition, factors such as inadequate supervision, insufficient training, worker reluctance, lack of safety equipment, and low education levels contribute to unsafe conditions in the construction industry (Halwatura & Jayatunga, 2012). Further, Vitharana et al. (2015) mentioned that the impact of workers' safety attitudes and safety training even though workers' unwillingness to follow safety norms has been identified as a cause of poor safety practices. Research shows that Sri Lanka's construction industry faces unique challenges, with safety practices below acceptable standards. Therefore, to mitigate accidents in the construction industry, contractors can develop safety programs, change work orders, and make safety equipment mandatory are better safety practices to reduce construction-related accidents (Delpachitra & Allis, 2022). Therefore, it is important to consider Proper safety management in the construction industry.

2.4 BARRIERS AND CAUSES FOR POOR SAFETY PRACTICES IN SRI LANKA

Construction workers in developing countries including India, Pakistan, and Sri Lanka are often unqualified and unskilled, leading to high-level accidents in the workplace (Li, 2018). The main reasons for those high-level construction accidents are a lack of safety attitude and the behaviours of the construction workers and a lack of knowledge and awareness of safety (Shamindi & Vithana, 2022). Further, the Sri Lankan construction industry faces a language barrier (English and technical words related to OSH) due to low education levels among workers, making it difficult for them to understand occupational health and safety training (Halwatura & Jayatunga, 2012). Despite safety training being implemented in Sri Lanka, its efficiency is low and there are drawbacks to current methods. To improve safety, proper safety training programs should be introduced, mixed with new technologies, to provide high-engaging training to construction workers (Shamindi & Vithana, 2022). This will help them identify potential hazards and take appropriate action, resulting in a safer workplace.

2.5 SAFETY TRAINING WITH NEW TECHNOLOGIES IN THE CONSTRUCTION INDUSTRY

The construction industry has seen a surge in automation and robotics, aiming to address safety concerns, and labour shortages, and enhance productivity. Safety training technologies, such as computer-aid training such as Serious Games (SG), Computer-generated Simulations (CGS), VR, AR, and MR, are being introduced to improve construction safety knowledge among workers (Lovreglio et al., 2021; Rahouti et al., 2021). Burke et al. (2006) state that both passive methods and active methods, such as computer-based instruction and apprenticeship models, have been linked to improved safety and health performance, while more engaging training leads to increased knowledge and reduced accidents. These methods, including VR, are more effective than traditional PowerPoint training methods that can be applied to increase construction safety in Sri Lankan construction industries (Buttussi & Chittaro, 2018). Learning retention rate in literature is based on the Learning Pyramid, which is a model that illustrates the relative effectiveness of different methods of learning. The pyramid shows that VR training is more effective in terms of retaining information compared to other traditional learning methods. Furthermore, some research articles have conducted a comparison of the effectiveness of VR training with traditional training methods (Buttussi & Chittaro, 2021; Sacks et al., 2013).

2.5.1 Virtual Reality Safety Training Applications in Different Industries

Over the past decade, training methods have seen a significant transformation due to virtual reality. For example, according to Cohen et al. (2005), several VR applications have been developed and tested for tsunami and earthquake training (Feng et al., 2021), aviation training (Chittaro, 2012), and counter-terrorism safety training (Buttussi & Chittaro, 2018; Rahouti et al., 2021). As Lucas et al. (2007) point out a computer-generated reality can be a useful option for training tasks that are dangerous in real life. For instance, VR offers a risk-free alternative to traditional surgical training, enhancing students' conceptual understanding of surgical operations and addressing critical training issues in surgeries (Cohen et al., 2005).VR has been utilised in the mining industry since 2014 to prevent accidents and fatalities, providing safety training and exercises for coal mining workers to enhance their understanding of safety protocols (Joshi et al., 2021).VR training allows for the tracking of each behaviour and decision made by users while receiving the training, providing them feedback on what they did correctly (Feng et al., 2021). Here, D'Amico et al. (2023) highlighted a few VR applications focusing on flood safety training such as a VR framework for enhancing disaster awareness. In the case of training and education, Lin et al.(2011) mention that a combination of immersion techniques and SG such as desktop-based VR games can be used to teach university students about safety knowledge in a virtual construction environment.

2.5.2 VR Safety Training in the Construction Industry

There are some research indicates that many applications areas of VR-based training in the construction industry including construction safety (Jeelani et al., 2020), operating construction equipment (Song et al., 2021), construction operation training (Vahdatikhaki et al., 2019) and performing construction activities (Barkokebas et al., 2019; Wolf et al., 2019). Among them, most of the studies have focused on hazard identification and safety training in the construction industry (Ahn et al., 2020; Jeelani et al., 2020). Xu and Zheng (2021) state that VR-based training is adequate and acceptable to construction sites and promotes learning and knowledge retention. Moreover, promoting learning, consequently, and safety behaviour improvements among the workers are some of the advantages of applying VR-based safety training in the construction industry. It has been demonstrated that VR-based training enhances self-efficiency and safety motivation in recognising safety hazards, with observable impacts on safety behaviours in both the short and long term (Nykänen et al., 2020). VR-based safety training was associated with improved safety behaviour among the non-experts rather than experienced field workers, indicating potential for training incoming construction workers (Yu et al., 2022). This is a significant outcome considering that the construction sector has been attracting young workers to fill the large number of job vacancies on construction sites at current. Further, Bosché et al.(2016) highlighted the use of an immersive virtual system to enable users to assess and experience working at dangerous heights on construction scaffolds, thereby enhancing workers' safety monitoring and high-risk work skills. Certain construction education researchers attribute several benefits to VR training over on-the-job training and traditional classroom education i.e. VR simulations create a risk-free environment where workers can fail without injuring themselves or others (Bosché et al., 2016) and simulations give workers immediate feedback instead of waiting for an individual to comment on their work. Apart from that VR simulations provide a highly effective means of developing technical skills related to construction work without the added stress of potentially injuring workers or confusing environments (Barkokebas et al., 2019). Accordingly, this study provides detailed information on the effectiveness of VR safety training in construction workers, aiming to enhance safety knowledge and awareness of construction activities.

3. RESEARCH METHODOLOGY

This research adopts a quantitative approach to assess the efficiency of VR tools in enhancing safety knowledge and awareness among construction workers. This research focuses on theories behind safety training methods and knowledge enhancement. This study involves conducting VR-based safety training and PowerPoint presentation-based safety training for selected groups. To evaluate the effectiveness of each method, the study measures the retention rate of safety information among the participants. Additionally, it analyses user experience to identify the strengths and weaknesses of each training method, providing a comprehensive understanding of their relative advantages in improving safety training outcomes. For that selected data gathering techniques is an experiment by conducting safety training for both the control group and test group of construction workers. A total of 60 construction workers took part in this experiment in two distinct groups as a sample size in this research experiment. Each group consisted of 30 workers, and they were tested immediately after the safety training. Each group received 20 minutes of training on the same construction safety topic which was “Work at Height”, yet the test group received a conventional lecture supported with PowerPoint slides (Photos, graphics, and text), while the control group received the same instruction in the virtual construction site. The experimental setup includes safety training sessions and subsequent assessments of safety knowledge retention. In the immersive virtual environment, construction workers undergo VR safety training focusing on hazard recognition and activities related to working at heights, utilising Oculus Go or Gear VR platforms. This scenario is chosen due to "working at height" being one of the highest contributors to construction accidents and hazards. Data collection methods encompass a literature review, questionnaires administered after safety training sessions, and unstructured interviews to gather feedback from workers. The same questions were given to both VR and lecture-based safety training workers, and their answers were collected. This test is called a short-term memory test and collects responses via questionnaires, marks were given to workers who correctly gained knowledge from the safety training, each question allocates ten marks for correct answers to assess their safety knowledge. Feedback sessions were conducted using short time interviews about workers' training experience of both traditional and VR training methods to evaluate the efficiency of safety training tools to assess the knowledge and awareness gained of construction safety. Furthermore, Data analysis entails descriptive analysis methods, including statistical analysis of questionnaire responses, to assess safety knowledge and awareness. This methodology aims to provide comprehensive insights into the effectiveness of VR tools for enhancing safety knowledge and awareness among construction workers, utilising rigorous experimental design and quantitative analysis techniques.

4. RESULTS AND DISCUSSION

This section presents the key research findings related to two areas; (i) outcomes of questionnaire safety test score analysis, and (ii) feedback gained from unstructured interviews with construction employees.

4.1 SCORE ANALYSIS OF SAFETY TRAINING TEST

4.1.1 Results of Data Collection from Construction Workers

The data collection process involved administering a questionnaire immediately after safety training to construction workers who are working in the construction industry. The questionnaire mainly focused on safety knowledge, particularly regarding working at heights which is one of the significant hazards in the construction industry. The safety tests were conducted immediately after training, with 60 construction workers participating, 30 in each control (VR training) and test group (PP training). Training sessions lasted 20 minutes each, conducted in the local language for clarity. All participants in the training were unskilled male workers in the age range of 20 to 55 years.

The result of the questionnaire (refer to Figure 1) showed that there were significant differences between the workers of the two experimental groups after the training. It is clearly shown that the workers of the control group (VR test) have obtained get relatively high level of scores when considering the dispersion of scores obtained for the graft given in Figure 1. The results for the VR training test showed less variation (with a higher mean) compared to the results for the PowerPoint training may have been more consistently effective among the workers, as evidenced by the narrower range marks.

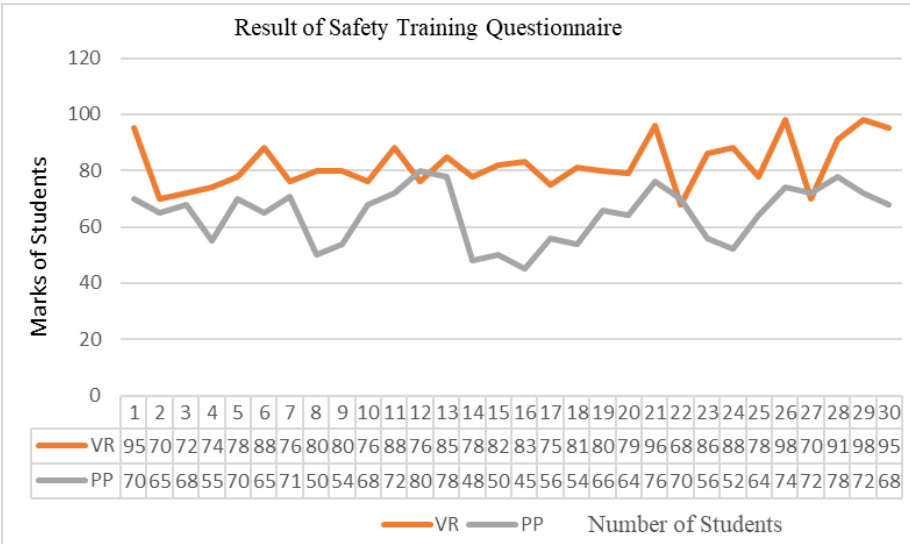


Figure 1: Score variation of safety tests

4.1.2 Descriptive Statistics of Presence Total Mean Score

The average scores of the safety training test obtained from participants of both VR and PP safety training test mentioned that the effectiveness of safety training methods impact to enhances safety knowledge and increases the retention rate of safety information. The following statistical analysis illustrates the effectiveness of safety training methods to enhance the knowledge and memory capacity of the workers.

$$\bar{x} = \frac{\sum x}{n} \qquad (01)$$

Where, $\bar{x}$ = Sample mean, n = No. of participants, $\sum x$ = Total marks of Participant's

The mean result of the VR test = $\frac{(95+72+82+74+ \ldots\ldots+95)}{30}$ = **82.13**

The mean result of the PP test = $\frac{(70+65+68+ \ldots\ldots+68)}{30}$ = **64.37**

When analysing the results of both safety training methods, it was found that the VR training test had a higher mean score of 82.13%, compared to the PP training test which had an average score of 64.37%. this suggests that a majority of workers who attended the VR training obtained an average mark of about 82%, while those who participated in the PP training obtained an average of 64%. According to the data that were analysed, it seems that VR training is more effective than PP training in improving safety knowledge and awareness among construction workers. The factors that may have contributed to this effectiveness of training methods include engagement, interactivity, immersion, and retention. Therefore, PP training might have been less engaging or memorable for the workers, leading to lower scores overall.

4.1.3 Comparison of Safety Training Methods

When considering the overall marks gained by workers who attended both safety tests, their performance can be categorised into three stages using appropriate benchmarking techniques for assessing and comparing the effectiveness of different training methods by classifying individuals' performance into below benchmarking categories which are shown in Figure 2.

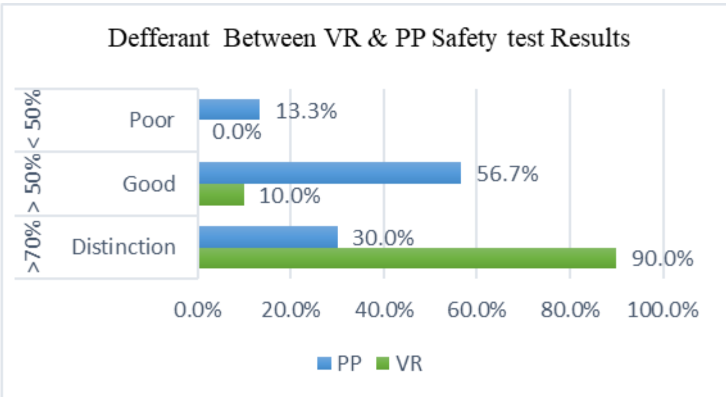


Figure 2: Percentage of result states

Based on the data shown in the figure, VR training is significantly more effective than PP training in achieving high levels of safety knowledge and awareness among workers. Specifically, 90% of workers in VR training achieved a distinction level, compared to only 30% in PP training. On the other hand, 56.7% of workers in PP training reached a good level, while only 10% achieved the same in VR training. Notably, no workers in VR training fell into the poor performance category, whereas 13.3% of those in PP training did. This indicates that VR training is more efficient in ensuring high proficiency and adherence to safety protocols. It states that workers who participated in VR safety training have maintained higher memory capacity and higher-level retention rates comparing PP Safety Training programmes. Factors such as Quality of instructions, engagement and interaction can impact this higher percentage of score level with the “Distinction category” created from VR safety training compared to PP safety training. Accordingly, this analysis demonstrates how VR training may be more effective than PowerPoint training in increasing construction worker safety knowledge and awareness. This analysis demonstrates how VR training may be more effective than PowerPoint training in increasing construction worker safety knowledge and awareness.

After analysis of the experiment data which were gathered from all participants, it was found that there was a significant impact on the scored differences among both training methods by the Age of the workers. Table 2 clearly shows these knowledge differences based on the worker's average score on the safety test.

Table 2: Average results in different age groups

Age group	VR Av. Score (%)	PP Av. Score (%)
Below 21	79	0
21 - 30	86.57	76.4
31 - 40	81.18	67.23
41 - 50	70	55.56
Above 50	0	58.33

Age-related discrepancies could be impacted by different memory capacities and familiarity with technologies. This impact difference indicates the above table comparison which is the average scores that workers obtain from their safety test in different age groups. When analysing average score levels in different age groups in VR and PP safety training methods, the immersive quality of VR training may positively affect to increased knowledge of younger workers. Moreover, both safety training test scores gradually decreased with the increasing age of the workers. Therefore, while age-related factors can influence safety knowledge scores, the design and implementation of training programmes must consider memory capacity and familiarity with technology into account to ensure that they are effective for different age groups. Accordingly, highly engaging safety training methods such as VR safety training contribute to maintaining higher capacity safety knowledge for both younger and older workers.

4.2 FEEDBACK DISCUSSION

User experience is another factor that can measure the effectiveness of the safety training methods. The level of engagement with the training material and methods can significantly impact workers’ understanding and retention of the safety knowledge. In this research, the target population consisted of unskilled construction workers with low levels of education (all participants had completed up to ordinary level or advanced level). Therefore, unstructured interviews in the form of discussions with participants were conducted to gather participants’ feedback on their user experiences with each safety training method. As per the feedback of the participants, it can be identified that highly engaging safety training methods such as Virtual Reality safety training methods are more effective than traditional training methods for enhancing safety knowledge and safety performance among construction workers. Furthermore, they highlighted that conducting safety training by using VR technology is practical for providing a clear understanding of the seriousness of the risks and giving real experiences about construction accidents and hazards within a safe environment rather than conducting lecture-based PP safety training. Analysing the feedback given by the construction workers who attended VR safety training, found that this is the first time they participated in a VR safety training program, and they preferred to actively participate in this kind of engaging safety training rather than PowerPoint training.

4.3 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study encountered several limitations that should be addressed in future research. One of the main limitations is that the VR training scenario was in the English language, which may not be familiar to the construction workers. Developing localized VR training modules in local languages will ensure that all trainees can fully understand and benefit from the training materials. Another one is that the data collection was limited to a one-time safety test due to time constraints, which hindered the ability to accurately measure the long-term retention of safety knowledge. For that, implementing long-term investigations that include safety tests conducted before the training, immediately after, and one-month post-training will provide a more accurate measurement of both short-term and long-term retention of safety knowledge. The study was also restricted to a single safety scenario, due to a lack of diverse and freely available VR safety training programs in Sri Lanka. However, expanding the VR training content to cover a variety of safety scenarios will offer a more comprehensive safety training program. Furthermore, the limited availability and high cost of suitable VR tools posed significant challenges, affecting the feasibility and scalability of VR safety training. However, developing or investing in affordable and locally available VR tools will support wider adoption and more effective implementation of VR safety training programs in the construction industry.

5. CONCLUSIONS

This study was conducted to assess the effectiveness of VR tools to enhance the safety knowledge and awareness of construction workers. The aim of this research is to evaluate the efficiency of VR tools to enhance the safety knowledge and awareness of construction workers. The research findings demonstrate the potential of VR technology as an innovative and engaging tool for improving safety training outcomes among construction workers in Sri Lanka. Further study’s finding highlighting VR safety training can significantly enhance safety knowledge and awareness, as evidenced by the higher scores obtained by workers in the VR test group compared to the control group that received PP-based training. Moreover, feedback from construction workers who participated in VR safety training indicates a preference for this interactive and immersive training approach (VR) over traditional methods. The study identifies the need for future research to address limitations such as language barriers and the frequency of safety test assessments to further enhance the effectiveness of VR safety training programs. In conclusion, the research underscores the importance of leveraging technological advancements such as VR tools to revolutionise safety training in the construction industry. By embracing innovative training methods that actively involve workers and simulate real-world scenarios, construction companies in Sri Lanka can enhance safety practices, reduce worksite accidents, and ultimately create a safer working environment for all employees.

6. REFERENCES

Adami, P., Rodrigues, P. B., Woods, P. J., Becerik-Gerber, B., Soibelman, L., Copur-Gencturk, Y., & Lucas, G. (2021). Effectiveness of VR-based training on improving construction workers' knowledge, skills, and safety behavior in robotic teleoperation. *Advanced Engineering Informatics*, *50*, 1–30. https://doi.org/10.1016/j.aei.2021.101431

Ahn, S., Kim, T., Park, Y. J., & Kim, J. M. (2020). Improving Effectiveness of Safety Training at Construction Worksite Using 3D BIM Simulation. *Advances in Civil Engineering*, 2020*(1)*, 2473138. https://doi.org/10.1155/2020/2473138

Babalola, A., Manu, P., Cheung, C., Yunusa-Kaltungo, A., & Bartolo, P. (2023). Applications of immersive technologies for occupational safety and health training and education: A systematic review. *Safety Science*, *166*, 106214. https://doi.org/10.1016/j.ssci.2023.106214

Bao, L., Tran, S. V. T., Nguyen, T. L., Pham, H. C., Lee, D., & Park, C. (2022). Cross-platform virtual reality for real-time construction safety training using immersive web and industry foundation classes.*Automationing Construction*,*143*,104565.https://doi.org/10.1016/j.autcon.2022.104565

Barkokebas, R., Ritter, C., Sirbu, V., Li, X., & Al-Hussein, M. (2019). Application of virtual reality in task training in the construction manufacturing industry. *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*, *May*, 796–803. https://doi.org/10.22260/isarc2019/0107

Bandara, S. M. M. S. K., & Perera, G. D. N. (2022). Impact of Health and Safety Practices on Employee Job Performance : Mediating Role of Employee Commitment in Selected Building Construction Companies in Sri Lanka Partners Universal International Research Journal (PUIRJ). *Partners Universal International Research Journal (PUIRJ)*, *1*(3), 1–12. https://doi.org/10.5281/zenodo.7111113

Bosché, F., Abdel-Wahab, M., & Carozza, L. (2016). Towards a mixed reality system for construction trade training. *Journal of Computing in Civil Engineering*, *30*(2), 1–12. https://doi.org/10.1061/(asce)cp.1943-5487.0000479

Burke, M. J., Sarpy, S. A., Smith-Crowe, K., Chan-Serafin, S., Salvador, R. O., & Islam, G. (2006). Relative effectiveness of worker safety and health training methods. *American Journal of Public Health*, *96*(2), 315–324. https://doi.org/10.2105/AJPH.2004.059840

Burke, M. J., Salvador, R. O., Smith-Crowe, K., Chan-Serafin, S., Smith, A., & Sonesh, S. (2011). The dread factor: How hazards and safety training influence learning and performance. *Journal of Applied Psychology*, *96*(1), 46–70. https://doi.org/10.1037/a0021838

Buttussi, F., & Chittaro, L. (2018). Effects of different types of virtual reality display on presence and learning in a safety training scenario. *IEEE Transactions on Visualization and Computer Graphics*, *24*(2), 1063–1076. https://doi.org/10.1109/TVCG.2017.2653117

Buttussi, F., & Chittaro, L. (2021). A Comparison of Procedural Safety Training in Three Conditions: Virtual Reality Headset, Smartphone, and Printed Materials. *IEEE Transactions on Learning Technologies*, *14*(1), 1–15. https://doi.org/10.1109/TLT.2020.3033766

Cha, M., Han, S., Lee, J., & Choi, B. (2012). A virtual reality based fire training simulator integrated with fire dynamics data. *Fire Safety Journal*, 50, 12–24. https://doi.org/10.1016/j.firesaf.2012.01.004

Chellappa, V., Mésároš, P., Špak, M., Spišáková, M., & Kaleja, P. (2022). VR-based safety training research in construction. *IOP Conference Series: Materials Science and Engineering*, *1252*(1), 012058. https://doi.org/10.1088/1757-899x/1252/1/012058

Chittaro, L. (2012). Passengers' safety in aircraft evacuations: Employing serious games to educate and persuade. In: Bang, M., Ragnemalm, E.L. (eds) Persuasive Technology. Design for Health and Safety. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (pp.215–226). https://doi.org/10.1007/978-3-642-31037-9_19

Cohen, C. J., Hay, R., Urquhart, A., Gauger, P., & Andreatta, P. (2005). A modular interactive virtual surgical training environment. *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*,12, 2074-2086. https://www.interplaylearning.com/hubfs/Blog/Case Studies/A Modular Interactive Virtual Surgical Training Environment.pdf

D'Amico, A., Bernardini, G., Lovreglio, R., & Quagliarini, E. (2023). A non-immersive virtual reality serious game application for flood safety training. *International Journal of Disaster Risk Reduction*, *96*, 103940. https://doi.org/10.1016/j.ijdrr.2023.103940

Darda, A., Shafiq, N., Othman, I., Aliyu, M. M., Alarifi, H., Ibrahim, A., Shehu, N., & Yaro, A. (2023). The effectiveness of utilising the building information modelling based tools for safety training and job hazard identification. *Journal of Technology Management and Business*, *10*(1), 1–12. https://publisher.uthm.edu.my/ojs/index.php/jtmb/article/view/12985.

Delpachitra, Y., & Allis, C. (2022). Mitigation practices for frequent accidents in high rise building construction. *Proceedings of the SLIIT International Conference On Engineering and Technology.* 11-Feb-2022, 91–102. SLIIT. http://rda.sliit.lk/handle/123456789/2998

Elrifaee, M.S. (2023).*Enhancing construction safety training of bridges using augmented reality and virtual reality* [Master's Thesis, the American University in Cairo]. AUC Knowledge Fountain. https://fount.aucegypt.edu/etds/2107

Feng, Z., González, V. A., Mutch, C., Amor, R., & Cabrera-Guerrero, G. (2021). Instructional mechanisms in immersive virtual reality serious games: Earthquake emergency training for children. *Journal of Computer Assisted Learning*, *37*(2), 542–556. https://doi.org/10.1111/jcal.12507

Gao, Y., Gonzalez, V. A., & Yiu, T. W. (2019). The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review. *Computers and Education*, *138*, 101–115. https://doi.org/10.1016/j.compedu.2019.05.003

Goh, A., Teck, P., Misnan, M. S., Jaafar, M. N., Lee, J., & Mei, Y. (2015). A Review on the Effectiveness of Safety Training Methods for Malaysia Construction Industry. *Jurnal Teknologi*, 74*(2)*, 742015. https://doi.org/10.11113/jt.v74.4518.

Goldenhar, L. M., Moran, S. K., & Colligan, M. (2001). Health and safety training in a sample of open-shop construction companies. *Journal of Safety Research*, *32*(2), 237–252. https://doi.org/10.1016/S0022-4375(01)00045-7

Halwatura, R. U., & Jayatunga, T. L. (2012). Health and Safety Aspects in Building Construction Industry in Sri Lanka. *International Research Journal of Engineering and Technology (IRJET)*, *2*(6), 624–636. https://www.researchgate.net/ publication/ 282747785_Investigation_the_Safety_ Health_and_Environment_SHE_Protection_in_Construction_Area

Huang, Y. H., Leamon, T. B., Courtney, T. K., Chen, P. Y., & Dearmond, S. (2011). A comparison of workplace safety perceptions among financial decision-makers of medium- vs. large-size companies. *Accident Analysis and Prevention*, *43*(1), 1–10. https://doi.org/10.1016/j.aap.2009.09.016

Jeelani, I., Han, K., & Albert, A. (2020). Development of virtual reality and stereo-panoramic environments for construction safety training. *Engineering, Construction and Architectural Management*, *27*(8), 1853–1876. https://doi.org/10.1108/ECAM-07-2019-0391

Joshi, S., Hamilton, M., Warren, R., Faucett, D., Tian, W., Wang, Y., & Ma, J. (2021). Implementing Virtual Reality technology for safety training in the precast/ prestressed concrete industry. *Applied Ergonomics*, *90*, 0003–6870. https://doi.org/10.1016/j.apergo.2020.103286

Kowalski, K. M., & Vaught, C. (2002). Training principles of adult learning: Application for mine trainers; strategies for improving miners' training, 3(8), 2002156. https://stacks.cdc.gov/view/cdc/8972/ cdc_8972_DS1.pdf.

Kumarasinghe, H. P. N. I., & Dilan, H. K. T. (2022). The impact of occupational health and safety practices on job performance of operational level employees : A study in the construction industry, Sri Lanka. *International Journal of Management, Accounting and Economics. 9*(1), 1–13. doi: 10.5281/zenodo.6463442

Lovreglio, R., Duan, X., Rahouti, A., Phipps, R., & Nilsson, D. (2021). Comparing the effectiveness of fire extinguisher virtual reality and video training. *Virtual Reality*, 25(1), 133–145. https://doi.org/ 10.1007/s10055-020-00447-5

Manca, D., Brambilla, S., & Colombo, S. (2013). Bridging between Virtual Reality and accident simulation for training of process-industry operators. *Advances in Engineering Software*, *55*, 1–9. https://doi.org/10.1016/j.advengsoft.2012.09.002

Ministry of Labour. (2021). *Annual Labour Statistics Report.* Department of Labour. Colombo 05: Ministry of Labour. Retrieved December 2022, from https://labourdept.gov.lk/images/PDF _upload/ statistics/ als2021.pdf

Nykänen, M., Puro, V., Tiikkaja, M., Kannisto, H., Lantto, E., Simpura, F., Uusitalo, J., Lukander, K., Räsänen, T., Heikkilä, T., & Teperi, A. M. (2020). Implementing and evaluating novel safety training methods for construction sector workers: Results of a randomized controlled trial. *Journal of Safety Research*, *75*, 205–221. https://doi.org/10.1016/j.jsr.2020.09.015

Perera, H. N., Somachandra, V., & Samarasiri, N. C. (2017). Preventing accidents in building construction through safety management. In *About the 2nd International Conference in Technology Management, iNCOTeM 2018* (p. 58).

Rahouti, A., Lovreglio, R., Datoussaïd, S., & Descamps, T. (2021). Prototyping and validating a non-immersive virtual reality serious game for healthcare fire safety training. *Fire Technology*, 57(6), 3041–3078. https://doi.org/10.1007/s10694-021-01098-x

Read, G. J. M., Lenné, M. G., & Moss, S. A. (2012). Associations between task, training and social environmental factors and error types involved in rail incidents and accidents. *Accident Analysis and Prevention*, *48*, 416–422. https://doi.org/10.1016/j.aap.2012.02.014

Risath, A. L. M., Sivatharsan, S., & Thishanth, P. (2017). Perception of construction workers on work motivation towards safety practices at building construction site: A case study in Oluvil. *SEUSL Journal of Marketing*, *2*(1), 33-39.

Rita Yi Man Li. (2018). Virtual reality and construction safety. *An economic analysis on automated construction safety: Internet of Things, artificial intelligence and 3D printing*, 117-136. https://doi.org/10.1007/978-981-10-5771-7_6

Rokooei, S., Shojaei, A., Alvanchi, A., Azad, R., & Didehvar, N. (2023). Virtual reality application for construction safety training. *Safety Science*, *157*, 105925. https://doi.org/10.1016/j.ssci.2022.105925

Robson, L. S., Stephenson, C. M., Schulte, P. A., Amick, B. C., Irvin, E. L., Eggerth, D. E., Chan, S., Bielecky, A. R., Wang, A. M., Heidotting, T. L., Peters, R. H., Clarke, J. A., Cullen, K., Rotunda, C. J., & Grubb, P. L. (2012). A systematic review of the effectiveness of occupational health and safety training. *Scandinavian Journal of Work, Environment and Health*, *38*(3), 193–208. https://doi.org/10.5271/sjweh.3259

Sacks, R., Perlman, A., & Barak, R. (2013). Construction Management and Economics Construction safety training using immersive virtual reality Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9). 1005–1017. https://doi.org/10.1080/01446193. 2013.828844

Shamsuddin, K. A., Ismail, A. K., Norzaimi, C. ani M., & bin Ibrahim, M. R. (2015). Health and Safety Aspects in Building Construction Industry in Sri Lanka. *International Research Journal of Engineering and Technology (IRJET)*, 2(6), 624636. https://www.researchgate.net/publication/ 282747785

Shang, G., Pheng, L. S., Bon-gang, H., & Ofori, G. (2012). Lean construction in large Chinese construction firms: A SWOT analysis. In *Proceedings of the CIOB World Construction Conference*.

Song, H., Kim, T., Kim, J., Ahn, D., & Kang, Y. (2021). Effectiveness of VR crane training with head-mounted display: Double mediation of presence and perceived usefulness. *Automation in Construction*, *122*, 103506. https://doi.org/10.1016/j.autcon.2020.103506

Vahdatikhaki, F., El Ammari, K., Langroodi, A. K., Miller, S., Hammad, A., & Doree, A. (2019). Beyond data visualization: A context-realistic construction equipment training simulators. *Automation in Construction*, *106*, 102853. https://doi.org/10.1016/j.autcon.2019.102853

Vitharana, V. H. P., De Silva, G. H. M. J. S., & De Silva, S. (2015). Health hazards, risk and safety practices in construction sites: A review study. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *48*(3), 35. https://doi.org/10.4038/engineer.v48i3.6840

Xu, Z., & Zheng, N. (2021). Incorporating virtual reality technology in safety training solution for construction site of urban cities. *Sustainability (Switzerland)*, *13*(1), 1–19. https://doi.org/10.3390/su13010243

Yoo, J. W., Park, J. S., & Park, H. J. (2023). Understanding VR-based construction safety training effectiveness: The role of telepresence, risk perception, and training satisfaction. *Applied Sciences (Switzerland)*, *13*(2). https://doi.org/10.3390/app13021135

Yu, W. Der, Wang, K. C., Wu, H. T., & Liu, K. C. (2022). the Effectiveness of Vr-Based Interactive Safety Training System for Hazardous Construction Site Scenarios. *Journal of Technology*, *37*(3), 149–164.

John, G.K.P., Munasinghe, A.M.M.G., Weerasinghe, K.G.N.H. and Halwatura, R.U., 2024. Design and development of a green roof substrate for the tropics. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 410-422. DOI: https://doi.org/10.31705/WCS.2024.32. Available from: https://ciobwcs.com/papers/

DESIGN AND DEVELOPMENT OF A GREEN ROOF SUBSTRATE FOR THE TROPICS

G.K.P. John[1], A.M.M.G. Munasinghe[2], K.G.N.H. Weerasinghe[3] and R.U. Halwatura[4]

ABSTRACT

Green roofs can be used as an effective climate change adaptation tool in South Asia. However, there is limited information on the type of substrate and the substrate depth best suited for extensive green roofs in this tropical climate. In this research, sixteen potential substrate mixtures were prepared using locally available materials and waste materials. The properties of these substrate mixtures were tested under laboratory and field conditions to identify the substrate mix best applicable for extensive green roofs for the tropical climate of Sri Lanka. Based on the results obtained from laboratory testing it was observed that substrate mixtures that contained coir and crushed recycled bricks displayed the properties most suited for a substrate in the tropical climate. Three different substrate depths (2.5cm, 5.0cm and 7.5cm) were also tested, in order to study their suitability for adequate plant development under tropical conditions. It was observed that the 2.5cm substrate depth had successful plant establishment and adequate plant coverage. Moreover, the 2.5cm depth substrate could be easily supported on an existing roof with little/no modifications. Therefore, for the tropical climate of Sri Lanka, a 2.5cm depth substrate composed of 10% compost, 5% coir, 5% rice husk, 40% sand and 40% crushed recycled bricks is recommended.

Keywords: *Green Roof Substrate; Substrate Depth; Tropical Climate*

1. INTRODUCTION

Green roofs have a great potential in South Asian countries such as Sri Lanka, where unplanned urbanisation has led to urban environmental issues such as urban flooding and heat islands (Vijayaraghavan & Raja, 2014). Green roofs can effectively mitigate these challenges and improve the urban micro-climate (Seyedabadi et al., 2021). However, despite this potential, the adoption of green roofs in these countries remains in its infancy (Dassanayake & Beneragama, 2011).

One of the major barriers to increasing the prevalence of green roofs in South Asia is the lack of local research and scientific data to evaluate their applicability to local conditions (Vijayaraghavan & Raja, 2014). Although green roofs have expanded beyond Europe in the recent decades, green roof research and implementation is still largely concentrated in the temperate regions (Blank et al., 2013; Lugo & Rullan, 2015).

[1] Department of Civil Engineering, University of Moratuwa, Sri Lanka, gayanthijohn@gmail.com
[2] Department of Civil Engineering, University of Moratuwa, Sri Lanka, madhushikag98@gmail.com
[3] Department of Civil Engineering, University of Moratuwa, Sri Lanka, nilanka8756@gmail.com
[4] Department of Civil Engineering, University of Moratuwa, Sri Lanka, rangikauh@gmail.com

A green roof consists of a number of layers. Each of these layers should be carefully selected according to the location and climatic conditions (Shafique et al., 2018). Green roof components from temperate regions cannot be completely adopted to the tropical climate because of differences in climatic condition and building characteristics (Williams et al., 2010; Wong & Lau, 2013). As a result of the limited research on green roofs in the tropics, the components of a green roof suitable to these geographical locations have not yet been identified (Vijayaraghavan, 2016). Therefore, local research must be conducted to identify the components of the green roof that is best suitable for the tropical climate of South Asia.

The substrate is one of the key components of a green roof system (Ampim et al., 2010). It functions as a support system for the vegetation and provide the plants with sufficient access to nutrients, water and oxygen (Handreck & Black, 2010). Moreover, the substrate assists the vegetation to adapt to long-term growth on the harsh conditions of a rooftop (Xiao et al., 2014). In addition to plant growth, the type of substrate also influences the thermal performance, stormwater performance and sound insulation of the green roof system (Vijayaraghavan, 2016). Therefore, the substrate used in a green roof must be carefully selected as it is crucial for the success of the green infrastructure (FLL, 2008; Vijayaraghavan, 2016).

The US and German green roof guidelines recommends the use of 80-90% inorganic constituents in the green roof substrate (Vijayaraghavan, 2016). Sand, pumice, heat-expanded shale and scoria, perlite and vermiculite are some popular inorganic materials used in green roof substrates in temperate regions (Ampim et al., 2010; Johnston & Newton, 2004; Xiao et al., 2014). The remaining 10 - 20% v/v of the green roof substrate should be made up of organic components such as peat, coconut coir, composted green waste and composted saw dust (Emilsson & Rolf, 2005; Farrell et al., 2012; Vijayaraghavan & Raja, 2014; Xiao et al., 2014). However, majority of these organic and inorganic materials, which are popular green roof substrate constituents in the temperate climate, may not be available in South Asia. Moreover, the use of locally sourced materials can help to reduce the environmental and financial costs associated with transportation. Therefore, local research must be conducted to identify appropriate substrate mixes best suited for the local climate and geographical location (Dunnett & Kingsbury, 2004).

This research aims to identify the most suitable substrate mixture for extensive green roofs in the tropical climate of Sri Lanka. For this purpose, 16 different substrate mixes, made from locally available materials, were evaluated through field and laboratory investigations, to identify the substrate mixture best applicable for tropical conditions.

In addition to the substrate composition, the thickness of the substrate also has a significant impact on the performance of the green roof system. Plant establishment and survival, thermal performance, stormwater performance and the weight of the system are all reliant on the thickness of the green roof substrate (Dassanayake & Beneragama, 2011; Durhman et al., 2007; Getter et al., 2009b; Kok et al., 2015; Ondoño et al., 2016; Panayiotis et al., 2003; Rowe et al., 2006).

Although a substrate depth of 2 - 15 cm is recommended for extensive green roofs, the actual depth of the substrate must be established based on the local geographical and climatic conditions (Panayiotis et al., 2003). In general, as the substrate depth increases, the performance of the green roof system improves (Durhman et al., 2007; Papafotiou et al., 2013; Rowe & Getter, 2006; Thuring et al., 2010). However, as majority of the weight in a green roof comes from the substrate, a deeper substrate translates to a heavier system (Xiao et al., 2014). This is particularly problematic when retrofitting an existing building, as the current roof structure must accommodate the added weight of the green roof system. Therefore, it is essential to consider local building characteristics when deciding on the substrate depth. Hence the second half of this paper details the steps taken to identify a suitable substrate depth for extensive green roofs in Sri Lanka.

2. DEVELOPMENT OF THE GREEN ROOF SUBSTRATE

2.1 PREPARATION OF SUBSTRATE MIXES AND FACTORS CONSIDERED

The standards for developing green roof substrates are detailed in various literature and in the guidelines provided by German and US green roof standards. These desired properties of the green roof substrate are outlined in Table 1. In this study, the substrate was developed using these existing guidelines as the starting point and modifications were made where necessary to suit the local climatic conditions.

Table 1: Desired properties of the green roof substrate

Source	Water Holding Capacity	Wet Bulk Density	Dry Bulk Density	Air Filled Porosity	pH
(Chow et al., 2018)	39.4%	912 kg/m^3	431 kg/m^3	19.5%	-
German Green Roof Guidelines (FLL, 2008)	20 - 65 %	-	600 – 1200 kg/m^3	> 10%	-
(Johnston & Newton, 2004)	35 - 45%	-	-	15 - 25%	6
(Xiao et al., 2014)	40 – 60%	-	-	10 – 20 %	-
(ASTM International, 2015)	30 – 45%	-	-	> 20 %	6.5 – 8.5

It is not practical for one material to possess all the characteristics listed in Table 1. Therefore, the general practice is to prepare the green roof substrate by using a mixture of different materials, so that the substrate mixture meets the performance requirements detailed in Table 1 (ASTM International, 2015; Johnston & Newton, 2004).

When selecting different materials for the green roof substrate mixture it is recommended to incorporate local waste materials as it can help to increase the green rating of the building while decreasing the overall cost (ASTM International, 2015; Johnston & Newton, 2004; Nagase & Dunnett, 2011; Vijayaraghavan & Raja, 2014).

Majority of the load on a green roof result from the substrate. Therefore, the weight of the substrate must be kept as low as possible while still providing sufficient anchorage for plants (Vijayaraghavan, 2016; Xiao et al., 2014). For this purpose, US and Germany green roof guidelines recommends the use of 80% inorganic constituents in the green roof substrate (Vijayaraghavan, 2016). Therefore, in this study, 80% of the substrate composition consisted of inorganic materials. Recycled crushed bricks of 10 mm – 4.75 mm and sand of 2 mm – 0.475 mm were used as the inorganic materials. Brick waste is one of the most prominent wastes produced from the construction industry (Wong et al., 2018). Coarse materials such as crushed bricks have surface and internal pores which helps to improve the porosity, hydraulic conductivity and water storage capabilities of the substrate. Additionally, by incorporating crushed recycled bricks, the density of the substrate can be reduced while also decreasing the waste output from the construction sector (Johnston & Newton, 2004; Vijayaraghavan & Raja, 2014).

The green roof substrate should possess an adequate level of micro and macro-nutrients to promote plant growth (Vijayaraghavan, 2016). Therefore, organic constituents must be incorporated in to the substrate (Molineux et al., 2014; Nagase & Dunnett, 2011; Vijayaraghavan & Joshi, 2015). However, as the amount of organic material in the substrate increases, the stability of the substrate will be compromised. As the organic materials decompose, the substrate will shrink and compact, hindering healthy root growth (Nagase & Dunnett, 2011; Vijayaraghavan, 2016). The rate of decomposition of organic matter is higher in tropical countries such as Sri Lanka compared to countries in the northern hemisphere (Ampim et al., 2010). Moreover, under the tropical climate, a high organic content in the substrate can lead to excessive weed growth which will in turn increase the amount of maintenance required. Therefore, in tropical climates, careful consideration must be given to the quantity of organic matter utilised in the green roof substrate. According to literature, an organic content of 10 - 20% is recommended for warm humid climates (Friedrich, 2005). Considering the tropical humid climate of Sri Lanka, the organic content of the green roof substrate was fixed at 20%.

Compost, coir and rice husk were selected as the organic constituents of the substrate mix. Rice husk is an agricultural waste that is generated in large quantities in Sri Lanka (Rodrigo & Perera, 2011). Incorporating rice husk helps to reduce the density of the substrate while enhancing the aeration ability and water permeability (Xiao et al., 2014). Coir fibre is widely used in different climate regions to enhance the properties of the green roof substrate (Razzaghmanesh et al., 2014). Compost is a recycled material which can be produced locally (Graceson et al., 2014). It helps to provide the plants with nutrients and contributes positively to the green roof substrate due to its high air-filled porosity and water holding capacity (Raviv et al., 2008). However, compost in the substrate mix can lead to high concentrations of nitrogen in the green roof runoff (Hashemi et al., 2015). Therefore, according to recommendations of previous literature, the amount of compost used in the substrate mix was limited to 20% (Friedrich, 2005; Nagase & Dunnett, 2011; Toland et al., 2012)

By varying the composition of these organic and inorganic constituents, 16 potential substrate mixtures were prepared for testing. The substrate mixtures are given in Table 2.

Table 2: Substrate configurations

	Sample	**Notation**	**Organic (20%)**			**Inorganic (80%)**	
			Compost	**Coir**	**Rice Husk**	**Sand**	**Brick**
Series 1	1	S11	10%	5%	5%	40%	40%
	2	S12	10%	-	10%	40%	40%
	3	S13	10%	10%	-	40%	40%
	4	S14	20%	-	-	40%	40%
Series 2	1	S21	10%	5%	5%	80%	-
	2	S22	10%	-	10%	80%	-
	3	S23	10%	10%	-	80%	-

	Sample	Notation	Organic (20%)			Inorganic (80%)	
			Compost	Coir	Rice Husk	Sand	Brick
	4	S24	20%	-	-	80%	-
Series 3	1	S31	10%	5%	5%	50%	30%
	2	S32	10%	-	10%	50%	30%
	3	S33	10%	10%	-	50%	30%
	4	S34	20%	-	-	50%	30%
Series 4	1	S41	10%	5%	5%	30%	50%
	2	S42	10%	-	10%	30%	50%
	3	S43	10%	10%	-	30%	50%
	4	S44	20%	-	-	30%	50%

2.2 DETERMINATION OF THE PROPERTIES OF THE SUBSTRATE

The following properties were determined for each substrate mixture, under laboratory conditions, to determine its suitability as a green roof substrate for the tropics.

- Dry Bulk Density (DBD): The DBD was determined by oven drying a known sample volume at 105℃ for 2 hours. The resulting dry weight was used to calculate the DBD.
- Wet Bulk Density (WBD): The WBD was determined by saturating the samples in water for 24 hours and then allowing it to drain freely under gravity for 24 hours. The wet weight of the samples was measured and the WBD was calculated.
- pH: The soil samples were mixed with deionised water at 1:1 soil suspension ratio. The samples were then agitated in a shaker for 1 hour and was allowed to stand undisturbed for 1 hour. Then pH of the samples was determined by using a pH meter.
- Water Holding Capacity (WHC): Was determined as per the Percolation method.
- Air Filled Porosity (AFP): AFP was determined according to the Australian Potting Mix Standard (AS 3743-2003).

2.3 SELECTION OF A SUITABLE SUBSTRATE DEPTH

Three different substrate depths (2.5cm, 5.0cm and 7.5 cm) were tested, in order to study their suitability for adequate plant development under tropical conditions.

Sample plots of 40 cm x 30 cm were prepared for each of the thicknesses. The sample plots were filled with two substrate mixes selected based on the laboratory analysis detailed in 2.2. Using the plant selection matrix for the tropical climate developed by John & Halwatura (2022), *Alternanthera Sessilis* was selected as the vegetation layer for the evaluation. The plants were transplanted as plugs, 9 plants per plot. The sample plots were kept on a horizontal plane for 1 week until the roots had anchored to the substrate and was then transferred to a conventional sloped roof. The coverage and survival rate, under the three substrate depths, were monitored for 12 weeks to identify the most suitable substrate and the optimum thickness for the tropical climate. The percentage plant cover was measured using a grid (frequency-cover), weekly for 12 weeks. The survival rate of the plants was determined by visual assessment.

3. RESULTS AND DISCUSSIONS

3.1 LABORATORY ANALYSIS OF THE SUBSTRATE MIXTURES

Following sections presents the results of laboratory analysis of the substrate mixtures.

3.1.1 Wet and Dry Bulk Density

Figure 1 represents the dry and wet bulk density of the tested samples.

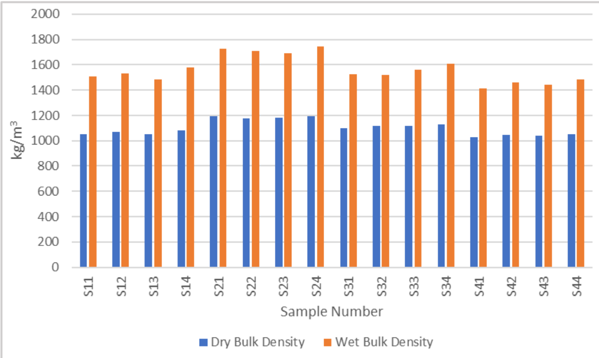


Figure 1: Dry and wet bulk density of substrate configurations

As expected, as the percentage of recycled crushed brick increased, the density of the substrate reduced. Majority of the load on a green roof result from the substrate. Moreover, during rainfall events the substrate can become saturated which can lead to an increase in the overall weight of the system. Most buildings are not designed to withstand heavy loads on the roof structure. Therefore, the WBD and DBD of a green roof substrate must be kept as low as possible (Vijayaraghavan, 2016; Xiao et al., 2014).

Additionally, the substrate used in a green roof should be sufficiently heavy to provide good anchorage for plants (Johnston & Newton, 2004). Lightweight substrates can be easily washed off or blown off. Therefore, according to the German Green Roof guidelines, the minimum permissible DBD of a green roof substrate is 600 kg/m^3. As shown in Figure 1, all substrate mixtures met this minimum performance requirement.

After conducting the WBD and DBD analysis, the samples were evaluated and ranked based on their suitability, as shown in Table 3. As previously mentioned, all substrate mixtures met the minimum DBD requirement. Therefore, in the ranking process, samples with lower wet and dry bulk densities were assigned higher ratings, given the importance of reducing the weight on the roof structure.

3.1.2 pH

The pH of the green roof substrate must be within the range that allows nutrient uptake by green roof plants (Beattie & Berghage, 2004; Friedrich, 2005). When tested for the pH, pH of all the substrate mixes were within the acceptable range given in Table 1.

3.1.3 Water Holding Capacity (WHC)

In extensive green roofs due to the shallowness of the substrate, and the extreme drought-like conditions that exist on a rooftop, especially in the tropical climate, the substrate tends to regularly dry out (Emilsson, 2006; Getter et al., 2009a; Vijayaraghavan, 2016). As the building acts as a barrier between the plant layer and the earth, there is no capillary rise of water from underground supplement the plant layer (Xiao et al., 2014). The WHC of the substrate enables the growth medium to store water thus enabling prolonged plant survival during periods of drought (Farrell et al., 2013; Graceson et al., 2014). Furthermore, the WHC of the substrate also affects the stormwater performance of the green roof system. Substrates with high WHC helps to retain water during rainfall events to delay the peak flow (Farrell et al., 2013; Vijayaraghavan, 2016). Therefore, according to the literature given in Table 1, the substrates used in a green roof must have a minimum WHC of 20%.

The WHC of the substrate mixtures are given in Figure 2a. All samples met the minimum requirement for WHC. As expected, the WHC of the samples increased with the increasing percentage of crushed bricks. This correlation can be attributed to the surface and internal pores present in crushed bricks which helps to retain water (Johnston & Newton, 2004; Vijayaraghavan & Raja, 2014).

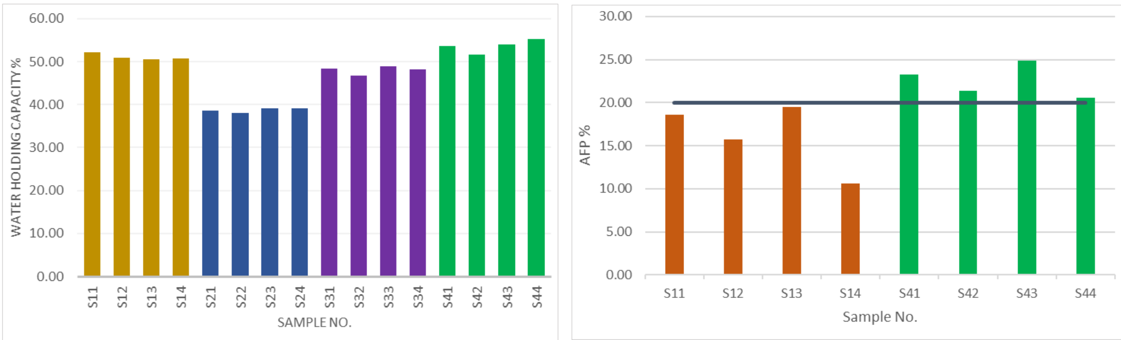


Figure 2: a) Water holding capacity b) Air filled porosity

A high WHC, within the guidelines given in Table 1, is recommended for green roof substrates used in the tropics (Vijayaraghavan, 2016). Therefore, when ranking the substrate mixtures by WHC, they were ranked in ascending order of their WHC as shown in Table 3.

3.1.4 Air Filled Porosity (AFP)

Oxygen diffusion through the substrate is an essential parameter for plant growth. Generally, in extensive green roofs, the shallowness of the substrate, limits the amount of oxygen diffused through the substrate. However, this can be addressed by incorporating coarse materials into the substrate mix. Coarse materials such a such as crushed recycled bricks, have surface and internal pores, which allow oxygen to be transported to the roots (Johnston & Newton, 2004). In addition to plant growth, a good AFP in the green roof substrate helps to minimises water logging and increases the ability of the substrate to act as an insulator (Saadatian et al., 2013). However, while a high AFP is always preferable, the AFP in the substrate should not exceed 20% (ASTM International, 2015; Chow et al., 2018; Xiao et al., 2014). This is because there is a significant correlation between the increase in AFP and a decrease in soil water content. Excessively high AFP can lead to water stress in the substrate, which can pose critical drawbacks, particularly in tropical countries like Sri Lanka. Therefore, maintaining an optimal balance in the substrate's AFP is essential.

Air-filled porosity was assessed only for Series 1 and Series 4 samples, as these substrate mixtures demonstrated the highest rankings following testing for wet and dry bulk density, pH, and WHC, as shown in Table 3.

The results of the AFP test are given in Figure 2b. As expected, the AFP increased as the fraction of crushed bricks increased. Series 4, which contained 40% crushed bricks, exhibited an AFP which exceeded the recommended 20%. As mentioned previously, a high AFP can negatively affect the water retention capabilities of the substrate. This holds particular significance in tropical climates, where consistent moisture availability in the substrate is crucial for plant growth. Therefore, the series 4 substrate mixtures, which had an AFP greater than the recommended 20% were thus rejected.

3.1.5 Ranking of the Substrate Mixtures based on Laboratory Testing

Following the analysis of wet and dry bulk density, WHC, and AFP, the 16 substrate mixtures were assessed and ranked based on their suitability, as given in Table 3.

Table 3: Ranking of substrate mixtures based on laboratory testing

Notation	DBD	WBD	WHC	AFP	Ranking
S11	13	11	13	15	52
S12	10	8	11	14	43
S13	11	13	9	16	49
S14	9	6	10	12	38
S21	2	2	2	N/A	6
S22	4	3	1	N/A	8
S23	3	4	4	N/A	11
S24	1	1	3	N/A	5
S31	8	9	7	N/A	24
S32	7	10	5	N/A	22
S33	6	7	8	N/A	21
S34	5	5	6	N/A	16
S41	16	16	14	0	46
S42	14	14	12	0	40
S43	15	15	15	0	45
S44	12	12	16	0	40

According to the ranking, the two substrate mixtures with the highest scores (S11 and S13) were chosen for further field investigations.

3.2 SELECTION OF A SUBSTRATE DEPTH FOR THE TROPICAL CLIMATE

3.2.1 Coverage

The percentage plant cover, measured weekly for 12 weeks, is given in Figure 3. As shown in Figure 3, deeper substrate depths showed a higher coverage in the initial weeks of the study. The deepest substrate depth, 7.5 cm, consistently showed the highest coverage throughout the study period. However, over time, the difference in coverage among different plot depths diminished, and by the end of the 12-week period, all plots achieved a coverage exceeding 50%.

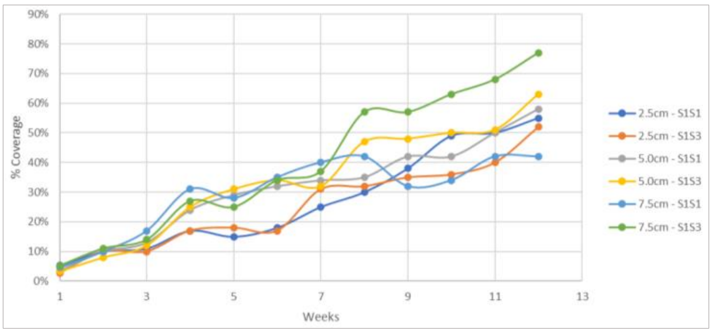


Figure 3: Percentage plant cover

It's worth mentioning that the *Alternanthera sessilis* planted in the 7.5 cm depth, specifically in the substrate S11, was affected by local pests towards the latter part of the study. Consequently, this led to a loss of coverage in that particular plot. However, aside from this isolated incident, there were no significant statistical differences observed in coverage between the S11 and S13 substrate mixes.

3.2.2 Survival Rate

Plant establishment was successful across all depths and in both substrate mixtures. All three substrate depths, 2.5 cm 5.0 cm and 7.5 cm, showed a 100% survival rate under both substrate mixtures, S11 and S13.

3.2.3 Weight of the System

Majority of the load on a green roof result from the substrate. Therefore, weight of the system is one of the key elements that must be considered when selecting a suitable substrate depth. The weight of the green roof system under each substrate type and substrate depth is given in Table 4.

Table 4: Weight of the system

Depth	Substrate	Weight of the System (kg/m^2)
2.5 cm	S1S1	28.26
2.5 cm	S1S3	28.19
5.0 cm	S1S1	56.51
5.0 cm	S1S3	56.37
7.5 cm	S1S1	84.77
7.5 cm	S1S3	84.56

According to the Department of Consensus and Statistics (2016), majority of the housing units in Sri Lanka (45.6%) are composed of Calicut tiled roofs. As such, existing roofing structures in Sri Lanka are typically designed to accommodate the average load of a Calicut tile, which is approximately 28kg/m^2.

The average weight of the system under a 2.5 cm substrate depth closely aligns with the weight of a Calicut tile. Therefore, a 2.5 cm depth can be supported on an existing roof with minimal/no modifications required. However, if the substrate depth is increased to 5.0 cm or 7.5 cm, the existing roof structure would need to undergo significant modifications to withstand the increased weight of the green roof system.

4. CONCLUSIONS

The substrate layer is one of the key components which affects the performance of the green roof system. The substrate used in a green roof must possess some unique properties. There is no universal green roof substrate and the most appropriate substrate mixture that suits the local climatic and geographical conditions must be selected based on local research (Ampim et al., 2010; FLL, 2008; Vijayaraghavan, 2016). This research aimed to identify the most suitable substrate mixture for an extensive green roof for the tropical climate of Sri Lanka. Sixteen (16) potential substrate mixtures were prepared using locally available materials including waste materials. The properties of these substrate mixtures were tested under laboratory and field conditions.

Based on the results obtained from laboratory testing it was observed that substrate mixtures that contained coir and crushed recycled bricks displayed the properties most suited for a substrate in the tropical climate. Hence, two substrate mixtures, S11 and S13, were selected for further field investigations.

In addition to the type of substrate, the depth of the substrate also affects the performance of the green roof system. The depth of the substrate must also be selected based on the local climate and geographical conditions. Within this study, three possible substrate depths (2.5cm, 5.0cm and 7.5cm) were investigated for their suitability for the tropical climate of Sri Lanka. Each substrate depth was prepared using the two selected substrate mixtures (S11 and S13) and field investigations were conducted.

The 2.5cm substrate depth showed successful plant establishment, with over 50% coverage and 100% survival rate, throughout the study period (12 weeks). Moreover, a green roof with a depth of 2.5cm can be readily supported on existing roof structures in Sri Lanka with minimal to no modifications required.

In field investigations, both substrate configurations (S11 and S13), displayed comparable performance for the same substrate depth. However, when considering the cost of the substrate, S11, which contains 5% coir and 5% rice husk proves to be more economical compared to S13, which contains 10% coir and 0% rice husk. This cost difference arises from the availability of rice husk as an agricultural waste, obtainable at no expense, while coir remains a relatively costly commodity.

Therefore, a 2.5cm substrate depth with 10% compost, 5% coir, 5% rice husk, 40% sand and 40% crushed recycled bricks can be recommended for the tropical climate of Sri Lanka.

5. REFERENCES

Ampim, P. A. Y., Sloan, J. J., Cabrera, R. I., Harp, D. A., & Jaber, F. H. (2010). Green roof growing substrates: Types, ingredients, composition and properties. *Journal of Environmental Horticulture*, *28*(4), 244–252. https://doi.org/10.24266/0738-2898-28.4.244

ASTM International. (2015). *Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roof Systems*. www.astm.org

Beattie, D., & Berghage, R. (2004). Green roof media characteristics: The basics. *Procedings of the 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities* (pp. 411–416).

Blank, L., Vasl, A., Levy, S., Grant, G., Kadas, G., Dafni, A., & Blaustein, L. (2013). Directions in green roof research: A bibliometric study. *Building and Environment*, *66*, 23–28. https://doi.org/10.1016/J.BUILDENV.2013.04.017

Chow, M. F.; Bakar, M. F. Abu; Wong, J. K. (2018). Green design and manufacture: advanced and emerging applications: An overview of plant species and substrate materials or green roof system in tropical climate urban environment. *Proceedings of the 4th International Conference on Green Design and Manufacture 2018,* Ho Chi Minh, Vietnam 29–30 April 2018. (pp. 020004-1 - 020004-4. https://doi.org/10.1063/1.506664

Dassanayake, D. H. B., & Beneragama, C. (2011). Development of roof vegetation as influenced by substrate composition and depth in an extensive green roof. *Proceedings of the Peradeniya University Research Sessions*. (pp.170).

Dunnett, N., & Kingsbury, N. (2004). *Planting green roofs and living walls*. Timber Press.

Durhman, A. K., Rowe, D. B., & Rugh, C. L. (2007). Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa. *HortScience*, *42*(3), 588–595. https://doi.org/10.21273/HORTSCI.42.3.588

Emilsson, T. (2006). *Extensive vegetated roofs in Sweden: establishment, development and environmental quality*. Department of Landscape Management and Horticultural Technology, Swedish University of Agricultural Sciences. https://res.slu.se/id/publ/13386

Emilsson, T., & Rolf, K. (2005). Comparison of establishment methods for extensive green roofs in southern Sweden. *Urban Forestry & Urban Greening*, *3*(2), 103–111. https://doi.org/10.1016/j.ufug.2004.07.001

Farrell, C., Mitchell, R. E., Szota, C., Rayner, J. P., & Williams, N. S. G. (2012). Green roofs for hot and dry climates: Interacting effects of plant water use, succulence and substrate. *Ecological Engineering*, *49*, 270–276. https://doi.org/10.1016/j.ecoleng.2012.08.036

Farrell, C., Ang, X. Q., & Rayner, J. P. (2013). Water-retention additives increase plant available water in green roof substrates. *Ecological Engineering*, *52*, 112–118. https://doi.org/10.1016/j.ecoleng.2012.12.098

FLL. (2008). *Guideline for the planning, execution and upkeep of greenroof sites*.

Friedrich, C. R. (2005). Principles for selecting the proper components for a green roof growing media. *3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Washington, United States, 4-6 May 2005. (pp. 262–273).

Getter, K. L., Rowe, D.B., & Cregg, B. M. (2009a). Solar radiation intensity influences extensive green roof plant communities. *Urban Forestry & Urban Greening*, *8*(4), 269–281. https://doi.org/10.1016/j.ufug.2009.06.005

Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M., & Andresen, J. A. (2009b). Carbon sequestration potential of extensive green roofs. *Environmental Science & Technology*, *43*(19), 7564–7570. https://doi.org/10.1021/es901539x

Graceson, A., Hare, M., Hall, N., & Monaghan, J. (2014). Use of inorganic substrates and composted green waste in growing media for green roofs. *Biosystems Engineering*, *124*, 1–7. https://doi.org/10.1016/j.biosystemseng.2014.05.007

Handreck, K., & Black, N. . (2010). *Growing Media for Ornamental Plants and Turf* (4th ed.). University of New South Wales Press.

Hashemi, S. S. G., Mahmud, H. Bin, & Ashraf, M. A. (2015). Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review. *Renewable and Sustainable Energy Reviews*, *52*, 669–679. https://doi.org/10.1016/j.rser.2015.07.163

John, G. K. P., & Halwatura, R. U. (2022). Selection of plants for extensive green roofs in climate zone A: A review. *AlfaBuild*, *23*(3). https://doi.org/10.57728/ALF.23.1

Johnston, J., & Newton, J. (2004). *Building green : a guide to using plants on roofs, walls and pavements* (Issue 21). Greater London Authority.

Kok, K. H., Mohd Sidek, L., Chow, M. F., Zainal Abidin, M. R., Basri, H., & Hayder, G. (2015). Evaluation of green roof performances for urban stormwater quantity and quality controls. *International Journal of River Basin Management*, *14*(1), 1–7. https://doi.org/10.1080/15715124.2015.1048456

Lugo, A., & Rullan, J. (2015). *The conservation message of the rehabilitated facilities of the international institute of tropical forestry*. U.S. Department of Agriculture Forest Service, International Institute of Tropical Forestry. https://doi.org/10.2737/IITF-RN-2

Molineux, C. J., Connop, S. P., & Gange, A. C. (2014). Manipulating soil microbial communities in extensive green roof substrates. *Science of The Total Environment*, *493*, 632–638. https://doi.org/10.1016/j.scitotenv.2014.06.045

Nagase, A., & Dunnett, N. (2011). The relationship between percentage of organic matter in substrate and plant growth in extensive green roofs. *Landscape and Urban Planning*, *103*(2), 230–236. https://doi.org/10.1016/j.landurbplan.2011.07.012

Ondoño, S., Martínez-Sánchez, J. J., & Moreno, J. L. (2016). The composition and depth of green roof substrates affect the growth of Silene vulgaris and Lagurus ovatus species and the C and N sequestration under two irrigation conditions. *Journal of Environmental Management*, *166*, 330–340. https://doi.org/10.1016/j.jenvman.2015.08.045

Panayiotis, N., Panayiota, T., & Ioannis, C. (2003). Soil Amendments Reduce Roof Garden Weight and Influence the Growth Rate of Lantana. *HortScience*, *38*(4), 618–622.

Papafotiou, M., Pergialioti, N., Tassoula, L., Massas, I., & Kargas, G. (2013). Growth of native aromatic Xerophytes in an extensive Mediterranean green roof as affected by substrate type and depth and irrigation frequency. *HortScience*, *48*(10), 1327–1333. https://doi.org/10.21273/HORTSCI.48.10.1327

Raviv, M., Lieth, H., & Bar-Tal, A. (2008). Significance of soilless culture in agriculture. *Soilless Culture*, 3-14. doi:10.1016/B978-0-444-63696-6.00001-3

Razzaghmanesh, M., Beecham, S., & Kazemi, F. (2014). The growth and survival of plants in urban green roofs in a dry climate. *Science of the Total Environment*, *476–477*, 288–297. https://doi.org/10.1016/j.scitotenv.2014.01.014

Rodrigo, A. S., & Perera, S. (2011). Electricity Generation Using Rice Husk in Sri Lanka: Potential and Viability. *National Energy Symposium 2011*, BMICH-Colombo, Sri Lanka, August 11-13. (pp. 104–108).

Rowe, D., Monterusso, M., & Rugh, C. . (2006). Assessment of heat-expanded slate and fertility requirements in green roof substrates. *HortTechnology*, *16*(3), 471–477. https://doi.org/10.21273/horttech.16.3.0471

Rowe, D. B., & Getter, K. L. (2006). The role of extensive green roofs in sustainable development. *HortScience*, *41*(5), 1276–1285.

Saadatian, O., Sopian, K., Salleh, E., Lim, C. H., Riffat, S., Saadatian, E., Toudeshki, A., & Sulaiman, M. Y. (2013). A review of energy aspects of green roofs. *Renewable and Sustainable Energy Reviews*, *23*, 155–168. https://doi.org/10.1016/j.rser.2013.02.022

Seyedabadi, M. R., Eicker, U., & Karimi, S. (2021). Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint. *Environmental Challenges*, *4*, 100119. https://doi.org/10.1016/j.envc.2021.100119

Shafique, M., Kim, R., & Rafiq, M. (2018). Green roof benefits, opportunities and challenges – A review. *Renewable and Sustainable Energy Reviews*, *90*, 757–773. https://doi.org/10.1016/j.rser.2018.04.006

Thuring, C. E., Berghage, R. D., & Beattie, D. J. (2010). Green roof plant responses to different substrate types and depths under various drought conditions. *HortTechnology*, *20*(2), 395–401. https://doi.org/10.21273/HORTTECH.20.2.395

Toland, D. ., Haggard, B. ., & Boyer, M. . (2012). Evaluation of nutrient concentrations in runoff water from green R=roofs, conventional roofs, and urban streams. *Transactions of the ASABE*, *55*(1), 99–106. https://doi.org/10.13031/2013.41258

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews*, *57*, 740–752. https://doi.org/10.1016/j.rser.2015.12.119

Vijayaraghavan, K., & Raja, F. D. (2014). Design and development of green roof substrate to improve runoff water quality: Plant growth experiments and adsorption. *Water Research*, *63*, 94–101. https://doi.org/10.1016/j.watres.2014.06.012

Williams, N. S. G., Rayner, J. P., & Raynor, K. J. (2010). Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia. *Urban Forestry and Urban Greening*, *9*(3), 245–251. https://doi.org/10.1016/j.ufug.2010.01.005

Wong, C. L., Mo, K. H., Yap, S. P., Alengaram, U. J., & Ling, T.-C. (2018). Potential use of brick waste as alternate concrete-making materials: A review. *Journal of Cleaner Production*, *195*, 226–239. https://doi.org/10.1016/j.jclepro.2018.05.193

Wong, J. K. W., & Lau, L. S. K. (2013). From the 'urban heat island' to the 'green island'? A preliminary investigation into the potential of retrofitting green roofs in Mongkok district of Hong Kong. *Habitat International*, *39*, 25–35. https://doi.org/10.1016/j.habitatint.2012.10.005

Xiao, M., Lin, Y., Han, J., & Zhang, G. (2014). A review of green roof research and development in China. *Renewable and Sustainable Energy Reviews*, *40*, 633–648. https://doi.org/10.1016/j.rser.2014.07.147

Hettiarachchi, H.A.Y.G. and Pathiraja, M.G., 2024. Design tolerance as a pedagogical tactic: The possible role of architectural design in facilitating on-site labour training. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 423-434. DOI: https://doi.org/10.31705/WCS.2024.33. Available from: https://ciobwcs.com/papers/

DESIGN TOLERANCE AS A PEDAGOGICAL TACTIC: THE POSSIBLE ROLE OF ARCHITECTURAL DESIGN IN FACILITATING ON-SITE LABOUR TRAINING

Gayathmi Hettiarachchi[1] and Milinda Pathiraja[2]

ABSTRACT

This paper is the initial publication from a research project examining the role of architectural design in enhancing the skills of the construction workforce in Sri Lanka. For years, the country has faced challenges in implementing effective capacity-building initiatives, resulting in a proliferation of substandard buildings and hindering the socio-economic advancement of construction workers. Regretfully, the practice of architecture rarely develops pragmatic strategies to confront labour training as a design prerogative. Birthed off in such a context, this paper investigates the potential contribution of architectural design to labour upskilling by adopting the function of 'Design Tolerance' as a pedagogical tactic. Given the theory-driven nature of this inquiry, the paper first evaluates 'Design Tolerance' as a theoretical construct before elucidating its contextual significance within the scope of the broader investigation on labour upskilling, particularly on the use of real building projects as on-site training grounds. Placing 'Design Tolerance' at the crux of the dual objective of 'compromising precision' and 'accommodating error', the theoretical arguments then lead to a case-study analysis organised under three categories: (i) tolerance by the system, (ii) tolerance by detail, and (iii) tolerance by procurement. Subsequently, 13 design tactics attributing to the idea of 'Design Tolerance' are identified, offering a technical foundation to re-interpret and define the role of architectural design in on-site labour training.

Keywords: *Architectural Design*; *Design Tolerance; Labour Training; On-site Upskilling.*

1. INTRODUCTION

A critical observation of the Sri Lankan construction industry; both empirical and embodied, reveals that the increasing skill shortage of its construction workforce is drastically hampering the demand and supply behaviour of the local building stock. Such labour market behaviour has inevitably contributed to distressing technical, social,

[1] MPhil Candidate, Department of Architecture, University of Moratuwa, Sri Lanka, gayathmi.research@gmail.com

[2] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka and Visiting Professor, FAR, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, m_pathiraja@yahoo.com.au

political, and institutional outcomes. Technically, substandard constructions have propagated the country's urban and rural landscapes, inducing significant environmental and social costs due to the reduced lifetime performances of the building units (Pathiraja & Tombesi, 2023). Socially, the construction workforce is among the most under-organised and regressive of the local labour profiles, being employed under conditions of low remuneration, inferior health and safety standards, and lack of job continuity (Fernando et al., 2016; Manoharan et al., 2022). Politically, the approaches taken to overcome skill and training limitations have been traditional, fragmented, and limited in their industrial potential; there has been little or no attempt to relate training needs to the workforce's cultural conditions, career development aspirations, and socio-economic growth (Silva et al., 2018). Institutionally, the formal upskilling programs initiated by the state-affiliated actors have not risen to the challenge, both quantity and quality-wise (Dundar et al., 2014; UNESCO-UNEVOC, 2018).

The failure to advance construction labour skills on the technical, social, political, and institutional fronts calls for drastic action by all industrial stakeholders to find alternative strategies to propel industry-wide upskilling and knowledge dissemination. However, such strategies must align with the limitations and potential of existing labour market behaviour, as otherwise, they will fail to enforce a meaningful impact on the situation on the ground. Generally, across developing economies and particularly in Sri Lanka, the construction workforce is organised informally concerning work access, training procedures, working conditions, and wage structures (Jayawardane & Gunawardena, 1998; Pathiraja & Tombesi, 2009; Pathiraja, 2010). Training follows an informal apprenticeship setup where an unskilled worker learns skills gradually on-site by seeing and doing tasks under the supervision of a master builder (Basunnehe in Sinhalese) or a construction manager (Pathiraja & Tombesi, 2009).

While this site-based informal apprenticeship supports industrial skill dissemination to a certain degree, it is nonetheless hindered by the unplanned, ad-hoc, and project-based nature of learning centred on an immediate technical outcome rather than structured and focused training. Furthermore, in this makeshift form of learning, the knowledge transferred to the trainee is confined to the exposure and capacity of the person who transfers that knowledge in the first place. But, given that a high majority of workers are daily wage earners who do not have either time or money to spend on institutionalised learning, ‘on-site apprenticeship’ offers the only viable option to advance their skills to remain employed in the building industry.

Such a problematic context of skill building raises a compelling question: can a particular type of architectural design strengthen the on-site apprenticeship by transforming real building sites into planned training grounds? In other words, can informal apprenticeship be formalised enabling on-site skill transferring is endorsed by design professionals and facilitated through focused design interventions? Discursively, the above inquiry also questions whether architectural design; as an intellectual activity, can play a role in overcoming labour-training limitations, fostering the industry's labour capacity, and supporting the socio-economic growth of its workforce.

Yet, suppose real building projects are to be used for upskilling the labour force. In that case, the subsequent architectural designs must tolerate permissible mistakes and affordable errors, as mistakes and errors will predictably happen during the learning process (Pathiraja, 2010). This is where the notion of 'design tolerance' becomes critical to the proposed on-site training strategy and the theoretical underpinning of this paper. To that end, 'design tolerance' presents the foundational theoretical body that forms the intellectual base of this theory-led research and, subsequently, the focus of this paper. The task of building up the theoretical base here is accomplished through a literature review supported by a pilot study that investigates 'tolerance' as a design tactic to accommodate - and train - less-skilled labour gangs.

2. THE NOTION OF 'DESIGN TOLERANCE'

The function of 'design' is generally understood as a process of creative and critical thinking. However, its etymology denotes actions of pragmatic aims – i.e., '*to point out*' (Hoad, 1996, p. 121), '*to plan, purpose and intend*' (Hoad, 1996, p. 121), and '*to delineate, draw'* (Hoad, 1996, p. 121). Used as both a noun and a verb, the term 'design' connotes, on the one hand, *'the general arrangement of the different parts of something… such as a building*' and, on the other hand, '*deciding how something will look and act… and planning something for a particular purpose or use*' (Hornby, 2005, p. 413). Collectively, 'design' exemplifies a problem-solving process that provides a cognitive framework for analysis, synthesis, evaluation, and action (Zande, 2006).

Such a 'problem-solving' notion of 'design' considers human needs or problems as the point of departure to a specific intellectual and technical process that formulates schemes or solutions through a problem-solver, either a human or a machine. The solutions thus derived inevitably depend on the nature of the problem and the capacity and, in the case of humans, the worldview of the problem solver (Lawson, 1972). However, as Jeremy Till claims, the history of architectural practice places its importance mainly on the performances of its end-products and the solutions thus generated rather than the contexts that birth the results in the first place (Till, 2009). In other words, architectural design is regarded for its ability to produce precise end-products with little or no regard for the contextual demands of widespread practice. However, shifting the focus from the product to the process i.e., from the solution to the path that led to it, can highlight the design's ability to address broader contextual challenges. This shift may also reveal the potential for design to facilitate on-site labor training and enhance skill development.

'Tolerance' is a term adopted from the old French word 'tolerance' (14c.), which, in turn, is an adoption of the Latin 'tolerantia' (Hoad, 1996, p. 497), depicting the ideas such as '*disposition to be indulgent'* (18c.) and '*endurance'* (Hoad, 1996, p. 497). The Oxford Dictionary defines 'tolerance' as *'the amount by which the measurement of a value can varies without causing problems*' (Hornby, 2005, p. 1615). However, within architecture, the idea of 'tolerance' has been historically presented as a confluence of two seemingly opposing meanings. On the one hand, it refers to the degree of dimensional variation that affects construction accuracy, thereby placing it as a function that strengthens construction precision (Taron, 2024). On the other hand, it denotes the allowable deviation for human or machine error in assembling building components, elements, and systems, thus aligning its purpose with overcoming construction errors (Baudoin, 2016). As Boudoin (2016) highlights, the idea of 'tolerance' in building production lies where the two opposites 'construction precision' and 'construction error' meet.

McVicar (2016), Bates and Sergison (1999), and Pathiraja (2010) provide further insights into the concept of 'design tolerance,' which primarily pertains to the task of on-site assembly. Accordingly, 'design tolerance': (i) provides an opportunistic response to overcome various challenges of the on-site building activity (McVicar, 2016), (ii) presents a design tactic with latitude for errors to inhabit varying socio-cultural performances (Pathiraja, 2010), (iii) offers a technological framework to use building systems and components for purposes other than for their prescribed use (Bates & Sergison, 1999), and (iv) postulates an architectural idea that helps compromising precision to accommodate on-site labour training (Pathiraja, 2010). This dual objective of 'compromising precision' and 'accommodating error' provides a key point of departure for understanding design tolerance's role in on-site labour upskilling.

3. PRECISION VS ERROR

Tracing back to its etymology, the 16th century French word précision referred to the act of "cutting off abstraction and the freedom from inessential elements," while the Latin word praecisionem conveyed a similar meaning of "a cutting off". However, from the 17th century onwards, the term 'precision' appeared to be associated with the "*quality or state of being precise*" (Harper, 2024). The Oxford Dictionary, for example, defines precision as "*the quality of being exact, accurate, certain and careful*" (Hornby, 2005, p. 1184).

This idea of 'precision' as 'reassuring certainty' has significantly influenced the agreements on the role of the architect-in-practice over the last few centuries (McVicar, 2016, as cited in Bartholomew, 1840). In reviewing the historical influence of 'precision' in architectural practice, McVicar (2016) even recalls Vitruvius's stipulation that 'architectural drawings' must present ' precise' communication of architectural intent. In a more critical review of the architectural work, Hughes (2014) claims that the obsession with 'precision' and the fear of 'error' has made architects hesitant to accept the gap between their conceptual thinking and the actual realisation of it. The author further suggests that the idea of 'precision' generally excludes inevitable realities of practice-on-site.

It must be mentioned firmly, however, that the specific notion of 'error' emphasised here does not align its meaning with the performance 'failures' of buildings. Instead, it is concerned with 'allowable' errors that accommodate labour and material realities by not relying on overly precise construction systems and applications. As Hughes (2014) repeatedly emphasises, the 'precision' encountered today in architectural design and practice is often excessive; this version of 'precision' has outgrown the intention of mitigating performative failures and maintaining accuracy in building construction to become one with an authoritative domineer.

The problem with the notion of excessive 'precision' is that it excludes human error in practice, thereby framing architecture within the exclusive realm of high culture, unaffordable by those who need to possess the means to achieve an elevated level of technical accuracy. Especially in construction industries subjected to low labour skills and limited spending capacities, the thrive for precision has created a restrictive framework for architecture to address the social building needs of the masses while forming challenges for on-site capacity building (Pathiraja, 2010). Inevitably, a low-skilled labour gang learning while building on-site would make construction mistakes and formal oversights. If the technological environment of individual projects refuses to accommodate such technical volatility of the building process, their ability to provide a sound pedagogical platform for on-site labour apprenticeship will be lost.

4. ON-SITE LABOUR TRAINING AND ITS DEMAND

The task of on–site labour training has always been one of the most natural modes of skill building for construction workers. As Coomaraswamy (1956) states, apprenticeship has been the cornerstone of craftsmanship training in historic Sri Lanka. In the 15th century Kandyan kingdom, for example, the buildings for royal patronage were built by a set of artisans i.e., carpenters (Vaduvo), masons, blacksmiths, etc. who worked under the guidance and supervision of a foreman-cum-master-builder called Mul-acharya (meaning 'first-guru' or the 'learned mentor' in English). These master builders were responsible for transferring craftsmanship skills to their disciples through structured training programs implemented in workshops and actual building sites.

Even now, learning on the job remains significantly evident and appears particularly impactful in industrialised economies such as Germany and the Netherlands. For example, the prominent labour theorists Linda Clarke and Christine Wall discuss how Germany and the Netherlands; as countries with comparatively comprehensive skill development and systematic training programs, have given significance to on-site training (Clarke & Wall, 1998). The authors further argue that the gradual move away from on-site training has resulted in the United Kingdom's abstract nature of construction skills and the subsequent deskilling of its workforce (ibid).

In contrast to the planned on-site training programs in Germany and the Netherlands, an unplanned, ad-hoc, and informal learning process occurs on construction sites in countries such as Sri Lanka, where formal training is often unavailable and unaffordable for most of the daily-waged workforce. Studies on the Sri Lankan construction industry reveal that almost all skill-building needs in masonry, carpentry, plumbing, and steel welding trades are fulfilled experientially on real building sites (Fernando et al., 2016; Jayawardena et al., 2007). For example, a labour market survey by Jayawardhana and Gunawardhana (1998) suggests that 86% of the local construction workers have entered the industry through informal channels and only gained informal training in a process characterised by ad-hoc on-site learning, poor discharge of skills, and the absence of regulations in practice.

Be that as it may, the urge to pursue on-site construction training in developing economies such as Sri Lanka seems obvious, given the prospective workers' socio-economic challenges, cultural difficulties in undergoing formal learning, the inflexibility of the formal training programs themselves, and the general lack of alternative employment choices. This creates a never-ending demand for on-site training in the construction industry, regardless of whether it has been implemented by choice or by default. It is, therefore, evident that any form of restructuring of construction worker training must consider the possibilities for on-site training, acknowledging its known benefits as a successful training model while overcoming its apparent failures in knowledge construction. The starting point for such an approach naturally lies in how much building professionals can support on-site training, not only ideologically and administratively yet design-wise, by designing real building projects to accommodate the technical volatility of on-the-job labor upskilling.

5. METHODOLOGY AND BUILDING UP THE THEORY

In endeavouring to define 'design tolerance' as applicable to architectural design that values and supports on-site labour training, this study took up a two-tier approach: a literature review and a case-study review. To that end, the ideas and information gathered from the literature review were critiqued, analysed, amended, advanced, and verified through the review of a case-study project, which has been developed to transfer skills during the on-site building process. Subsequently, 13 design tactics attributing to the idea of 'design tolerance' have been derived through a lengthy cross-examination between the literature and case-study findings and semi-structured questionnaires posed to the workers (construction labour) and architects (design labour) of the case-study project. Due to the space limitations of this paper, the outcome of this entwined two-tier approach: i.e., the 13 design tactics-is presented as a singular framework with brief examples extracted from the case study project.

The project subjected to the study concerned building two sanitary blocks for a public school in Kandy, one of Sri Lanka's major urban centres located in the central highlands. Designed by the local architectural firm Robust Architecture Workshop (RAW), co-directed by one of the authors of this paper, the sanitary blocks were part of a larger project aimed at providing social infrastructure to a physically derelict, socially neglected, economically challenged, and institutionally maltreated public school system. Due to the project's financial constraints, a team of volunteer Air Force soldiers was appointed to provide construction labour in masonry, carpentry, and steel work, thus requiring upskilling on the site to meet the targeted formal and environmental expectations of the building outcome.

In organising the theoretical framework for 'design tolerance', the study emphasised 'building' as both a noun and a verb – i.e., a product and a process. As a noun, 'building' is a product that consumes capital and labour to transfer wealth from one form to another (Groak, 1992); a physical representation of several interdependent systems and sub-systems that, using joints and details, must be connected, coordinated, and integrated with the building's overall three-dimensional form and spatial structure (Ching, 2008). On the other hand, Turin (2003), for example, emphasises the dynamic process that shapes building as an activity, which focuses on assembling inputs or resource flows; such as materials, knowledge, and labour. In such a definition of 'building' as a verb, the roles of the participants and their changing relationships are also included as critical to the success of the final product (ibid). Following this dual comprehension of 'building' as a product and a process, the framework on 'design tolerance' was deemed necessary to organise under three categories: (i) tolerance by the system, (ii) tolerance by detail, and (iii) tolerance by procurement.

6. STRATEGIES OF DESIGN TOLERANCE

6.1 TOLERANCE BY SYSTEM

Under 'tolerance by system', the design of building systems and components to withstand unexpected technical deviations to their formal, dimensional, and organisational conditions have been considered. To that end, it becomes important to design building systems and components with a greater level of clarity and intelligibility in their technical formation while imparting an adequate level of technical complexity to trigger the training needs. This objective forms the first principle identified under 'tolerance by system': *complexity by completing - clarity in the making (DTS-01)* (Refer to Figure 1).

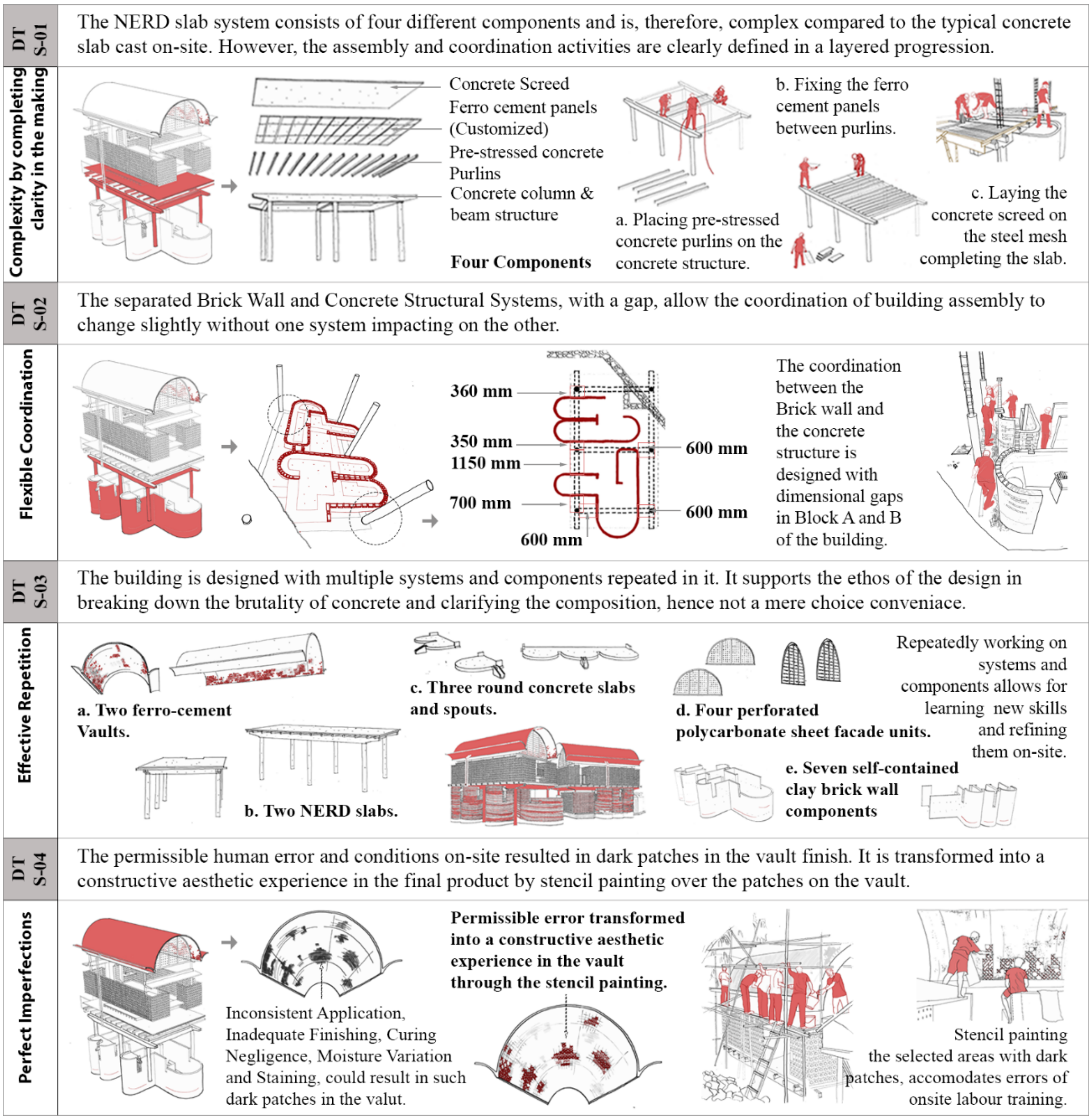


Figure 1: Building example - tolerance by system

Secondly, a degree of *flexible coordination (DTS-02)* between building systems, sub-systems, and components must be established so that their assembly on site can accommodate unexpected and varying site conditions without resulting in performative failures (refer to Figure 1).

Thirdly, the architectural design must strategically involve replication of the systems and sub-systems without subjecting negatively to economic or experiential effectiveness, as repetition and intensification of activities support gradual skill improvement on-site *(effective repetition-DTS-03)* (Refer to Figure 1).

Fourthly, to accommodate unavoidable human error, formal imperfections of the final product must be acknowledged and, where possible, celebrated by making them opportunistically part of the intended design ethos *(perfect imperfections-DTS-04)* (refer to Figure 1).

6.2 TOLERANCE BY DETAIL

'Tolerance by detail' focuses on achieving technical tolerance when two components are joined. The first principle acknowledged under this theme; 'loose fit', calls for joints to be 'fit' to achieve a given performative attribute while being 'loose' enough to accommodate slight changes in sizes, dimensions, and technical imperfections. Thus, it caters to the need for components and systems to be installed with a capacity to endure dimensional fluctuations in their positioning and laying (Refer to Figure 2).

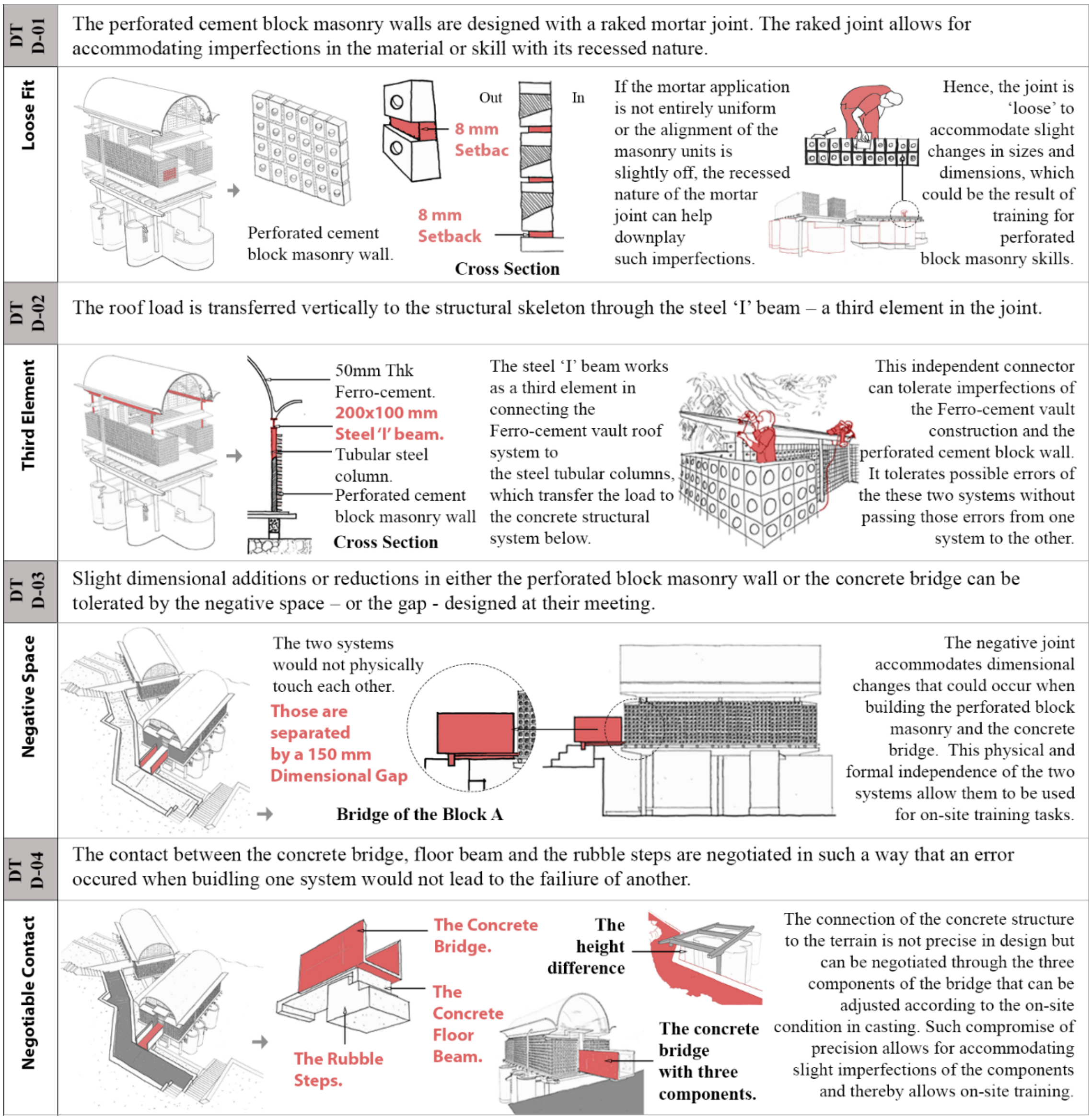


Figure 2: Building example - tolerance by detail

Secondly, when joining two components or systems, a *Third element (DTD-02)* can be used as a tolerance mediator to house various imperfections of the first two systems/components (refer to Figure 2).

Thirdly, instead of detailing two components or systems as a direct physical touch between them, their meeting can be planned as a separation by a gap so that the space in-between could take up any unforeseen addition or reduction of dimensions between the two *(Negative space-DTD-03)* (refer to Figure 2).

Fourthly, and partly related to the first principle (loose fit), adequate provision must be kept for unforeseen on-site changes through possible technical negotiations at the point of joining different systems or components together. This principle is identified as *Negotiable contact (DTD-04)*. While 'loose fit' refers to achieving a level of technical flexibility when 'fitting' one component within the space of another, thereby requiring the first component to accommodate a specific design configuration to facilitate such technical suppleness, the 'negotiable contact' calls for both components to traverse the unforeseen technical variations at the point of their contact (refer to Figure 2).

6.3 TOLERANCE BY PROCUREMENT

The third subset of the theoretical framework posited here; 'tolerance by procurement', looks at how a level of technical and cultural tolerance to accommodate pressures of on-site training can be imparted at the level of organising and strategising the building process. To that end, it becomes essential to seek the contribution of all actors throughout the on-site construction work, not only in their predefined roles or limited stages, thus demanding everyone to work collaboratively as a team on-site. Accordingly, *Collaborative work (DTP-01)* furnishes the first principle acknowledged under 'tolerance by procurement' and such a collection of means by human resources could support finding unique design solutions against various on-site challenges (refer to Figure 3).

Secondly, architects' *On-site engagement (DTP-02)* must be direct and effective in acknowledging, accepting, and interpreting unforeseen on-site changes without penalising the anticipated design ethos (refer to Figure 3).

Thirdly, architectural projects must be procured with flexible resource flows supported by well-established technical and cultural links between all actors involved (including suppliers and manufacturers) to enrich the project's resource base and help it grow organically while accommodating unforeseeable changes and requirements during the construction phase *(Organic links-DTD-03)* (refer to Figure 3). In addition, architectural practice must cultivate working relationships with actors already involved in the formal training of construction workers, such as industry development authorities and technical colleges, to seek their input when implementing upskilling programs on site.

Fourthly, industrial practices must be adjusted according to the specific project context; economic, technical, environmental, and cultural, to bring out alternative design and building solutions instead of always conforming to popular and pre-defined material and resource practices *(Industrial adaptability-DTP-04)* (Refer to Figure 3).

Fifthly, it is imperative to follow a *Robust design language (DTP-05)* that does not overly depend on the perfection of singular elements but on the appropriateness of the overall composition and construction, where the assembly, formation, and coordination between systems, sub-systems, and components are organised with latitude for errors and non-optimal application (refer to Figure 3).

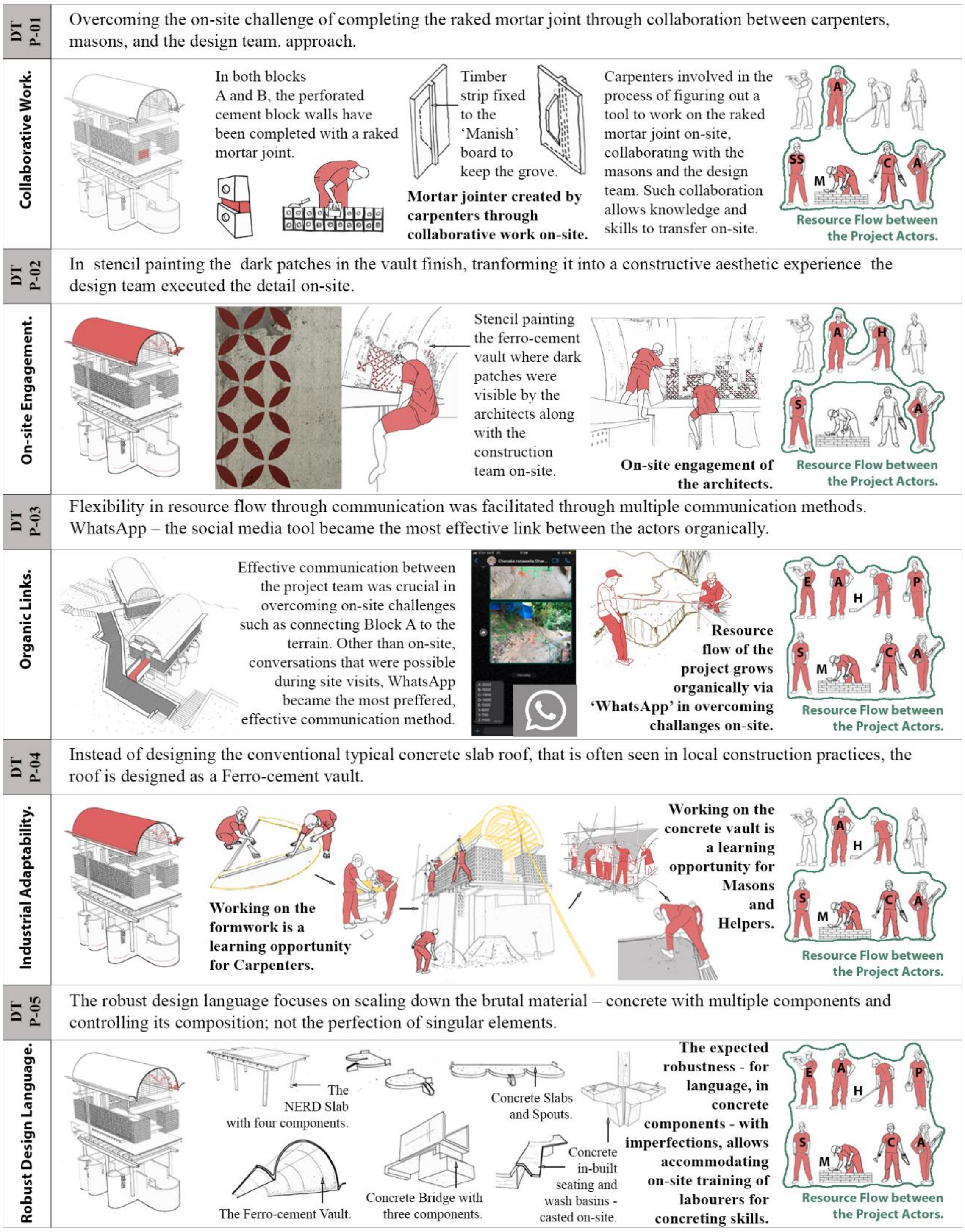


Figure 3: Building example - tolerance by procurement

7. CONCLUSIONS

The framework on 'design tolerance' presented in this paper is built on redefining architectural design's role in supporting the on-site labour training needs of the construction industry, especially in developing economies (refer to Table 1). As a theoretical construction, the first two categories of this framework; i.e., 'tolerance by system' and 'tolerance by detail', identify eight design principles in enabling building systems, sub-systems, components, and details to compromise their precision to accommodate permissible errors without penalising the performative attributes of the building artefact. The third subset i.e.; 'tolerance by procurement', focuses on building as a process emphasising flexible sourcing and managing resources.

Table 1: Theoretical framework- design tolerance for on-site labour training

		Design principles		
Designing for tolerance	**Tolerance by System**	1.	Complexity by completing; clarity in the making.	**Building as a product**
		2.	Flexible Coordination.	
		3.	Effective Repetition.	
		4.	Perfect Imperfections.	
	Tolerance by Detail	5.	Loose Fit.	
		6.	Third Element.	
		7.	Negative Space.	
		8.	Negotiable Contact.	
	Tolerance by Procurement	9.	Collaborative Work.	**Building as a process**
		10.	On-site Engagement.	
		11.	Organic Links.	
		12.	Industrial Adaptability.	
		13.	Robust Design Language.	

However, for such a framework to successfully disseminate on-site labour training as a formal strategy, it must draw professional interest, discursive acceptance, and institutional support.

8. ACKNOWLEDGEMENTS

The data collection for the case study was supported by the Robust Architecture Workshop (RAW), specifically by design team members Sajeewa Mendis and Sajith Sivayogaraj.

9. REFERENCES

Bates, S., & Sergison, J. (1999). Working with tolerance. *Architectural Research Quarterly*, *3*(3), 220–234. https://doi.org/10.1017/S1359135500002050

Baudoin, G. (2016). A matter of tolerance. *The Plan Journal*, 33–46. https://doi.org/10.15274/tpj-2016-10004.

Ching, F. D. (2008). *Building construction illustrated* (4th ed.). John Wiley & Sons.

Clarke, L., & Wall, C. (1998). UK construction skills in the context of European developments. *Construction Management and Economics*, *16*(5), 553–567. https://doi.org/10.1080/014461998372097.

Coomaraswamy, A. K. (1956). *Medieval Sinhalese art*: *Being a monograph on mediaeval Sinhalese arts & crafts, mainly as surviving in the eighteenth century, with an account of the structure of society*. White Lotus Press. New York.

Dundar, H., Millot, B., Savchenko, Y., Aturupane, H., & Piyasiri, T. A. (2014). Cost and financing of technical and vocational education and training. In *Building the skills for economic growth and competitiveness in Sri Lanka.* (pp. 107-151). Directions in Development- Human Development, Washington, DC: World Bank Group. https://doi.org/10.1596/978-1-4648-0158-7_ch5

Fernando, P. G. D., Fernando, N., & Gunarathna, M. A. C. L. (2016). Skills developments of labourers to achieve the successful project delivery in the Sri Lankan construction industry. *Civil and Environmental Research*, *8*(5), 86–97. https://nrl.northumbria.ac.uk/id/eprint/31127/3/30376-33213-1-PB.pdf.

Groak, S. (1992). *The idea of building*: *Thought and action in the design and production of buildings* (*1st ed.)* Taylor & Franscis: London.. https://doi.org/10.4324/9780203133781

Harper, D. (2024). Precision (n.). In *Online etymology dictionary*. https://www.etymonline.com/search?q=precision.

Hoad, T. (1996). *The concise Oxford Dictionary of English etymology*. Oxford University Press. http://doi.org/10.1093/acref/9780192830982.001.0001

Hornby, A. S. (2005). *Oxford advanced learner's Dictionary of current English* (7th ed.). Oxford University Press.

Hughes, F. (2014). *The architecture of error: Matter, measure, and the misadventures of precision*. The MIT Press Cambridge, Massachusetts.

Jayawardane, A. K. W., & Gunawardena, N. D. (1998). Construction workers in developing countries: A case study of Sri Lanka. *Construction Management and Economics*, *16*(5), 521–530.

Jayawardena, H. K., Senevirathne, K., & Jayasena, H. S. (2008). Skilled workforce in Sri Lankan construction industry : Production vs acceptance. In *Proceedings of the CIB International Conference on Building Education and Research, Heritance Kandalama, Sri Lanka,* 11-15 February 2008. (pp 82-83). CIB Task Groups 53 and 63.

Lawson, B. R. (1972). *Problem solving in architectural design* [Unpublished doctoral dissertation]. Aston University, Birmingham, UK.

Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2022). Labour- related factors affecting construction productivity in Sri Lankan building projects: Perspectives of engineers and managers. *Frontiers in Engineering and Built Environment*, *2*(4), 218–232. https://doi.org/10.1108/FEBE-03-2022-0009

McVicar, M. (2016). *Precision in Architectural Production*. Cardiff University.

Pathiraja, M. (2010). *The idea of "robust technology" in the definition of a'third-world' practice: Architecture, design and labour training* [Unpublished doctoral dissertation]. The University of Melbourne.

Pathiraja, M., & Tombesi, P. (2009). Towards a more ' robust ' technology ? Capacity building in post-tsunami Sri Lanka. *Disaster Prevention and Management*, *18*(1), 1206–1218. https://doi.org/10.1108/09653560910938547.

Pathiraja, M., & Tombesi, P. (2023). Circularity by stock in Sri Lanka: Economic necessity meets urban fabric renovation. *Frontiers in Built Environment*, *8*(January), 1–19.

Silva, G. A. S. K., Warnakulasuriya, B. N. F., & Arachchige, B. J. H. (2018). A review of the skill shortage challenge in construction industry in Sri Lanka. *International Journal of Economics, Business and Management Research*, *2*(1). 75-89.

Taron, J. (2016). *Critical tolerance*. Offramp. https://offramp.sciarc.edu/articles/critical-tolerance#:~:text=Agaphasemergedbetween,automatedimagingofthecity.

Till, J. (2009). *Architecture depends*. The MIT Press Cambridge, Massachusetts.

Turin, D. A. (2003). Building as a process. *Building Research & Information*, *31*(2), 180–187.

UNESCO-UNEVOC International Centre for Technical and Vocational Education and Training. (2018). *TVET country profile, Sri Lanka*. https://unevoc.unesco.org/wtdb/worldtvetdatabase_lka_en.pdf

Zande, R. (2006). The design process of problem solving. *Academic Exchange Quarterly*, *10*(4), 150–154.

Divaneth, D.R., Mapa, M.M.I.S., Konara, G. and Samarakoon, W.K.U.R.M.K.P.K., 2024. Enhancing data security in smart buildings leveraging blockchain technology. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 435-445. DOI: https://doi.org/10.31705/WCS.2024.34. Available from: https://ciobwcs.com/papers/

ENHANCING DATA SECURITY IN SMART BUILDINGS LEVERAGING BLOCKCHAIN TECHNOLOGY

D. Rashmitha Divaneth[1], M.M.I.S. Mapa[2], Gayani Konara[3], and W.K.U.R.M.K.P.K. Samarakoon[4]

ABSTRACT

This article investigates the use of blockchain technology to improve data security in smart buildings, addressing the growing vulnerabilities caused by the interdependence of IoT devices. The paper thoroughly examines the existing issues and limitations of traditional security solutions in smart buildings. Through a comprehensive literature review and qualitative analysis, this research identifies decentralisation, cryptographic mechanisms, transparency, and distributed ledger technology as core features of blockchain that can significantly improve data security and confidentiality in smart buildings. This paper qualitatively assesses the importance of the identified blockchain features which enhance data security in the context of smart buildings aiming to create a secured system environment that enhances data security and prevents unauthorised access. The methodology employs a qualitative approach, including semi-structured interviews with industry experts and data analysis, to validate the effectiveness of the identified blockchain features. According to the findings, blockchain not only improves data transaction security yet nurtures a resilient infrastructure to meet the changing demands of smart building management. The study contributes to academic literature and provides practical insights for professionals looking to adopt blockchain-based security solutions in smart buildings, with implications for legislation and future research paths.

Keywords: *Blockchain Technology; Data Security; Internet of Things; Smart Buildings.*

1. INTRODUCTION

As digitisation progresses, smart buildings have emerged as integral components of the Internet of Things (IoT) revolution, blending sophisticated technologies such as sensors, automation, and data analytics within a cyber-physical-social system to enhance efficiency, comfort, and management (Brad & Murar, 2014). These buildings transform traditional architectures into responsive, interconnected hubs that employ extensive IoT

[1] Undergraduate, Department of Building Economic, University of Moratuwa, Sri Lanka, dilanikaneshapalan@gmail.com
[2] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, isuru.mapa@uom.lk
[3] Lecturer, Ritsumeikan University, Japan, gy_kaushi@yahoo.com
[4] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, samarakoonk@uom.lk

devices to optimise various functions. However, this increased connectivity and reliance on networked systems introduce potential security vulnerabilities.

The integration of numerous IoT devices in smart buildings heightens risks such as unauthorised access, data breaches, and other cyber threats that could compromise sensitive information. Such vulnerabilities may lead to significant financial losses, privacy invasions, and even physical harm (Nawari & Ravindran, 2019). Traditional security measures such as encryption protocols and firewalls often fall short due to their centralised nature, which creates single points of failure and exposes systems to sophisticated cybercriminals (Alshahrani, 2021). Amidst these challenges, blockchain technology emerges as a promising solution to bolster data security in smart buildings. Originally developed for digital currencies such as Bitcoin, blockchain offers a decentralised and irreversible ledger system that can significantly secure data transactions and storage (Nehe & Jain, 2019). Its key features are decentralisation, cryptographic hashing, and consensus-based validation for a robust framework for secure, transparent management of building operations and data.

Blockchain ensures tamper-proof records and enhances data integrity by distributing data across a network, thus eliminating single points of failure, and reducing susceptibility to cyberattacks. Its cryptographic protocols enable secure, peer-to-peer transactions and data exchanges, minimising the risks associated with centralised data storage systems. The transparency and immutability of blockchain increase trust and accountability in digital interactions within smart buildings (Ramachandran & Kantarcioglu, 2017). Equipped with blockchain, smart buildings can leverage automated smart contracts to facilitate secure and efficient property management tasks, access control, and energy transactions. These contracts execute automatically based on pre-set rules and conditions, ensuring only authorised entities and devices can operate within the network, thereby bolstering security (Nanayakkara et al., 2021).

However, implementing Blockchain in smart buildings presents challenges such as scalability, interoperability with existing systems, and the energy consumption of blockchain operations, particularly those using proof-of-work consensus mechanisms (Krishnamurthi & Shree, 2021). These challenges necessitate collaborative efforts between blockchain developers, cybersecurity experts, and building management professionals to design solutions that are both effective and sustainable.

This research addresses the vulnerability of IoT-based smart buildings to cyberattacks due to their interconnectedness and the insufficiency of traditional security measures. The main objectives are to review literature on smart buildings, data security, and blockchain technology, and to identify key blockchain characteristics that enhance data security in smart buildings through expert opinions. The study aims to provide valuable insights for researchers and industry professionals on which blockchain features should be prioritised for developing secure systems in smart buildings. Additionally, it seeks to inform policymakers about blockchain's capabilities, promoting its integration into smart building infrastructures to enhance data security. Through analysis and application of blockchain technology, this paper seeks to demonstrate how the convergence of smart building technology and blockchain can lead to more secure, efficient, and user-centric building environments.

2. LITERATURE REVIEW

2.1 DATA SECURITY

Data security involves safeguarding digital data from unauthorised access, corruption, or theft at every phase of its lifecycle. This includes a range of protective measures aimed at maintaining the confidentiality, integrity, and availability of data (Tellenbach et al., 2019). The scope of data security covers a broad spectrum of information protection activities. These activities include protecting physical hardware and storage devices, implementing administrative controls, setting access restrictions, and integrating logical security mechanisms within software applications (Yang et al., 2020). Additionally, organisational policies and procedures are vital in strengthening the overall framework of information security (Yang et al., 2020).

The CIA Triad, comprising confidentiality, integrity, and availability, significantly shapes the criteria for data security. Anand et al. (2020) describe how these three fundamental properties, encapsulated by the CIA Triad, have historically provided the foundation for defining the parameters of data security. Data confidentiality ensures that information is only accessible to those who are allowed to view it, preventing unlawful disclosure. Data integrity is concerned with ensuring that data is accurate and reliable and that it has not been tampered with. Finally, data availability ensures that authorised users may access information when it is required, allowing for smooth and ongoing access.

2.2 DATA SECURITY IN SMART BUILDINGS

The necessity for robust data security in smart buildings is underscored by their reliance on interconnected systems to perform essential operations. The integration of new protocols complicates security frameworks, necessitating comprehensive measures to protect these environments (Ciholas et al., 2019). In contemporary smart buildings, the widespread use of IoT devices and wireless technologies introduces new vulnerabilities to cyber threats. These buildings generate and process extensive data volumes to enhance efficiency but raise concerns regarding data privacy and the potential for unauthorised access or misuse of sensitive information (Ciholas et al., 2019). Additionally, the challenge of managing vast data collections in smart cities can lead to compromised privacy if not properly governed (Li et al., 2016). Moreover, research by Harper et al. (2022) highlights a significant gap in residents' understanding of data collection practices in smart buildings, impacting their privacy. This lack of awareness underscores the urgent need for clearer policies and regulations to protect the privacy of building occupants (Harper et al., 2022).

2.3 BLOCKCHAIN TECHNOLOGY (BCT)

Blockchain technology has revolutionised various industries by offering a decentralised, transparent, and secure method for recording transactions and managing data. Initially developed for Bitcoin, its foundational principles rely on consensus mechanisms and cryptographic techniques to ensure data confidentiality and integrity without a central authority (Nanayakkara et al., 2021; Perera et al., 2020). Beyond cryptocurrencies, blockchain has significant applications in fields such as smart contracts, financial services, healthcare, and education, demonstrating its transformative potential (Beck et al., 2017).

Blockchain's influence extends to sectors such as supply chain management, healthcare, and voting systems, where it provides a secure framework that enhances transparency and promotes innovation (Krichen et al., 2022). However, as blockchain technology evolves, it faces challenges such as scalability, transaction latency, and energy consumption, particularly with Proof of Work processes (Krichen et al., 2022). Ongoing development of alternative consensus mechanisms such as Proof of Stake highlights the technology's adaptability and commitment to overcoming these limitations, supporting sustainable growth and continued innovation across various fields.

2.4 CURRENT APPLICATION OF BLOCKCHAIN TECHNOLOGY

Blockchain technology has evolved beyond Bitcoin, significantly impacting various industries. In finance, it enhances transparency and efficiency in international transactions, reducing costs and boosting security (Krichen et al., 2022). Its influence extends to supply chain management, increasing traceability, reducing fraud, and ensuring product authenticity (Zhu et al., 2020). In the legal and corporate sectors, Blockchain deploys smart contracts to automate processes and streamline operations (Nanayakkara et al., 2021).

Beyond cryptocurrencies, Blockchain transforms financial services by enabling real-time transaction processing and improving fraud protection. For instance, it streamlines financial processes and lowers costs through smart contracts (Polyviou et al., 2019). In healthcare, Blockchain enhances the management of Electronic Health Records (EHRs), protects data and patient privacy, and expedites insurance claims and fraud detection (Angraal et al., 2017). In the industrial sector, blockchain supports Industry 4.0 and the Industrial IoT, improving data quality and security across complex networks. Logistics benefit from real-time tracking and administration of goods and materials (Alladi et al., 2019). Blockchain's adaptability and decentralised nature make it a powerful tool for modernising operations across various fields, promising a future where it is integral to global business and governance strategies.

2.5 BLOCKCHAIN TECHNOLOGY IN THE CONTEXT OF SMART BUILDINGS

Extensive research has explored blockchain's application in smart buildings, particularly its effectiveness in managing smart grid operations, as noted by studies by Alladi et al. (2019). This technology significantly enhances security and privacy through smart contract services in IoT-enabled urban environments, supporting activities such as secure e-voting systems which bolster the security framework of smart cities (Rahman et al., 2020). Blockchain also protects data integrity by preventing unauthorised access or modifications to crucial information systems, overseeing access control, surveillance, and environmental monitoring (Li et al., 2019). Moreover, it streamlines and automates transactions within smart buildings, reducing administrative costs and ensuring the timely execution of maintenance contracts, thereby improving operational efficiency (Nanayakkara et al., 2021). These diverse applications highlight Blockchain's role in transforming urban infrastructure through the integration of advanced technologies in smart buildings.

2.6 FEATURES OF BLOCKCHAIN TECHNOLOGY IN THE CONTEXT OF SMART BUILDINGS

Blockchain technology is revolutionising data management across various industries with its decentralised architecture, enhancing security and efficiency in smart buildings. Key features include:

I. Decentralisation: Distributes data across a network, reducing dependency on central authorities and mitigating risks of centralised system failures (Khalid et al., 2023; Mingxiao et al., 2017).

II. Cryptographic Mechanisms: Employs advanced encryption and hashing to secure data, enhancing confidentiality and preventing data breaches (Ahubele & Musa, 2022; Raikwar et al., 2019).

III. Consensus Mechanisms: Facilitates agreement among network nodes to validate transactions, ensuring data accuracy and trust (Kassab, 2021).

IV. Transparency: Provides clear, verifiable records of transactions while maintaining user privacy, which enhances trust and compliance (Afanasyev et al., 2020).

V. Distributed Ledger: Maintains data consistency and availability even if some nodes are compromised (Karaarslan & Konacakli, 2020).

VI. Immutability: Prevents data alteration after recording, providing a strong defence against tampering and enhancing transaction reliability (Ratta et al., 2021).

VII. Interoperability: Interoperability in blockchain enhances data security by enabling secure data exchange across blockchain systems, protecting data integrity and reducing security breaches through decentralisation (Khalid et al., 2023).

These features underscore Blockchain's potential to enhance security protocols and operational efficiency in smart building environments, supporting data management systems against a variety of threats and failures.

3. RESEARCH METHODOLOGY

To enhance data security in smart buildings using Blockchain technology, characteristics of Blockchain technology which aid in enhancing data security were identified based on existing literature. Qualitative research tools are used to extensively study and understand human experiences and social phenomena, capturing expressive aspects that quantitative methods may miss (Busetto et al., 2020).

Initially, a comprehensive review of the literature was carried out to understand the key concepts, such as Blockchain technology, smart buildings, and data security. A comprehensive analysis of some sub-elements, such as features and the evolution of Blockchain technology, was adequately addressed in this piece of work.

To gather data for the analysis, semi-structured interviews were conducted with four industry experts specialising in data security within the information technology sector, guided by a structured interview protocol. The aim was to collect expert opinions on each Blockchain characteristic identified in the literature and to pinpoint the most significant features of blockchain technology that could enhance data security in the context of smart buildings by conducting a thematic analysis. Interviews were conducted with four interviewees, selected for their expertise in the data security sector and their managerial or higher roles. The number of interviews was limited to four due to the extreme scarcity of experts in the data security sector who are knowledgeable about Blockchain technology in Sri Lanka (refer to Table 1).

Table 1: Interviewee profile

Respondent	Profession	Designation	Expertise	Experience in the industry
I01	Managed Security Services	Analyst	Information Security/Blockchain	4 years
I02	Information Security	Engineer	Information Security	5 years
I03	Information Security	Engineer	Information Security	5 years
I04	Cloud Technologies	Project Manager	Data security/Blockchain	8 years

4. RESEARCH FINDINGS AND RESULTS

4.1 THEMATIC ANALYSIS

Information derived from the expert interviews with data security experts allowed for the classification of each variable identified through literature. The interview guideline was developed based on the characteristics of Blockchain identified as related to enhancing data security in smart buildings. The questions were structured to obtain the interviewees' opinions on the importance of each identified characteristic in enhancing data security within the context of smart buildings. The interviewees rated the importance of each variable as Highly Important, Moderately Important, and Less/Not Important. A thematic analysis was then conducted, treating these identified characteristics as themes.

Table 2 represents the opinions of the interviewees regarding the importance of each blockchain technology characteristic to enhance data security in smart buildings (Interviewees are denoted as IO1, IO2, IO3 and IO4).

Table 2: Importance of blockchain technology characteristics

Themes	I01	I02	I03	I04
Decentralisation	✔	✔	✔	✔
Cryptography Mechanisms	✔	✔	✔	✔
Transparency	✔	✔	✔	✔
Distributed Ledger Technology	✔	✔	✔	✔
Immutability	○	○	✕	✔
Consensus Mechanisms	○	✔	○	○
Interoperability	○	✕	✕	✕

Highly Important ✔ Moderately Important ○ Not /Less Important ✕

4.2 RESULTS AND DISCUSSION

The opinions of each interviewee on the importance of the identified blockchain characteristics are summarised in Table 2.

Decentralisation is unanimously recognised by interviewees as a pivotal feature for enhancing security in smart buildings. As I01 and I02 emphasize, decentralisation distributes control across the network, thus increasing robustness and reliability ("*... decentralisation is a critical feature of Blockchain to increase system security and stability," I01; "...decentralisation in smart buildings is extremely important,"* I02). This view is also supported by literature indicating that decentralisation minimises vulnerabilities and dependency on central authorities (Khalid et al., 2023; Mingxiao et al., 2017; Nawari & Ravindran, 2019).

Cryptography is vital for ensuring the security of data within smart building systems, as acknowledged by all interviewees. Techniques such as encryption help maintain the confidentiality, integrity, and authenticity of transactions, making cryptographic mechanisms indispensable ("*...cryptography in my opinion contributes greatly to security*," I02). The literature reinforces this perspective, highlighting the role of cryptographic algorithms in developing secure systems and the foundation they provide for preserving data security (Leng et al., 2022; Ahubele & Musa, 2022; Raikwar et al., 2019; Zhang et al., 2020).

Transparency is heralded for its role in enhancing data security and trustworthiness within systems, particularly when balanced with privacy. Interviewees argue that transparency fosters accountability and trust while protecting sensitive information ("*...transparency offered by blockchain makes the system a lot more trustworthy and secure*," I04). The literature suggests that transparency can improve data security and trustworthiness by developing accountability, although it raises privacy concerns (Afanasyev et al., 2020; Lu et al., 2021).

DLT is recognised for its significant impact on enhancing data security by distributing the ledger across a network, effectively reducing unauthorised access and data tampering ("*...blockchain's distributed ledger feature is a game-changer for data security in smart buildings*," I04). Literature corroborates the efficacy of DLT in syncing across the network and minimising data tampering threats, underscoring its crucial role in protecting against cyberattacks (Karaarslan & Konacakli, 2020; Lyu et al., 2023).

Immutability is valued for its role in maintaining a tamper-resistant record of transactions, crucial for data integrity and trust. It is considered a sub-feature of the distributed nature of blockchain that enhances security by reducing data tampering ("*The immutability characteristic of Blockchain technology significantly impacts the security of data*," I04). This characteristic aligns with the consensus that immutability ensures data remains unchanged and secure. These insights highlight immutability as a sub-feature in the distributed nature of Blockchain, maintaining a tamper-resistant record of transactions, crucial for data integrity and trust.

Consensus mechanisms are highlighted for their critical role in validating transactions, indirectly contributing to data security. They are essential for maintaining the integrity and reliability of the network, as they validate and secure transactions across Blockchain systems ("*...consensus mechanism plays a crucial role in preserving the integrity and reliability of the network*," I03). Literature supports this by showing how consensus mechanisms, such as Proof of Work and Proof of Stake, are pivotal in ensuring data privacy and network security (Kassab, 2021; Wei et al., 2021; Yassein et al., 2019). These viewpoints identify consensus mechanisms as an indirect contribution of consensus procedures to improved data security in smart buildings.

Interoperability is discussed with varied opinions on its direct impact on data security. It is recognised for enhancing the functionality and quality of Blockchain technologies, facilitating wider adoption, though not necessarily boosting data security directly ("*...it's more of a feature that enhances the quality of what Blockchain offers*," I04). The literature notes interoperability's importance for Blockchain development and acceptance yet points to potential security vulnerabilities (Domingo-Ferrer et al., 2022).

The findings indicate that decentralisation, cryptographic mechanisms, transparency, and distributed ledger characteristics were identified as the most important factors for enhancing data security in smart buildings by four interviewees. These insights underscore immutability as a sub-feature inherent in the distributed nature of Blockchain, maintaining a tamper-resistant record of transactions essential for data integrity and trust. Consensus mechanisms were identified as a characteristic indirectly contributing to improved data security in smart buildings, while interoperability was considered a characteristic that does not have a direct impact on enhancing data security in smart buildings.

5. CONCLUSIONS

This research focuses on a complete exploration of the applicability of Blockchain technology in enhancing data security within the context of smart buildings, motivated by the significant vulnerabilities presented by modern interconnected systems. The study thoroughly identified and analysed various characteristics of Blockchain that could be leveraged to fortify the security frameworks of smart buildings, effectively countering the cyber threats that these advanced infrastructures face. Among these characteristics, industry experts emphasised decentralisation, cryptographic techniques, transparency, and distributed ledger technology as important for establishing a robust defence against the variety of security challenges frequently encountered today.

Decentralisation emerged as a prominent feature, crucial for mitigating risks associated with centralised data control, which often leads to single points of failure. By dispersing data across a network, blockchain reduces the impact of cyber-attacks and enhances system resilience. Cryptographic mechanisms protect sensitive information from unauthorised access with robust encryption. This not only secures data transactions yet maintains confidentiality within smart buildings. Transparency, another significant attribute of Blockchain, fosters trust and accountability in transactions. Blockchain enables traceable and verifiable record-keeping, crucial in environments where data integrity and auditability are key. Its immutable nature ensures that records cannot be altered without consensus, preventing tampering and enhancing reliability. Distributed ledger technology supports this by maintaining data consistency and availability, ensuring system functionality even if parts of the network are compromised.

The integration of these Blockchain characteristics into smart building management not only secures data transactions yet introduces efficiency in operations through automated processes such as smart contracts, which execute tasks based on predefined rules and agreements without human intervention. This automation potential, coupled with enhanced security features, points towards a transformative shift in how building management systems operate, making them more secure, efficient, and user-centric.

In conclusion, the application of Blockchain in smart buildings presents a promising avenue to address the complex security and operational challenges posed by the digital era. By adopting Blockchain, stakeholders in the smart building sector can ensure a more secure, transparent, and efficient management system, thereby safeguarding both data and infrastructure. Future research should continue to explore and refine Blockchain applications in this field, focusing on scalability, energy efficiency, and integration with existing technologies, to fully realise its potential in enhancing smart building environment.

This study is limited by the possibility of response bias due to how data collection was conducted. Since the technology itself is very new, different respondents might have different views and understandings, leading to varied responses. The limitations of such methods can be overpowered in future studies by taking more stringent and varied data collection methods that would take measures to reduce response bias, along with increasing the levels of awareness and education regarding Blockchain technology, ensuring a more informed and consistent set of responses from participants.

6. REFERENCES

Afanasyev, V. Y., Lyubimova, N. G., Ukolov, V. F., & Shayakhmetov, S. R. (2020). Impact of blockchain technology for modification of the supply chain management in energy markets. *International Journal of Supply Chain Management*, *9*(3), 757-762. https://download.garuda.kemdikbud.go.id/article.php?article=1730561&val=13549&title=impact%20of%20blockchain%20technology%20for%20modification%20of%20the%20supply%20chain%20management%20in%20energy%20markets

Ahubele, B. O., & Musa, M. O. (2022). Towards a scalable and secure blockchain based on post-quantum cryptography. *International Journal of Advanced Research in Computer and Communication Engineering*, *11*(7). https://doi.org/10.17148/ijarcce.2022.11703

Alladi, T., Chamola, V., Parizi, R. M., & Choo, K. R. (2019). Blockchain applications for Industry 4.0 and industrial IoT: A review. *IEEE Access*, *7*, 176935–176951. https://doi.org/10.1109/access.2019.2956748

Alshahrani, M. M. (2021). Secure multifactor remote access user authentication framework for IoT networks. *Computers, Materials & Continua*, *68*(3), 3235–3254. https://doi.org/10.32604/cmc.2021.015310

Anand, P., Singh, Y., Selwal, A. K., Alazab, M., Tanwar, S., & Kumar, N. (2020). IoT vulnerability assessment for sustainable computing: Threats, current solutions, and open challenges. *IEEE Access*, *8*, 168825–168853. https://doi.org/10.1109/access.2020.3022842

Angraal, S., Krumholz, H. M., & Schulz, W. L. (2017). Blockchain technology. *Circulation. Cardiovascular Quality and Outcomes*, *10*(9). https://doi.org/10.1161/circoutcomes.117.003800

Beck, R., Avital, M., Rossi, M., & Thatcher, J. B. (2017). Blockchain technology in business and information systems research. *Business & Information Systems Engineering*, *59*(6), 381–384. https://doi.org/10.1007/s12599-017-0505-1

Busetto, L., Wick, W., & Gumbinger, C. (2020). How to use and assess qualitative research methods. *Neurological Research and Practice*, *2*(1). https://doi.org/10.1186/s42466-020-00059-z

Ciholas, P., Lennie, A., Sadigova, P., & Such, J. M. (2019, January 17). *The Security of Smart Buildings: a Systematic Literature Review*. arXiv.org. http://arxiv.org/abs/1901.05837

Domingo-Ferrer, J., Blanco-Justicia, A., Manjon, J., & Sanchez, D. (2022). Secure and privacy-preserving federated learning via co-utility. *IEEE Internet of Things Journal*, *9*(5), 3988–4000. https://doi.org/10.1109/jiot.2021.3102155

Harper, S., Mehrnezhad, M., & Mace, J. (2022). User privacy concerns in commercial smart buildings1. *Journal of Computer Security*, *30*(3), 465–497. https://doi.org/10.3233/jcs-210035

Karaarslan, E., & Konacaklı, E. (2020). Data storage in the decentralized world: Blockchain and derivatives. *User Privacy Concerns in Commercial Smart Buildings*, 37–69. https://doi.org/10.26650/b/et06.2020.011.03

Kassab, M. (2021, September 20-24). *Exploring non-functional requirements for blockchain-oriented systems*. 2021 IEEE 29th International Requirements Engineering Conference Workshops (REW), Notre Dame. https://doi.org/10.1109/rew53955.2021.00040

Khalid, M. I., Ehsan, I., Al-Ani, A. K., Iqbal, J., Hussain, S., Ullah, S. S., & Nayab, N. (2023). A comprehensive survey on blockchain-based decentralized storage networks. *IEEE Access*, *11*, 10995–11015. https://doi.org/10.1109/access.2023.3240237

Krichen, M., Ammi, M., Mihoub, A., & Almutiq, M. (2022). Blockchain for modern applications: A survey. *Sensors*, *22*(14), 5274. https://doi.org/10.3390/s22145274

Krishnamurthi, R., & Shree, T. (2021). A brief analysis of blockchain algorithms and its challenges. In *IGI Global eBooks* (pp. 23–39). https://doi.org/10.4018/978-1-7998-5351-0.ch002

Leng, J., Zhou, M., Zhao, J. L., Huang, Y., & Bian, Y. (2022). Blockchain security: A survey of techniques and research directions. *IEEE Transactions on Services Computing*, *15*(4), 2490–2510. https://doi.org/10.1109/tsc.2020.3038641

Li, Y., Dai, W., Ming, Z., & Qiu, M. (2016). Privacy protection for preventing data over-collection in smart city. *IEEE Transactions on Computers*, *65*(5), 1339–1350. https://doi.org/10.1109/tc.2015.2470247

Lu, Y., Liu, Z., Wang, S., Li, Z., Liu, W., & Chen, X. (2021). Temporal index scheme of hyperledger fabric system in IoT. *Wireless Communications and Mobile Computing*, *2021*, 1–15. https://doi.org/10.1155/2021/9945530

Lyu, Z., Cheng, C., Lv, H., & Song, H. (2024). Blockchain based intelligent resource management in distributed digital twins cloud. *IEEE Network*, *1*. https://doi.org/10.1109/mnet.2023.3326099

Mingxiao, D., Xiaofeng, M., Zhe, Z., Xiangwei, W., & Qijun, C. (2017, October 5-8). *A review on consensus algorithm of blockchain*. 2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Banff. https://doi.org/10.1109/smc.2017.8123011

Nanayakkara, S., Perera, S., Senaratne, S., Weerasuriya, G. T., & Bandara, H. M. N. D. (2021). Blockchain and smart contracts: A solution for payment issues in construction supply chains. *Informatics*, *8*(2), 36. https://doi.org/10.3390/informatics8020036

Nawari, N. O., & Ravindran, S. (2019). Blockchain and the built environment: Potentials and limitations. *Journal of Building Engineering*, *25*, 100832. https://doi.org/10.1016/j.jobe.2019.100832

Nehe, M., & Jain, S. A. (2019, March 8-9). *A survey on data security using blockchain: Merits, demerits and applications*. 2019 International Conference on Recent Advances in Energy-efficient Computing and Communication (ICRAECC), Nagercoil. DOI: 10.1109/ICRAECC43874.2019.8995064

Perera, S., Nanayakkara, S., Rodrigo, M., Senaratne, S., & Weinand, R. (2020). Blockchain technology: Is it hype or real in the construction industry? *Journal of Industrial Information Integration*, *17*, 100125. https://doi.org/10.1016/j.jii.2020.100125

Polyviou, A., Velanas, P., & Soldatos, J. (2019). Blockchain technology: Financial sector applications beyond cryptocurrencies. *Proceedings, 28*(1). https://doi.org/10.3390/proceedings2019028007

Rahman, A., Nasir, M. K., Rahman, Z., Mosavi, A., S, S., & Minaei-Bidgoli, B. (2020). DistBlockBuilding: A distributed blockchain-based SDN-IoT network for smart building management. *IEEE Access*, *8*, 140008–140018. https://doi.org/10.1109/access.2020.3012435

Raikwar, M., Gligoroski, D., & Kralevska, K. (2019). SOK of used cryptography in blockchain. *IEEE Access*, *7*, 148550–148575. https://doi.org/10.1109/access.2019.2946983

Ramachandran, A., & Kantarcioglu, M. (2017, September 28). *Using Blockchain and smart contracts for secure data provenance management*. arXiv. https://arxiv.org/abs/1709.10000

Ratta, P., Kaur, A., Sharma, S., Shabaz, M., & Dhiman, G. (2021). Application of blockchain and internet of things in healthcare and medical sector: Applications, challenges, and future perspectives. *Journal of Food Quality*, *2021*, 1–20. https://doi.org/10.1155/2021/7608296

Tellenbach, B., Rennhard, M., Schweizer, R. (2019). Security of data science and data science for security. In M. Braschler, T. Stadelmann, & K. Stockinger (Eds.) *Applied Data Science*. (pp. 265-288). Springer. https://doi.org/10.1007/978-3-030-11821-1_15

Wei, Y., Liang, L., Zhou, B., & Feng, X. (2021, June 4-7). *A modified blockchain DPoS consensus algorithm based on anomaly detection and reward-punishment*. 2021 13th International Conference on Communication Software and Networks (ICCSN), Chongqing. https://doi.org/10.1109/iccsn52437.2021.9463634

Yang, P., Xiong, N., & Ren, J. (2020). Data security and privacy protection for cloud storage: A survey. *IEEE Access*, *8*, 131723–131740. https://doi.org/10.1109/access.2020.3009876

Yassein, M. B., Shatnawi, F., Rawashdeh, S., & Mardin, W. (2019, November 3-7). *Blockchain technology: Characteristics, security and privacy; issues and solutions*. 2019 IEEE/ACS 16th International Conference on Computer Systems and Applications (AICCSA), Abu Dhabi. https://doi.org/10.1109/aiccsa47632.2019.9035216

Zhang, R., Xue, R., & Liu, L. (2019). Security and privacy on blockchain. *ACM Computing Surveys*, *52*(3), 1–34. https://doi.org/10.1145/3316481

Zhu, L., Zheng, B., Shen, M., Gao, F., Li, H., & Shi, K. (2020). Data security and privacy in bitcoin system: A survey. *Journal of Computer Science and Technology/Journal of Computer Science and Technology*, *35*(4), 843–862. https://doi.org/10.1007/s11390-020-9638-7

Olanrewaju, A., Sanmargaraja, S., Tan, S.Y. and Chu, H.C., 2024. Evaluation of the benefits of the implementation of digital twins in sustainable construction projects. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 446-457. DOI: https://doi.org/10.31705/WCS.2024.35. Available from: https://ciobwcs.com/papers/

EVALUATION OF THE BENEFITS OF THE IMPLEMENTATION OF DIGITAL TWINS IN SUSTAINABLE CONSTRUCTION PROJECTS

AbdulLateef Olanrewaju[1], Shalini Sanmargaraja[2], Seong Yeow Tan[3] and Hui Chen Chu[4]

ABSTRACT

Digital twin technology has emerged as a promising tool for enhancing sustainability in construction projects by providing a virtual representation of physical assets and processes. This research explores the benefits of implementing digital twins to drive sustainable construction projects. Through a review of the literature and a survey, the findings show that digital twin technologies provide significant benefits in the implementation of sustainable construction projects. Particularly, they allow faster internal decisions, improve communication, and enhance productivity. Furthermore, digital twins' implementation promotes employee innovation, engagement, and project team trust and minimises project risks. While certain benefits are more noticeable than others, digital twins contribute positively to project outcomes, demonstrating their importance in sustainable construction management. The findings also provide insights into the challenges and opportunities associated with the adoption and integration of digital twin technology in sustainable construction management, paving the way for future research.

Keywords: *Digitisation; Productivity; Sustainable Construction Management; Information.*

1. INTRODUCTION

The construction sector stands pivotal in the reduction of carbon emissions. The creation of virtual replicas of physical assets with digital twin technology will enable real-time monitoring and analysis, which has the potential to improve the performance and productivity of the construction sector. In recent years, the construction sector has undergone a paradigm shift towards sustainable methods, spurred by rising awareness of environmental concerns, resource restrictions, and the urgency to minimise the impacts of climate change (Olanrewaju, et al., 2019). As stakeholders work to meet ambitious sustainability goals, emerging technologies have emerged as significant tools for

[1] Lecturer, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, olanrewaju20002000@gmail.com
[2] Lecturer, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, shalinis@utar.edu.my
[3] Lecturer, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, tsyeow@utar.edu.my
[4] Lecturer, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, chuhc@utar.edu.my

improving the productivity and performance of construction sector. Among these technologies, digital twins have received substantial attention for their potential to enhance the processes and strategies by which construction projects are planned, developed, built, and operated (Bartlett, 2020; Madubuike et al., 2022). Digital twins are now being used more frequently in the construction sector to improve project outcomes, optimise resource utilisation, and reduce environmental consequences (Bartlett, 2020). Digital twins integrate advanced sensors, data analytics, and simulation technologies, allowing stakeholders to visualise, analyse, and optimise many elements of building projects, from design and planning to operation and maintenance phases. There is already significant research that has demonstrated the benefits of digital twins in construction (Bartlett, 2020; Madubuike et al., 2022; Su et al., 2023), but there is less research on the benefits of adopting and integrating digital twins in sustainable construction. Further, research on the benefits of digital twins in construction is fragmented and based on a literature review. However, there is the potential for a clear understanding of the positive impact of technology in the delivery of sustainable construction projects. It is argued that the benefits of digital twin in conventional construction projects may not be applicable to sustainable construction projects because the requirements of sustainable construction are different from the requirements of traditional construction (Olanrewaju, 2022). Against this backdrop, this study seeks to investigate the benefits of adopting digital twins in the delivery of sustainable construction projects. The article stressed the place of digital twins in the procurement of sustainable construction projects and particularly the impact of digital twins on productivity, performance, communication, engagement, and efficiencies.

2. BACKGROUND AND THEORETICAL FRAMEWORK

The construction sector, which has a long history of conservatism, is one of the least mechanised and digitalised, with data retained on paper documents. However, as the construction sector's unpredictability and challenges increase, construction companies are turning to digital construction to promote productivity, collaboration, and competitiveness. Contractors, architects, engineers, and suppliers are increasingly interacting and collaborating digitally, from video-calling site meetings to digital order fulfilment (Bartlett, 2020). Demand for digital collaboration, wearables, BIM 3D printing, artificial intelligence, and modular building has increased dramatically (Obando, 2021). A survey predicted that the need for construction technologies would rise by more than 70%, and more than 60% of respondents stated they had hired new employees specifically to focus on new technologies (Brown, 2022). According to a recent survey, digital construction is used for a variety of purposes, including increasing productivity (77%), reducing risk/safety improvement (73%), saving money (67%), addressing skill shortages (51%), gaining confidence in project delivery time (37%), and shortening project duration (32%). Construction technologies are defined as those that have a particular use in the construction sector. There are several construction-oriented tools, software, and technologies available to help reduce or eliminate process-related difficulties and improve project delivery, performance, and profit margins (Azhar, 2017; Bartlett, 2020). Construction companies face intense pressure to increase productivity, profit margins, client satisfaction, and risk reduction through greater collaboration and communication, which is possible with construction technologies (Gambatese & Hallowell, 2011). Bartlett (2020) presented the construction technologies industry map that provides connectivity among the technologies. Digital twin is one of the prominent technologies whose application and adoption are gaining popularity. Similarly, Olanrewaju et al. (2024) develop a framework for the relationship among the latest construction technologies. The relationship or connectivity is important because it represents the relationship of data, processes, activities, and workflow among projects and organisations. Companies used construction technologies to reduce unnecessary procedures and activities, as well as low productivity caused by a lack of collaboration, communication, repetitive duties, and trust. Construction technologies include a diverse set of equipment, procedures, and materials used in planning, designing, constructing, and operating structures and infrastructure. Building information modelling, 3D printing, robotics and automation, augmented and virtual reality, drones, the Internet of Things, and digital twins are some of the most prominent construction technologies. Construction digital twins refer to the fabrication of virtual counterparts of physical structures or infrastructure. These digital representations use real-time data from sensors, IoT devices, and other sources to provide a complete picture of the project's state, performance, and behaviour during its entire lifecycle. Construction digital twins allow stakeholders to visualise, simulate, and analyse different parts of a project, such as design, construction, operation, and maintenance. They help to improve decision-making, collaboration among project teams, and resource utilisation.

A "digital twin" has been defined as a "digital representation of a physical object or system" (Grieves & Vickers, 2016) that can be used to simulate and analyse the behaviours of construction projects in a virtual environment. A digital twin is dynamic, as opposed to a static 3D replica. Even after the construction is finished, it continues to change and update itself as more information is available. A digital twin's real-time project data enables advanced monitoring and management from an operational standpoint, enabling design-centric smart planning and optimised design. The operation of digital twins for a building involves the seamless integration of data, modelling, simulation, monitoring, analysis, and decision support processes to optimise performance, enhance sustainability, and improve the overall operation and management of the building throughout its lifecycle. The mechanism for the operation of digital twins in a building involves several key components and processes. A digital twin can be developed for part of a building, a complete building, or groups of buildings. A digital building can be developed for a city, factories, or land. Construction digital twins are sometimes referred to as data twins, virtual models, or the next generation of built drawings. Construction digital twin can be created using data from design, construction, and operation of construction projects. The application and uses of construction digital twin is extensive, including validation of design, evaluation of constructability and maintenance and operation of the projects. It often created from using data from various sources including, BIM, sensors, survey, drones, laser scanning, mobile mappings. All these data are used to create point clouds, which are crucial parts of the fundamentals of digital twin (Stojanovic et al., 2018; Xue et al., 2020). Figure 1 display the mechanism for the operation of the digital twin technologies for building projects. Several studies have been conducted on the use of construction twins (Hou et al., 2021; Jiang, 2021; Lee and Lee, 2021; Sack et al., 2020; and Zhang et al., 2021). However, despite the potential benefits of digital construction twins, their implementation and adoption in the construction sector remain limited. Unlike a digital model or a simulation, a digital twin is responsive and continues to evolve as more data is provided to the twin. Digital twins are customised to a specific project.

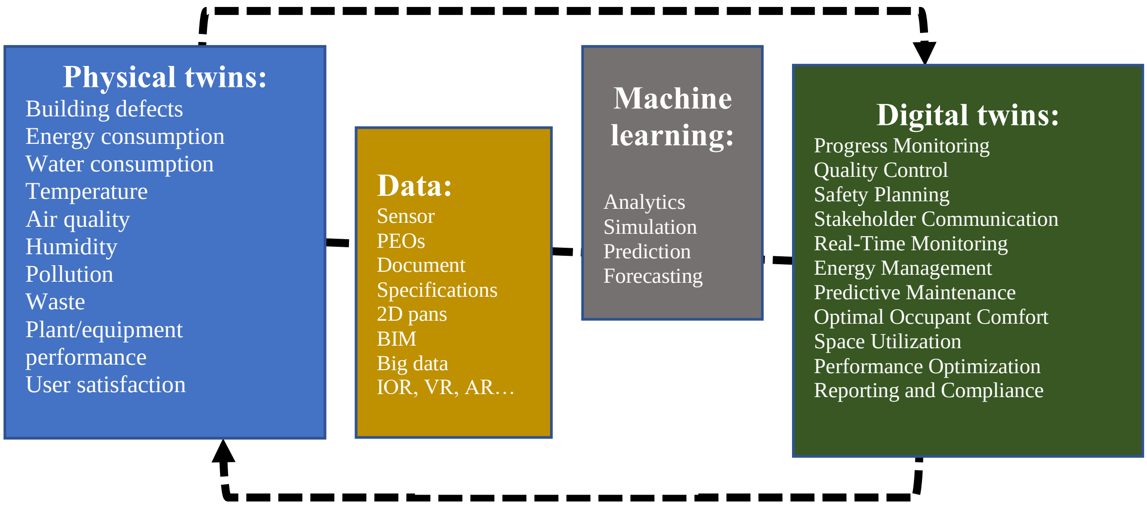


Figure 1: Mechanism for the operation of digital twins for a building

2.1 Conceptual Framework of Digital Twins

The conceptual framework of digital twins includes data collection, modelling and simulation, real-time monitoring, analysis, and decision support. Digital twins allow stakeholders to visualise and simulate building designs, evaluate alternative scenarios, and optimise energy efficiency, resource utilisation, and environmental performance beginning with the early stages of project development. During the construction phase, digital twins provide real-time monitoring of construction progress, quality control, and safety compliance, resulting in improved project efficiency, decreased rework, and increased worker safety. The digital twin technologies also enable stakeholders to identify inefficiencies, predict maintenance needs, and optimise building operations to maximise energy efficiency, occupant comfort, and overall sustainability by continuously monitoring and analysing building performance data. Digital twins provide a single platform for stakeholders to interact, share information, and make data-driven decisions on construction projects. By incorporating sustainability requirements into decision-making processes, digital twins enable stakeholders to assess the environmental and social impacts of design and operational choices, identify trade-offs, and make informed decisions that align with sustainability goals.

Despite the growing popularity of digital construction twins, there remains a lack of understanding about the challenges and opportunities associated with this emerging technology. Existing research reveals that a lack of awareness and integration among various construction stakeholders, as well as technological constraints and a skilled workforce shortage, may impede the widespread implementation of digital twins in the construction industry. With specific relevance to the aim of this research, while digital twins have the potential to increase project efficiency, cost savings, safety, and sustainability, there has been little research on the specific benefits and drawbacks of using digital twins in sustainable construction projects. As a result, this study seeks to fill this gap by investigating the benefits of digital twin adoption in sustainable construction projects. Specifically, the impact of the technologies on project efficiency, resource optimisation, and sustainability outcomes across diverse geographical contexts will be explained. By identifying and analysing the global benefits associated with digital twin implementation in sustainable construction, this research seeks to provide valuable insights and recommendations for stakeholders in the construction sector to improve sustainability practices and achieve sustainable development goals.

3. RESEARCH DESIGN

The question that this research aims to address is: what are the advantages of digital twin technology in the procurement of sustainable construction? It is critical to understand the benefits of adopting and applying digital twin technologies to boost construction productivity and profit margins while reducing claims, disputes, and penalties. The original data were collected using convenience sampling. Convenience sampling is a data collection method in which surveys are administered to respondents who are available, accessible, and willing to participate in the survey. The method is appropriate when adequate information on population size and sample frame is unavailable (Sekaran & Bougie, 2016). While its findings may not be generalisable, they can be representative if enough respondents are included. Thus, the key idea is that if enough data are collected while keeping objective, the results will be representative of the population. The survey was conducted online. The survey was conducted from July 2023 to September 2023. Respondents were asked to rate their agreement with each of the benefits of digital twins in the procurement of sustainable construction based on evidence. The levels of agreement were measured on a five-point scale, with 5 denoting extreme benefit and 1 denoting the least benefit. 3 represents a moderate benefit. Two and four were positioned in between. The questionnaire went through two pilot stages of surveys consisting of key stakeholders. An Average Benefit Index (ABI) (Eq. 1) was used to measure the extent to which the technologies provided the listed benefits. The average benefit index was based on the cumulative weighting of the initial frequency scores of each construct.

$$ABI = \frac{\sum_{i=0}^{5} a_i x_i}{5\sum_{i=0}^{5} x_i} \times 100 \qquad \text{(Eq. 1)}$$

Where a_i was the index of a group; constant expressing the weight given to the group; x_i was the frequency of the responses, i = 1, 2, 3, 4, and 5 and described as below: x_1, x_2, x_3, x_4, x_5 were the frequencies of the responses corresponding to $a_1 = 1, a_2 = 2, a_3 = 3, a_4 = 4, a_5 = 5$, respectively. An ABI score of 1.00 - 20.00 denotes the least benefit; 21.00-40.00 defines less benefit; 41.00-60 denotes moderate benefit; 61.00-80 denotes significant benefits; and 81.00-100.00 denotes highly beneficial. There is a 1.0% difference between the scales. The construct associated with the highest ABI score will be the most beneficial. Other statistical tests performed were the one-way t-test, Crunbach alpha reliability tests, convergent validity tests, factor analysis tests, mode tests, and standard deviation tests. IBM SPSS Statistics was used to analyse the data.

4. RESULTS AND DISCUSSION

The survey forms were administered to over 500 stakeholders who filled out the online survey form. However, 36 online responses were received by the deadline, following multiple reminders. However, because the snowballing technique was used, the exact number of forms that were administered is unknown.

4.1 ANALYSING THE RESPONDENTS' PROFILE

According to the findings, almost 90% of respondents have more than five years of work experience, while around 40% have more than ten years (Table 1). Table 2 contains the respondents' locations. Investment in construction technology is modest (see Table 3). The respondents held strategic positions are shown in Figure 2.

Table 1: Your work experience

Year	Less than 5 years	5 years to 10 years	11years - 15 years	16years - 20 years	More than 20 years
Frequency	4	10	8	22.2	8
Percentage	11.1	27.8	22.2	16.7	22.2

Table 2: Respondent's location

Year	Malaysia	Singapore	Nigeria	Pakistan	Other
Frequency	9	6	12	3	6
Percentage	25.0	16.7	33.3	8.3	16.7

Table 3: How much has your company invested in construction digital twins?

Size of investment	Percentage	Cumulative Percentage
Less than 5%	13	40.625
5% to 10%	3	9.375
10% to 15%	5	15.625
15% to 20%	3	9.375
20% to 25%	2	6.25
25% to 30%	2	6.25
35% to 40%	1	3.125
40% to 45%	2	6.25
50 and above	1	3.125

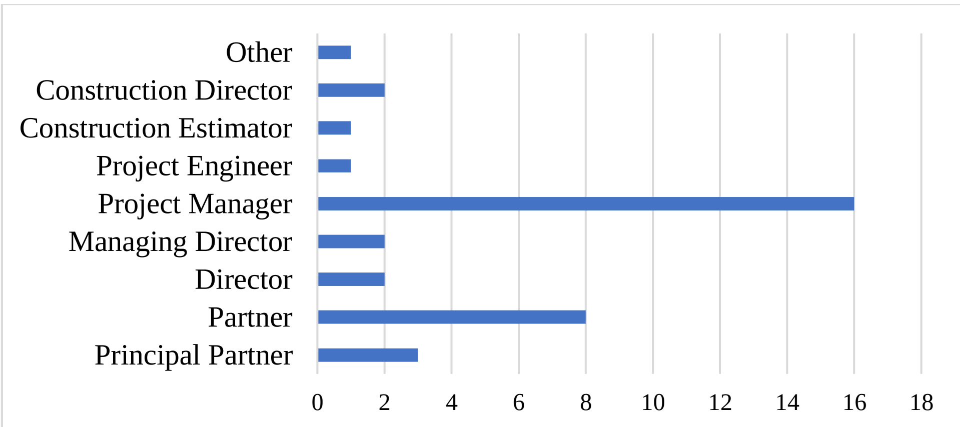


Figure 2: Respondent position in their organisation

4.2 RESULTS OF THE BENEFITS OF DIGITAL TWIN IN SUSTAINABLE CONSTRUCTION

The goodness of fit of the benefits was performed through reliability and validity analyses. Both the Spearman-Brown Coefficient and the Guttman Split-Half Coefficient have high values (0.987 for both), indicating very high reliability for the overall survey instrument (Table 4). This suggests that the survey instrument consistently measures the constructs of interest and produces reliable results, both when the instrument is split into halves and when it is treated as a single entity. The construct validity of the data ranges from 0.72 to 0.93. These results provide strong evidence for the reliability and validity of the survey instrument, indicating that it effectively measures the constructs of interest and produces consistent and dependable results. The data revealed that about 20% of the respondents measured that digital twins have the least or less benefits to sustainable projects (Table 5). While 27% of respondents agreed that digital twins have moderate benefits, evidently more than 50% of the respondents measured that the technologies have high or extreme benefits in the procurement of sustainable construction and for the performance of sustainable construction projects.

Table 4: Guttman split-half coefficient

Cronbach's Alpha	Part 1	Value	0.978
		N of Items	9a
	Part 2	Value	0.982
		N of Items	8b
	Total N of Items		17
Correlation Between Forms			0.975
Spearman-Brown Coefficient	Equal Length		0.987
	Unequal Length		0.987
Guttman Split-Half Coefficient			0.985

a. The items are reduced cost, Increased innovation/better ideas, Able to launch products/services more quickly, Able to scale the business more easily/faster, Reduced paper-based process, Improved efficiency, more satisfied customers, Easier to plan and make better business decisions, more engaged and motivated staff.

b. The items are: More engaged and motivated staff, better reputation, reduces project risk, Higher valuation, Collaboration among partners, gaining an edge on the teams, making faster internal decisions, Improved communication, Improves trust among project team.

Table 5: Descriptive statistics of benefits of digital twin technologies

Benefit	Least beneficial	Less beneficial	Moderate beneficial	Strong beneficial	Extreme beneficial	Std. Deviation	ABI
Making faster internal decisions	3	4	6	18	5	22.69	70.00
Easier to plan and make better business decisions	4	3	6	17	5	23.67	69.14
Improved communication	4	3	6	19	4	23.16	68.89
Improved efficiency	4	3	7	16	5	23.62	68.57
More engaged and motivated staff	3	4	10	13	5	22.41	67.43
Increased innovation /better ideas	5	2	10	13	6	24.97	67.22
Reduced paper-based process	4	4	8	15	5	23.98	67.22
Better reputation	2	6	9	15	4	21.95	67.22
Improved trust among project team	5	2	11	11	7	25.45	67.22
Able to launch products/services more quickly	3	4	11	13	4	22.41	66.29
Reduce project risk	3	5	11	12	5	23.47	66.11
Higher valuation	3	5	11	13	4	22.85	65.56
Collaboration among partners	4	4	12	10	6	24.77	65.56
More satisfied customers	3	5	13	10	5	22.44	65.00
Able to scale the business more easily /faster	5	2	12	14	3	23.50	64.44
Reduced project cost	3	7	11	10	5	23.85	63.89
Gaining an edge on the teams	5	3	12	12	4	24.36	63.89

5. DISCUSSION OF THE BENEFITS OF DIGITAL TWIN

These results highlight the multifaceted benefits of digital twin technologies in sustainable construction projects, ranging from improved decision-making and communication to enhanced efficiency, innovation, and staff engagement. The consistent recognition of these benefits underscores the transformative potential of digital twins in driving positive outcomes and advancing sustainability goals within the construction sector. It is interesting that making faster internal decisions is the highest benefit of the digital twin technologies in sustainable construction. It is understandable that stakeholders' value faster internal choices enabled by digital twin technologies. The ability to expedite decision-making processes can significantly impact project success and overall organisational performance. Faster decision-making directly improves operational efficiency by decreasing delays and bottlenecks in project execution. Digital twin technologies offer real-time data and insights, allowing project stakeholders to make data-driven decisions quickly. Organisations that can make quick judgements are better positioned to seize new opportunities and respond quickly to market developments.

Timely decisions help to optimise resource allocation, ensuring that personnel, materials, and equipment are used properly. This optimisation can result in cost savings and better project outcomes.

Similarly, the data revealed that implementing digital twins in sustainable construction will make it easier to plan and make better business decisions. Digital twin technologies provide a significant advantage in sustainable construction projects by allowing for more effective planning and better commercial decisions. Digital twins enable real-time access to detailed and accurate data on numerous areas of a construction project, such as design, construction progress, resource utilisation, and environmental conditions. It also enables stakeholders to see the complete project lifecycle in a virtual environment. This visualisation capacity allows them to model multiple situations, assess the possible impact of different actions, and identify the best solutions prior to implementation. By viewing the effects of their actions in a simulated environment, stakeholders can make more informed decisions that correspond with project objectives and stakeholders' value systems for the projects.

It is not surprising that improved communication emerges as a critical advantage facilitated by digital twin technologies for sustainable construction. Improved communication enabled by digital twin technology will boost collaboration, transparency, and efficiency in sustainable construction projects. Digital twins act as central repositories for project data, documentation, and communication channels (Madubuike et al., 2022). This centralisation guarantees that all project stakeholders have access to current information, promoting transparency and alignment within the project team. Digital twins enable project stakeholders to share data and insights in real time, regardless of location or time zone. This real-time communication lowers delays, which are common for sustainable construction, and allows for fast decision-making, therefore improving overall project efficiency and responsiveness (Olanrewaju, 2022). Improved communication plays a pivotal role in enhancing project efficiency and productivity by facilitating timely decision-making, reducing rework, fostering collaboration, optimising resource allocation, mitigating risks, engaging stakeholders, and supporting continuous improvement efforts. As a fundamental aspect of sustainable construction project management, effective communication ensures that projects are delivered on time, within budget, and to the satisfaction of all stakeholders involved.

The data also revealed that improved efficiency has a strong rating. This is intuitive because a digital twin can help improve efficiency. Digital twins contribute to the project's overall sustainability by finding inefficiencies and optimising resource allocation, thereby reducing waste and environmental effects. It improves construction workflows and processes by providing a single platform for project management and coordination. The increased efficiency enabled by digital twins in construction projects is critical to ensuring sustainability because it optimises resource management, streamlines workflows, improves decision-making, reduces downtime and rework, promotes collaborative project management, and allows continuous performance tracking and optimisation. In addition, the data revealed that digital twins can help engage and motivate staff. For instance, the use of digital twin technologies in sustainable construction projects can significantly increase employee engagement and motivation by improving communication, facilitating collaboration and input, providing recognition and feedback mechanisms, supporting professional development, and aligning with sustainability goals. By exploiting these benefits, project teams may foster a good and motivating work environment that inspires employees to give their all and achieve project success. The technologies offer a platform for better collaboration and transparency in construction projects and provide team members with real-time information by centralising project data, status updates, and communication channels. This transparency helps to build trust and engagement among employees, who feel more informed and involved in project decisions. Also, because the staff members can access full project information using digital twins, the accessibility empowers employees by providing them with the necessary knowledge and resources to contribute effectively to the project. Employees who feel empowered and equipped with the necessary information are more likely to be engaged and driven to work at their best.

The data also revealed that digital twins also help to increase innovation and generate better ideas, suggesting that digital twins are catalysts for fostering innovation and generating better ideas within construction projects. To explain the visualisation tool that the digital twin enables, it fosters creativity and innovation by allowing users to experiment with new ideas and approaches to design and construction by comparing multiple scenarios on a project. In addition, the digital twins allow stakeholders to make educated decisions and identify opportunities for innovation and improvement within the project by providing them with access to extensive data and analytics.

Digital twins also help to promote environmental sustainability by reducing paper consumption and the associated environmental implications such as deforestation, energy consumption, and greenhouse gas emissions. This is consistent with the overall goals of sustainable construction, which are to reduce resource use and prevent environmental degradation. Digitalising paper-based operations lowers the expenses of printing, storing, and managing physical records. Unlike traditional construction, a lot of information and documents are involved in sustainable construction. However, digital twins can help because they save money and time by streamlining document management and automating operations. The use of digital twins in sustainable construction projects reduces paper-based processes, which not only improves environmental sustainability but also saves money, increases accessibility and transparency, improves data integrity and security, streamlines workflows and compliance, and allows for future growth.

6. CONCLUSIONS

This research presents the preliminary results of research on the implementations, constraints, benefits, and shortcomings of construction technologies in Malaysia. The findings underscore the transformative potential of digital twins in advancing sustainability, efficiency, and innovation in construction projects. By leveraging digital twin technologies strategically and collaboratively, stakeholders can drive positive outcomes, improve project performance, and contribute to the advancement of sustainable construction practices. The results demonstrate that digital twin technologies offer a wide range of benefits for sustainable construction project. These benefits span various aspects of project management and operations, indicating the significant potential of digital twins to drive efficiency, innovation, and success in construction projects. The benefits identified in the study address the needs and priorities of diverse stakeholders involved in sustainable construction projects. Digital twins add value across the project lifecycle, catering to the needs of owners, contractors, designers, and other stakeholders. Certain benefits, such as better productivity, less project risk, and faster decision-making, emerge as particularly strategic advantages of digital twin adoption. These benefits not only contribute to project success but also align with broader organisational goals, such as achieving sustainability targets, maintaining competitive advantage, and maximising return on investment. While the study identifies several benefits of digital twins, there is also room for further exploration and optimisation. As technology continues to evolve and construction practices evolve, there may be opportunities to enhance the performance and capabilities of digital twin systems, unlocking additional value and benefits for sustainable construction projects. To fully advance the benefits of digital twins, stakeholders must carefully consider various factors, such as data quality, interoperability, cybersecurity, and organisational readiness. Effective implementation strategies, robust governance frameworks, and stakeholder engagement are essential for maximising the value of digital twins while mitigating potential challenges and risks. Furthermore, while the respondents held strategic positions and had cognisance work experience, the sample size was small. Therefore, future research should be conducted with a larger sample size.

7. REFERENCES

Azhar, S. (2017). Role of visualization technologies in safety planning and management at construction jobsites. *Procedia Engineering, 171*, 215-226. https://doi.org/10.1016/j.proeng.2017.01.329

Bartlett, K., Blanco, J.L., Johnson, J., Fitzgerald, B., Mullin, A., & Ribeirinho, M.J. (2020). *Rise of the platform era: The next chapter in construction technology*. McKinsey Global Publishing. https://www.mckinsey.com/industries/private-capital/our-insights/rise-of-the-platform-era-the-next-chapter-in-construction-technology#/

Brown, A. (2022, January 13). *Investment in construction tech to increase*. Retrieved June 20, 2024, from https://www.constructiontechnology.media/news/investment-in-construction-tech-to-increase/8017418.article.

Gambatese, J. A., & Hallowell, M. (2011). Factors that influence the development and diffusion of technical innovations in the construction industry. *Construction Management and Economics, 29*(5), 507-517. https://doi.org/10.1080/01446193.2011.570355

Grieves, M., & Vickers, J. (2017). Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems. In: Kahlen, J., Flumerfelt, S., Alves, A. (eds*). Transdisciplinary Perspectives on Complex Systems. Springer, Cham*. (pp.85-113) https://doi.org/10.1007/978-3-319-38756-7_4.

Hou, L., Wu, S., Zhang, G., Tan, Y., & Wang, X. (2020). Literature review of digital twins' applications in construction workforce safety. *Applied Sciences, 11*(1), 339. http://dx.doi.org/10.3390/app11010339

Jiang, Y. (2021). Intelligent building construction management based on BIM digital twin. *Computational Intelligence and Neuroscience*, 2021.1-11. https://doi.org/10.1155/2021/4979249

Lee, D., & Lee, S. (2021). Digital twin for supply chain coordination in modular construction. *Applied Sciences*, *11*(13), 5909. https://doi.org/10.3390/app11135909

Madubuike, O. C., Anumba, C. J., & Khallaf, R. (2022). A review of digital twin applications in construction. *Journal of Information Technology in Construction, 27*, 145-172. https://dx.doi.org/10.36680/j.itcon.2022.008

Obando, S. (2021, October 06). *Construction technology funding skyrockets to record levels*. Retrieved June 20, 2024, from https://www.constructiondive.com/news/construction-technology-funding-skyrockets-to-record-levels/607769/

Olanrewaju, A., Shari, Z., & Gou, Z. (Eds.). (2019). *Greening affordable housing: An interactive approach*. CRC Press.

Olanrewaju, A., Sanmargaraja, S., Oni, O., Anavhe, P., & Mewomo, C. M. (2024). An association rule mining model for the application of construction technologies during COVID-19. International *Journal of Construction Management*, *24*(4), 443-453. https://doi.org/10.1080/15623599.2023.2212420

Olanrewaju, A. L. (2022, November). An artificial neural network analysis of rework in sustainable buildings. In *IOP Conference Series: Earth and Environmental Science,1101*(2). 022003. IOP Publishing. https://doi.org/ 10.1088/1755-1315/1101/2/022003

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering, 1* (14). https://doi.org/10.1017/dce.2020.16

Sekaran, U., & Bougie, R. (2016). *Research methods for business*, 6th ed.; *A skill building approach*. John Wiley & Sons. Hoboken, NJ, USA.

Su, S., Zhong, R. Y., Jiang, Y., Song, J., Fu, Y., & Cao, H. (2023). Digital twin and its potential applications in construction industry: State-of-art review and a conceptual framework. *Advanced Engineering Informatics, 57*, 102030. https://doi.org/10.1016/j.aei.2023.102030

Stojanovic, V., Trapp, M, Richter, R, Hagedorn,B & Döllner, J (2018) Towards the generation of digital twins for facility management based on 3d point clouds In Gorse, C and Neilson, C J (Eds) *Proceeding of the 34th Annual ARCOM Conference*, 3-5 September 2018, Belfast, UK, Association of Researchers in Construction Management, 270-279.

Xue, F., Lu, W., Chen, Z., & Webster, C. J. (2020). From LiDAR point cloud towards digital twin city: Clustering city objects based on Gestalt principles. *ISPRS Journal of Photogrammetry and Remote Sensing, 167*, 418-431. https://doi.org/10.1016/j.isprsjprs.2020.07.020

Zhang, J., Cheng, J. C., Chen, W., & Chen, K. (2022). Digital twins for construction sites: Concepts, LoD definition, and applications. *Journal of Management in Engineering, 38*(2), 04021094. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000948.

Yahanpath, R., Wijekoon, W.M.C.L.K. and Kumarathunga, J., 2024. Exploratory study on adAptability of wall-mounted solar panels for high-rise buildings in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 458-469. DOI: https://doi.org/10.31705/WCS.2024.36. Available from: https://ciobwcs.com/papers/

EXPLORATORY STUDY ON ADAPTABILITY OF WALL-MOUNTED SOLAR PANELS FOR HIGH-RISE BUILDINGS IN SRI LANKA

Ravindu Yahanpath[1], W.M.C.L.K. Wijekoon[2], and Janani Uvasara Kumarathunga[3]

ABSTRACT

The global energy crisis and the unsustainable resource consumption patterns of the construction industry has driven a growing interest in sustainable practices. The integration of renewable energy sources, such as solar energy, has emerged as a key strategy to achieve sustainability goals. While various applications of solar systems exist, wall-mounted solar panels have not been widely utilised in Sri Lanka, and no prior research has been conducted on this topic in the country. This study acts as an exploratory study which aims to investigate the feasibility and adaptability of implementing wall-mounted solar panels in high-rise buildings in Sri Lanka. Data was gathered through a comprehensive literature review and semi-structured interviews with experts on solar energy and construction practices. The study found several barriers towards the implementation of wall-mounted solar panels in Sri Lanka. Notably, the effectiveness of the wall-mounted solar panel system was found to be hindered by the path of the sun in Sri Lanka. The absence of proper regulations or Sri Lanka Standards (SLS) specific to wall-mounted solar panels presented an additional challenge. Despite the barriers identified, expert interviews revealed potential strategies to overcome these challenges. The findings of this research study contribute to the understanding of the feasibility of implementing wall-mounted solar panels in high-rise buildings in Sri Lanka, shedding light on the unique context and factors influencing their adoption. This study underscores the importance of considering local factors and developing appropriate regulations to promote sustainable energy practices in the construction industry.

Keywords: *Adaptability; High-Rise Buildings; Wall-Mounted Solar Panels.*

1. INTRODUCTION

The concern for sustainable development has increased among the global community in the face of unprecedented population growth and significant industrial and technological advancements. As a major economic sector, the construction industry is compelled to contribute to these sustainability objectives. Hence, there has been much discourse on feasible sustainability and improving the environmental impact of construction activities.

---

[1] Junior Quantity Surveyor, QS Practice (Pvt) Ltd, Sri Lanka, ravinduyahanpath2000@gmail.com
[2] Senior Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, kumari.l@sliit.lk
[3] Quantity Surveyor, Nawaloka Constructions Company (Pvt) Ltd, Sri Lanka, janauvasara@gmail.com

The construction industry is directly responsible for over one-third of global energy consumption and 39% of the total direct carbon emissions (Min et al., 2022) However, renewable energy systems have the potential to mitigate the risk of disruptions in the energy supply and decrease dependency on foreign fuels (Jakštas, 2020). Furthermore, by reducing the production of greenhouse gases, renewable energy-based technologies can provide a great opportunity to decrease global warming (Baidya & Nandi, 2020). The most powerful source of energy known to us is the Sun (Şenpinar, 2018). By utilising the sun's energy (which is renewable, clean and reliable) in place of unsustainable energy sources, numerous environmental, economic and social benefits can be achieved (Letcher, 2022). Electricity generation through solar panels is a green technique that has gained popularity in the past decade owing to its environmental benefits (Allouhi et al., 2015). There are many variations of solar panel applications ranging from the most used rooftop solar panels, to specialised systems such as solar-powered road lighting systems, solar ponds etc. (Smith et al., 2022). However, one major constraint associated with the use of solar energy is the task of allocating space for the panels. In cities where commercial high-rise buildings have limited roof area and ground area, the task of reserving space for solar panels is often tedious and costly, thus discouraging potential clients. A promising alternative is the application of wall-mounted solar panels, which have shown potential for achieving the desired results while utilising the often-unused wall area in high-rise buildings. However, its adaptability within the built environment of Sri Lanka remains unexplored. Furthermore, there is a notable lack of research focusing on the adaptability of the wall-mounted solar panels in high-rise buildings. Therefore, this study aims to bridge these gaps by investigating the adaptability of wall-mounted solar panel design concept in high-rise buildings in Sri Lanka. The objectives set to achieve this aim were: (i) Review the concept of wall-mounted solar panel design, its importance and its availability in Sri Lanka, (ii) Investigate the suitability and the associated barriers to adopting wall-mounted solar panels in high-rise buildings in Sri Lanka, and (iii) Propose strategies to overcome the identified barriers.

2. LITERATURE REVIEW

2.1 SOLAR ENERGY FOR SUSTAINABLE CONSTRUCTION

The construction industry plays a significant role in regulating the trajectory of a country's growth, often acting as a determinant of the country's technological, infrastructural, social and economic development (Hussain et al., 2022). Consequently, the built environment accounts for over 40% of the energy consumed across the globe (Devi & Palaniappan, 2017). Unfortunately, the energy wastage associated with these functions has a substantial negative impact on the environment. Therefore, it is imperative for both the industry and the individual structures to prioritise sustainable energy solutions (Dräger & Letmathe, 2022). As the predominant renewable energy source, solar energy boasts the characteristics of being clean, inexhaustible, renewable, and widely spread compared to other energy sources (Peng et al., 2020). Yan et al. (2019) found that solar energy systems now can generate electricity at costs equal or to lower than local grid-supplied electricity.

2.2 SOLAR CELL FUNCTIONALITY AND ELECTRICITY GENERATION

Solar cells are semiconductor devices that can convert sunlight into electricity through the photovoltaic effect. An assembly of interconnected solar cells is known as a "Solar

Module" (Sharma & Kothari, 2017). The energy conversion process includes the absorption of protons which produces electron-hole pairs in the semiconductor, and charge carrier separation through a P-N junction (Soga, 2006). Primarily, solar cells are made up of semiconductor material (such as Silicon) which absorbs the photons emitted through sun rays (Bhatia, 2014). A typical solar cell comprises two layers of semiconductors (P and N), with the junction between them acting as a diode which allows electrons to move from N to P (Mellit & Kalogirou, 2022). This movement is created when photons with sufficient energy hit the solar cell, causing excess electrons in the N-layer and an electron deficiency in the P-layer, thus creating extra spaces known as "holes" (Mellit & Kalogirou, 2022; Asdrubali & Desideri, 2019). Then, the negatively charged electrons flow from the N-layer to the holes in the P-layer, causing a free flow of electrons which generates electricity (Mellit & Kalogirou, 2022; Asdrubali & Desideri, 2019; Hussain, 2018). The generated electricity is then converted from DC to AC using an inverter to be used locally or fed to the main electrical grid (Khare et al., 2023).

2.3 WALL-MOUNTED SOLAR PANELS FOR HIGH-RISE BUILDINGS

Urban areas are experiencing an increase in high-rise building construction due to the impending shortage of land (Sharma & Kothari, 2017). While roof-top panels are the most common application of solar panels, the potentials of this application are restricted due to the limited roof area of high-rise buildings in urban areas (Zhou et al., 2019). Hence, roof-top solar panels may not be sufficient to fulfil the energy requirements. However, the wall area in high-rise buildings is significantly greater than the roof area and thus, as suggested by Nguyen et al. (2019), can be utilised as an alternative by installing a large number of solar panels on the vertical walls. Saadatian et al. (2013) noted that wall-mounted solar panels are an ideal option considering the long-term goal to improve sustainability within the construction industry through renewable energy sources. Sharma and Kothari (2017) identified two prominent types of building façade systems that are suitable for wall-mounted solar panels: Rainscreen cladding and curtain walling systems. Rain screen cladding systems consist of a stainless-steel sub-frame fitted with cladding panels and fixing brackets which are bolted onto the internal walls of the building (Pérez et al., 2012). Curtain walls use lightweight Aluminium or Stainless-Steel frames and are fitted with transparent or opaque solar panels (Sharma & Kothari, 2017). They are airtight and can resist wind and weather (Kurian & Karthi, 2021; Roberts & Guariento, 2009).

2.4 BENEFITS OF WALL-MOUNTED SOLAR PANELS FOR HIGH-RISE BUILDINGS

Traditionally, solar panels are mounted on horizontal surfaces at high elevations, most commonly on rooftops or slightly inclined surfaces which are exposed to direct sunlight (Osigbemeh et al., 2022). This system allows the panels to harness solar energy to the max. However, on account of practical difficulties such as restricted access to rooftops and space limitations, wall-mounted solar panels are being proposed as alternatives (Kiboi & Moses, 2022). Many unique benefits that are associated with wall-mounted solar panels. Primarily, using wall-mounted solar panels allows the rooftop space to be saved. Since the rooftop space in high-rise buildings is limited due to reasons such installation of HVAC systems, infrastructure maintenance systems, communication equipment etc., wall-mounted solar panels are a convenient option to generate renewable energy without compromising rooftop space (Osigbemeh et al., 2022). In high-rise buildings, the wall area that is exposed to sunlight is greater than the roof area. Therefore, wall-mounted solar panels can generate more electricity than rooftop solar panels (Salama, 2018). Another advantage is the ease of installation and maintenance of wall-mounted solar panels compared to rooftop solar panels. Wall-mounted solar panels can be designed and installed so that the high wind load applied in high-rise buildings can be withstood (Kiboi & Moses, 2022).

3. METHODOLOGY

This study was initiated with an outlook on the significance of solar energy and solar energy generation mechanisms. This was cemented by a survey of past literature leading to insights on the benefits of wall-mounted solar panels for high-rise buildings. Journal articles, conference proceedings, newspaper articles, and reports relating to solar energy and the benefits of wall-mounted solar panels were gathered and scrutinised to perform the literature review. The study follows a qualitative research approach, allowing for an in-depth understanding of the factors affecting the adaptability of wall-mounted solar for Sri Lankan high-rise buildings. Considering the novelty of the subject in the context of Sri Lanka, it was decided that a qualitative approach is more suitable for the study. The data for this study was collected through semi-structured interviews with qualified construction professionals with experience in solar installations. This research strategy was chosen as it would allow for a large amount of required data to be gathered with flexibility. According to Fellows and Liu (2015), semi-structured interviews offer a combination of the greatest qualities of structured and unstructured interview formats, allowing for greater freedom in the questions and more clarity in the responses. This study utilises an interpretivism research paradigm, where the interviewees' answers are based on their present experiences, knowledge, and comprehension of solar energy adaptability. Purposive sampling was applied in choosing interviewees. This method enables the selection of respondents that are most suited to the research topic and therefore, ensures that all respondents are well-versed regarding construction, solar energy applications and the adoptability of wall-mounted panels (Saunders et al., 2019). Among the respondents, R10 had the most knowledge regarding the study topic, as a solar energy specialist. R2 and R9 had worked with reputed solar-power suppliers for over two years in their careers. R3, R4, R6, R7 and R8 knew regarding solar energy and solar panel installation through project work experience. R1 and R5, who had the least years of work experience, had worked in projects which utilised solar power and therefore, had sufficient exposure to the subject. The profiles of the chosen respondents (Nr =10) have been illustrated in Table 1.

Table 1: Semi-structured interview respondent profile

Code	Profession	Years of Experience			
		Below 10	10-20	21-30	Over 30
R1	Architect	✓			
R2	Architect		✓		
R3	MEP Engineer		✓		
R4	MEP Engineer			✓	
R5	Quantity Surveyor	✓			
R6	Quantity Surveyor			✓	

Code	Profession	Years of Experience			
		Below 10	10-20	21-30	Over 30
R7	Civil Engineer		✓		
R8	Civil Engineer				✓
R9	Project Manager				✓
R10	Solar energy specialist				✓

The qualitative data was structured and summarised using manual content analysis. Manual content analysis was preferred over software-based analysis because it allowed the information to be contextualised better, thus capturing the opinions and other subjective elements of the interview findings.

4. ANALYSIS

4.1 AVAILABILITY OF WALL-MOUNTED SOLAR PANELS IN SRI LANKA

Considering the broad range of disciplines from which the respondents hailed, the authors were able to gather a wide variety of knowledge. The semi-structured interviews commenced with a set of questions which gathered demographic data and primary data of the interviewees. In the beginning, all interviewees identified solar energy as a good source of renewable energy, unanimously agreeing on its renewable and unlimited nature. The interviewees were inquired regarding the availability of wall-mounted solar panels in Sri Lanka. Out of the ten respondents, nine (Nr=9) stated that this concept is not available in Sri Lanka yet, while one respondent (Nr=1) R2, stated that there is a possibility that the concept may have been introduced to Sri Lanka already. However, R10 confirmed that the Sri Lanka Sustainable Energy Authority (SLSEA) has not permitted the installation of wall-mounted solar panels in Sri Lanka yet.

4.2 SUITABILITY OF WALL-MOUNTED SOLAR PANELS FOR HIGH-RISE BUILDINGS IN SRI LANKA

Among the ten respondents, nine (Nr=9) stated that there are advantages of wall-mounted solar panels that make them suitable for Sri Lanka. R5 and R8 expressed concerns regarding the cost implications. R10 pointed out that because the main point of concern for the clients is the cost, the feasibility highly depends on the cost difference between wall-mounted solar panels and rooftop solar panels. R5 stated that considering the novelty of the concept in Sri Lanka, finding suitable contractors, experts and consultants would be difficult, and thus costly. On the other hand, R2 and R10 believed that this concept would be ideal for high-rise buildings. The walls of high-rise buildings can accommodate a bulk area, particularly in a country such as Sri Lanka which is primarily sunny for most of the year. For these reasons, R2 and R10 maintained that wall-mounted panels could generate a large amount of electricity. However, R9 held the view that the disadvantages of this concept outweigh the advantages and that the effectiveness is far lesser compared to rooftop solar panels. R9 argues that considering the lower efficiency, the adoption of wall-mounted panels will not be feasible, especially when a more suitable option is already in use.

4.3 BARRIERS TOWARDS ADOPTING WALL-MOUNTED SOLAR PANELS INTO HIGH-RISE BUILDINGS IN SRI LANKA

A critical barrier towards adopting wall-mounted solar panels is the lack of a regulated procedure in Sri Lanka to implement the concept. R10 elaborated that at present, only rooftop, ground-mounted and floating solar applications are in use in Sri Lanka. Sri Lanka Sustainable Energy Authority (SLSEA) is the regulatory body of Sri Lanka responsible for the implementation, regulation and monitoring of sustainable energy applications. The authors further verified this by contacting the SLSEA, which revealed that there is no legal framework available to approve wall-mounted solar applications for Sri Lanka. Further, the SLS quality certificates only exist for the above-mentioned solar applications. The trajectory of the sun is another barrier towards the implementation of wall-mounted solar in Sri Lanka. Sri Lanka is closer to the equator compared to European countries. Therefore, the sun passes directly above the country, whereas in the West, the trajectory is slightly tilted, making it ideal to utilise wall-mounted solar panels. R10 stated that several pilot tests conducted by their organisation have revealed the negative impact caused by the sun's trajectory.

A major barrier that most respondents recognised is the initial investment compared with the effectiveness of wall-mounted solar panels. R1, R3, R5, R6, R7, R9 and R10 expressed concerns regarding the capital investment recovery period. To quote R10, "*Wall-mounted solar panels may have its advantages, but when compared to roof-top solar, it takes a longer time to generate the same number of units. This ultimately means that it is harder to recover the initial investment*". Compared to rooftop solar panels, wall-mounted solar panels receive less time of sunlight. According to R9 and R10, the peak hours for typical solar panels to generate electricity are 10 am to 2 pm. However, according to R3 and R4, when compared with rooftop solar panels, the effectiveness of wall-mounted solar panels is around 50% less. Therefore, the quantity of electricity units produced is relatively less. Ultimately, the time taken to recover the initial investment increases. R7 stated that the investment recovery period has increased by about 80% compared to rooftop solar panels. R1 and R4 both noted that to accurately calculate the effectiveness and investment recovery period, a comprehensive quantitative study should be done on a case study basis. According to R4, "*This is a concept that must be explored further. We must not dismiss the advantages of wall-mounted solar due to the setbacks. But, to get the most accurate data, in-depth studies must be done to get the actual number*". Furthermore, R9 noted that "*To get the most out of the advantages of wall-mounted solar, we can use it in conjunction with roof-mounted solar*".

R1, R2, R3, and R4 expressed concern over the reflection of the sunlight falling on the wall-mounted solar panels. In the rooftop solar application, the reflected sunlight is not a major concern because it is directed back towards the sky. However, as stated by the interviewees, wall-mounted solar panels are more likely to reflect the sunlight horizontally, thus shining onto nearby buildings and interfering with their operations. To compound matters, this reflection can be a hindrance to nearby vehicle drivers, threatening to block their vision and cause accidents. The respondents concluded that unless mechanisms were implemented to redirect or block the reflected sunlight, the adaptability of wall-mounted panels would be greatly reduced due to this barrier. R4, who is an MEP engineer, noted that "*There have been suggestions made to the CEB about fixing solar panels along the expressway, to utilise the unused space. However, a major* *concern that arose was whether the panels would be a hindrance to drivers due to the reflection of sunlight*"

All respondents except R1 and R2 agreed that wall-mounted solar panels could increase the aesthetic appearance of the building. However, it is noteworthy that both R1 and R2 are experienced architects. They argue that due to the limited flexibility of the appearance of wall-mounted panels, it would give the buildings a monotonous and unappealing look. According to R1 and R2, the perspective of architects in general regarding the appearance of wall-mounted solar panels is negative due to the aforementioned reasons. This barrier is graver than it may be perceived because the best means of raising client awareness regarding wall-mounted solar panels is through the architect. If architects hold a critical opinion regarding this concept, it may be difficult to persuade clients regarding the concept's merits. R5 commented that wall-mounted solar panels may not be as effective if shadows are covering portions of the panels. R9 also mentioned that in a city with multiple high-rise buildings and other tall structures, there is a high chance for the panels to get blocked by the shadows, thus decreasing their efficiency. R7 and R8 agreed that this is a major barrier which could have architectural, as well as legal implications. Three (Nr=3) respondents claimed that wall-mounted solar panels can be difficult to maintain once installed. R1 stated that without a gondola system or window cleaning system, it would be difficult to maintain and repair the system. R6 and R8 voiced concerns over the cost it would incur for maintenance and repair works as the walls of high-rise buildings are not easily accessible. The interviewees pointed out that maintenance difficulties would be a significant barrier towards adoption in Sri Lanka, particularly in regions outside of the economic hub, Colombo.

Another problem identified by R3, R4, and R8 is that wall-mounted solar panels increase the temperature inside the building. Several interviewees brought up the building orientation as a barrier towards adoption. As the building cannot be rotated according to the path of the sun, wall-mounted solar panels should be installed after checking the maximum angle of effectiveness. Therefore, it would be difficult to apply this technology to all high-rise buildings. Furthermore, there are various elements including windows, balconies, etc, on the walls of high-rise buildings. Wall-mounted solar panels can interfere with the operations of those elements. Especially the apartment buildings facing the sea which have large windows. This type of technology cannot be used for such buildings. Another unique problem identified by R2 is that due to delayed payments by the CEB to those who generate electricity through solar panels and supply electricity to the national grid, potential clients are hesitant to invest in solar panels. Therefore, the probability of investing in a new solar application is bleak.

Table 2 encompasses a summary of the barriers that were identified through this study.

Table 2: Summary of identified barriers

Barrier	**Code**	**Arch.**		**MEP**		**QS**		**CE**		**PM**	**SE**	**Frequency**
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	
Permissions from SLSEA	B1										✓	1
Solar trajectory	B2		✓								✓	2
Initial investment return	B3	✓		✓		✓	✓	✓		✓	✓	7

Barrier	**Code**	**Arch.**		**MEP**		**QS**		**CE**		**PM**	**SE**	**Frequency**
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	
Reflection of sunlight	B4	✓	✓	✓	✓							4
Aesthetic appearance	B5	✓	✓									2
Shadows on the panels	B6					✓		✓	✓	✓		4
Maintenance	B7	✓					✓		✓			3
Increased building temperature	B8			✓	✓				✓			3
Building orientation	B9				✓		✓			✓		3
Blocking other wall elements	B10			✓		✓				✓		3
Late payments to clients	B11		✓									1

4.4 STRATEGIES TO OVERCOME BARRIERS

Multiple respondents stated that a proper policy is needed for wall-mounted solar panels. After consulting with the SLSEA, the authors were informed that yet, the output of the wall-mounted solar panels has not been allowed to connect to the national grid. However, a pilot project has been proposed that has the support of the SLSEA. It was concluded that to enforce a policy, firstly a wall-mounted solar panel project should be done properly with the intervention of the government or by SLSEA or any other subsidiary body and its results should be monitored. According to the observations of the pilot project, problems and strategies should be identified for them and a fitting policy should be implemented so that wall-mounted solar panels can be used properly for construction projects in Sri Lanka.

The main problem for any solar application is the high initial cost. The specific problem with wall-mounted solar panels is that since the efficiency is lower, it takes a relatively longer time to recover the investment. Respondents suggested that through government intervention, tax concessions can be made to reduce the initial cost, thus reducing the investment recovery period. This creates a win-win situation where clients can afford this renewable energy source for a low cost whereas the government can benefit from the increase of solar energy use within the country, which in turn is a long-term economically sustainable solution. The experts further suggested that if wall-mounted solar panel application can be carried out at an industrial scale, there will be a shared risk with mass benefits. Due to the path of the sun, the way the sunlight hits the walls of high-rise buildings changes. Therefore, if solar panels are fixed firmly on the walls of high-rise buildings, the time the solar panels receive sunlight will be limited. As many interviewees said, if the solar panels are installed in an adjustable manner, sunlight can be received on the solar panels for a relatively long time. It can increase the efficiency of wall-mounted solar panels. Electricity generation can be increased by using high-efficiency solar panels.

Another problem identified previously is that the wall-mounted solar panels interfere with the elements on the walls and obstruct the outside view of the people inside the building. One of the strongest objections of both architects was that the aesthetic of the building would be lost due to these wall-mounted solar panels. As a strategy for this, R2 suggested that it is appropriate to use transparent solar panels. This is a very good strategy in terms of aesthetic appearance and visibility. However, transparent solar panels are very expensive. Therefore, if transparent solar panels are used, the initial cost will increase even more. When considering a high-rise building wall, according to the sun's path, the sunlight falls on it only in the morning or evening. Therefore, R3 and R9 suggested that if wall-mounted solar panels can be installed on both sides of the building, the solar panels can capture sunlight at any time of the day. However, R3 further stated that although the amount of electricity generated will be increased, the initial cost will increase by about 80%. To prevent the shadows of other buildings falling from the panels, it was suggested that the panels should be installed at the highest possible points of the buildings.

A major barrier identified was that wall-mounted solar panels reflected sunlight onto other buildings. As a solution, R1 suggested that if the surface can be given a matte-finish surface, the reflection can be prevented. Generally, those who produce electricity by solar panels and contribute to the national grid are paid according to the unit quantity. However, due to reasons such as the current economic crisis in Sri Lanka, these payments have been delayed. R2 suggests that if the payments are paid at an attractive rate, people will invest in wall-mounted solar panels. If wall-mounted solar panels are feasible in Sri Lanka, this would be a good strategy for marketing.

Table 3: Summary of suggested strategies

Strategy	**Code**	**Arch.**		**MEP**		**QS**		**CE**		**PM**	**SE**	**Frequency**
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	
Carry out a regulated pilot project to enforce a policy on wall-mounted solar panels	S1							✓			✓	2
Provide tax concessions to ease initial investment and speed up return	S2		✓			✓		✓				3
Implement wall-mounted solar panels on industry scale	S3	✓										1
Install panels in an adjustable manner	S4				✓		✓		✓	✓		4
Use transparent solar panels	S5		✓									1
Install panels on multiple sides of the building	S6			✓						✓		2
Install as high as possible	S7			✓		✓						2
Panels with matte-finish surface	S8	✓										1
Timely and sufficient payments to users	S9		✓									1

5. DISCUSSION

In the context of Sri Lanka, the concept of wall-mounted solar panels is entirely novel and untested. This exploratory study aimed to investigate the suitability of this concept for Sri Lanka and bridge the knowledge gap surrounding the adaptability of wall-mounted panels in Sri Lanka. Eleven (Nr=11) significant barriers were discovered through this study. The expert interviewees agreed that adjustable wall-mounted solar panels could be a solution to prevent shadows, blocks and solar trajectory issues (S4). Similar studies (Osigbemeh et al., 2022; Nguyen et al., 2019) have introduced design and mounting implementations for wall-mounted solar panels hence maximum efficiency can be obtained. Therefore, this strategy (S4) can be an effective solution when implementing wall-mounted solar within Sri Lanka. The authors recommend for this strategy to be explored through further research, to investigate the ideal implementation layout for wall-mounted solar panels in Sri Lanka. Certain strategies that were discussed by the respondents are useful to overcome specific barriers, however, they are not feasible in the context of Sri Lanka. For example, installing wall-mounted solar panels on both sides of the building can capture sunlight at different times of the day (S6). However, S6 may not be economically viable for Sri Lanka, where the main concern of clients is the initial cost. Using transparent solar panels (S5) can solve the issue of sunlight reflection, which was the main barrier identified in this study (B4). However, this option is also significantly costly and may not be feasible when applied to Sri Lanka. The most pressing concern within Sri Lanka is the high initial investment associated with wall-mounted solar panels, and the subsequent period of return (B3). Most interviewees expressed doubt whether the invested amount can be recovered within a reasonable time given that the effectiveness of the supplied energy is comparatively less than rooftop solar panels. The same issue was observed by Osigbemeh et al. (2022) in a study on the plausibility of using wall-mounted photovoltaics in inaccessible or restricted rooftops. However, according to Osigbemeh et al. (2022), wall-mounted solar panels displayed an 80% power efficiency on typical sunny days compared to the 100% efficiency of roof-mounted solar. Therefore, the findings present wall-mounted photovoltaics as an efficient alternative to rooftop solar, where the roof area is inaccessible. Additionally, this study suggests that government intervention to provide tax concessions can help ease the burdens of barriers such as B3 and that it would motivate more investment in solar energy (S2).

6. CONCLUSIONS

The construction industry must take proactive measures to enhance sustainability and reduce the energy consumption of its activities. Embracing solar power stands out as a compelling solution in this context. Although Sri Lanka employs solar energy, the concept of wall-mounted solar panels is still novel within the country. This concept has massive space-saving and sustainable potential if it can be utilised for high-rise buildings in Sri Lanka, where the limited rooftop area is often an issue when implementing solar energy. This research acts as an exploratory study which begs the question if wall-mounted solar panels are a feasible option for Sri Lanka. This study aims to investigate the adaptability of the wall-mounted solar panel design concept in high-rise buildings in Sri Lanka. Through this aim, the study shall bridge the knowledge gap of whether the concept is suitable to be pursued in Sri Lanka, with an emphasis on the views of solar energy experts and construction professionals. The first objective of the study was to review the concept of wall-mounted solar panel design, its importance and its availability in Sri Lanka. This objective was achieved through an in-depth literature review which gathered and summarised the existing discourse on wall-mounted solar panels. The knowledge gap, especially in the context of Sri Lanka was highlighted through the literature review. The next objectives were to investigate the suitability and the associated barriers to adopting wall-mounted solar panels in high-rise buildings in Sri Lanka and to propose strategies to overcome the identified barriers. Eleven barriers were identified by this study and nine strategies were proposed. However, some strategies were not entirely feasible for Sri Lanka, especially considering the high cost. This study concludes that while the concept of wall-mounted solar energy has merit, the feasibility must first be tested through a pilot project. As noted by the interviewees as well as through past studies, wall-mounted solar panels present some advantages that must not be overlooked and could even be used in conjunction with rooftop solar panels, where space limitations are an issue. Thus, even if no projects with this concept have been completed in Sri Lanka yet, it would be extremely important to test this concept here as it contributes to sustainability, which is crucial for the building sector. Additionally, it is a viable solution to the energy crisis, which is a global mission for Sri Lanka.

7. REFERENCES

Allouhi, A., Fouih, Y. E., Kousksou, T., Jamil, A., Zéraouli, Y., & Mourad, Y. (2015). Energy consumption and efficiency in buildings: Current status and future trends. *Journal of Cleaner Production*, *109*, 118–130. https://doi.org/10.1016/j.jclepro.2015.05.139

Asdrubali, F., & Desideri, U. (Eds.). (2019). *High efficiency plants and building integrated renewable energy systems*. In Elsevier eBooks (1st ed., pp. 441–595). https://doi.org/10.1016/b978-0-12-812817-6.00040-1

Baidya, S., & Nandi, C. (2020). *Green energy generation using renewable energy technologies*. *In green energy and technology* (pp. 259–276). Springer Singapore. https://doi.org/10.1007/978-981-15-4246-6_16

Bhatia, S. (2014). *Solar devices*. In Elsevier eBooks (pp. 68–93). https://doi.org/10.1016/b978-1-78242-269-3.50003-6

Devi, L. P., & Palaniappan, S. (2017). A study on energy use for excavation and transport of soil during building construction. *Journal of Cleaner Production*, *164*, 543–556. https://doi.org/10.1016/j.jclepro.2017.06.208

Dräger, P., & Letmathe, P. (2022). Value losses and environmental impacts in the construction industry – Tradeoffs or correlates? *Journal of Cleaner Production*, *336*, 130435. https://doi.org/10.1016/j.jclepro.2022.130435

Fellows, R. F., & Liu, A. M. M. (2015). *Research methods for construction*. John Wiley & Sons.

Hussain, C. M. (Ed.). (2018). *Engineered nanomaterials for energy applications*. In Elsevier eBooks (1st ed., pp. 751–767). https://doi.org/10.1016/b978-0-12-813351-4.00043-2

Hussain, C. M., Paulraj, M. S., & Nuzhat, S. (2022). *Source reduction and waste minimization in construction industry*. In Elsevier eBooks (pp. 111–126). https://doi.org/10.1016/b978-0-12-824320-6.00005-8

Jakštas, T. (2020). *What does energy security mean?* In Elsevier eBooks (pp. 99–112). https://doi.org/10.1016/b978-0-12-817688-7.00005-7

Khare, V., Khare, C., Nema, S., & Baredar, P. (2023). *Fundamental and basic principles*. In Elsevier eBooks (pp. 1–33). https://doi.org/10.1016/b978-0-323-85761-1.00005-6

Kiboi, T. M., & Moses, P. M. (2022). Effectiveness of vertically mounted solar panels on buildings - A case study of Radisson Blu Hotel, Nairobi. *2022 IEEE PES/IAS PowerAfrica*. https://doi.org/10.1109/powerafrica53997.2022.9905393

Kurian, J., & Karthi, L. (2021). Building integrated photovoltaics- an overview. *SAFER*, *10*(1). https://doi.org/10.7770/safer-v10n1-art2495

Letcher, T. M. (2022). *Global warming, greenhouse gases, renewable energy, and storing energy*. In Elsevier eBooks (pp. 3–12). https://doi.org/10.1016/b978-0-12-824510-1.00011-8

Mellit, A., & Kalogirou, S. A. (2022). *Solar radiation and photovoltaic systems: Modeling and simulation*. In Elsevier eBooks (pp. 1–41). https://doi.org/10.1016/b978-0-12-820641-6.00001-6

Min, J., Yan, G., Abed, A. M., Elattar, S., Khadimallah, M. A., Jan, A., & Ali, H. E. (2022). The effect of carbon dioxide emissions on the building energy efficiency. *Fuel*, *326*, 124842. https://doi.org/10.1016/j.fuel.2022.124842

Nguyen, L. D. L., Ngoc, S. D., Cong, D. T., Thuong, D. L., Van, S. N., Vu, N. H. M., & Le, N. T. (2019). *Facade integrated photovoltaic systems: Potential applications for commercial building in Vietnam*. In 2019 International Conference on System Science and Engineering (ICSSE). https://doi.org/10.1109/icsse.2019.8823134

Osigbemeh, M. S., Asaolu, O., & Nwachukwu, A. N. (2022). Sustainable solar power from wall mounted photovoltaics. *Energy Systems*, *14*(4), 1007–1022. https://doi.org/10.1007/s12667-021-00497-x

Peng, J., Yan, J., Zhai, Z., Markides, C. N., Lee, E. S., Eicker, U., Zhao, X., Kuhn, T. E., Sengupta, M., & Taylor, R. A. (2020). Solar energy integration in buildings. *Applied Energy*, *264*, 114740. https://doi.org/10.1016/j.apenergy.2020.114740

Pérez, M., Fthenakis, V., Kim, H. C., & Pereira, A. O. (2012). Façade–integrated photovoltaics: A life cycle and performance assessment case study. *Progress in Photovoltaics*, *20*(8), 975–990. https://doi.org/10.1002/pip.1167

Roberts, S., & Guariento, N. (2009). 4. *Design of the building envelope*. In De Gruyter eBooks (pp. 43–60). https://doi.org/10.1007/978-3-0346-0486-4_4

Saadatian, O., Haw, L. C., Sopian, K., & Salleh, E. (2013). A state of the art review of solar walls: Concepts and applications. *Journal of Building Physics*, *37*(1), 55–79. https://doi.org/10.1177/1744259113479336

Salama, F. (2018). *An analysis of the benefits of vertical solar photovoltaic systems and the effect of artificial ground cover on energy output*. University of Saskatchewan.

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research methods for business students*, (8th ed). https://www.researchgate.net/publication/330760964_Research_Methods_for_Business_Students_Chapter_4_Understanding_research_philosophy_and_approaches_to_theory_developmentŞenpinar, A. (2018). *Optimization of slope angles of photovoltaic arrays for different seasons*. In Elsevier eBooks (pp. 507–521). https://doi.org/10.1016/b978-0-12-813734-5.00028-7

Sharma, A. K., & Kothari, D. P. (2017). Solar PV facade for high-rise buildings in Mumbai. International *Journal of Civil Engineering Research*, *8*(1), https://www.ripublication.com/ijcer17/ijcerv8n1_02.pdf

Smith, B., Dvorak, J. S., Semmens, K., & Colliver, D. G. (2022). Using a computer-based selection model for sizing of solar panels and battery back-up systems for use in a floating in-pond raceway. *Aquacultural Engineering*, *97*, 102238. https://doi.org/10.1016/j.aquaeng.2022.102238

Soga, T. (2006). *Fundamentals of Solar Cell*. In Elsevier eBooks (pp. 3–43). https://doi.org/10.1016/b978-044452844-5/50002-0

Yan, J., Yang, Y., Campana, P. E., & He, J. (2019). City-level analysis of subsidy-free solar photovoltaic electricity price, profits and grid parity in China. *Nature Energy*, *4*(8), 709–717. https://doi.org/10.1038/s41560-019-0441-z

Zhou, Z., He, Y., Jia, L., & Zhang, X. (2019). Feasibility of balcony wall-mounted solar water heating system in high-rise residential buildings. *Journal of Engineering Science and Technology Review*, *12*(6), 142–147. https://doi.org/10.25103/jestr.126.18

Sendanayake, H., Nawarathna, A. and Fernando, N., 2024. Exploring opportunities and challenges in integrating Industry 4.0 for advancements in the Sri Lankan construction sector. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 470-480. DOI: https://doi.org/10.31705/WCS.2024.37. Available from: https://ciobwcs.com/papers/

EXPLORING OPPORTUNITIES AND CHALLENGES IN INTEGRATING INDUSTRY 4.0 FOR ADVANCEMENTS IN THE SRI LANKAN CONSTRUCTION SECTOR

Hasara Sendanayake[1], Amalka Nawarathna[2], and Nirodha Fernando[3]

ABSTRACT

Industry 4.0 (I4.0) holds significant potential for the construction sector by introducing advanced technologies and innovative practices that enhance efficiency, productivity, safety, and sustainability. However, the Sri Lankan construction industry is still in the early stages of adopting these novel technologies. Therefore, this research investigates the potential opportunities and challenges of implementing I4.0 in the Sri Lankan construction industry. A survey approach was employed, incorporating a comprehensive literature review and a questionnaire conducted among building and construction professionals in Sri Lanka. The findings revealed that respondents identified efficient resource management, optimised construction processes, energy efficiency, and waste management as the top opportunities of I4.0. Conversely, they ranked high initial costs, a lack of skilled workforce, resistance to change, and limited industry standards as significant challenges. To unveil the benefits of I4.0, policymakers and industry professionals must collaborate to mitigate these challenges. Key recommendations include strategic investments, robust training programs, enhanced industry standards, and effective change management strategies.

Keywords: *Construction Industry; Industry 4.0; Sri Lanka.*

1. INTRODUCTION

I4.0, known as the Fourth Industrial Revolution, is a concept that guides the adoption and implementation of advanced digital technologies to achieve the desired transformations in industrial processes (Popkova et al., 2019). It comprises several technological pillars, including the Internet of Things (IoT), Big Data and Analytics, Artificial Intelligence (AI) and Machine Learning (ML), Cloud Computing (CC), Cyber-Physical Systems (CPS), Additive Manufacturing (3D Printing), Augmented Reality (AR) and Virtual Reality (VR), Blockchain Technology, Robotics, and Drones.

[1] Postgraduate Student, School of Architecture and Environment, University of The West of England, UK, hasarasendanayake@gmail.com
[2] Senior Lecturer, School of Architecture and Environment, University of The West of England, UK, amalka.nawarathna@uwe.ac.uk
[3] Associate Professor, School of Computing Engineering and the Built Environment, Edinburgh Napier University, UK, N.Fernando@napier.ac.uk

These technologies are dramatically transforming various industries, enhancing efficiency, productivity, safety, and sustainability (Daribay et al., 2019). The construction industry is one of the sectors reaping significant benefits from this concept.

Alaloul et al. (2016) emphasised that the construction industry, compared to others, has a unique potential to incorporate the I4.0 concept into its practices. Consequently, several recent studies have focused on the adoption of I4.0 technologies in the construction industry. Research by Gálvez-Martos et al. (2018) and Yang et al. (2020) identified that I4.0 technologies could be successfully integrated to enhance core construction capacities in project management, cost control, contract administration, procurement, and health and safety management. Additionally, the World Economic Forum (2016) highlighted that these technologies help make construction more environmentally friendly and sustainable. Moreover, Moshood et al. (2020) and Balasubramanian et al. (2021) noted that I4.0 presents a fantastic opportunity to advance sustainability in the construction sector in terms of social, environmental, and economic aspects. Recognising this potential, many countries are developing national policies to incorporate I4.0 initiatives within the construction sector to compete in the global economy (Bortolini et al., 2017), with this adoption being more visible in developed countries.

Despite the rapid development of the buildings and construction sector in developing countries, the adoption of technological aspects remains relatively low. Sri Lanka is one such country. Therefore, this study aims to investigate the potential challenges and opportunities of implementing I4.0 to advance the Sri Lankan construction sector. This paper initially presents a comprehensive literature review on I4.0 technologies and the general opportunities and challenges associated with their implementation. Subsequently, it discusses the findings related to the specific opportunities and challenges in the Sri Lankan construction industry and offers recommendations for overcoming these challenges.

2. LITERATURE REVIEW

2.1 INDUSTRY 4.0 AND OPPORTUNITIES TO IMPROVE THE CONSTRUCTION INDUSTRY

The construction industry, once known for its reliance on traditional methods and tools (Tay et al., 2017), is currently benefiting from I4.0 technologies, enhancing project quality, efficiency, safety, and sustainability (Maskuriy et al., 2019). All the technological pillars identified in Figure 1 can be leveraged to improve the construction sector in different ways.

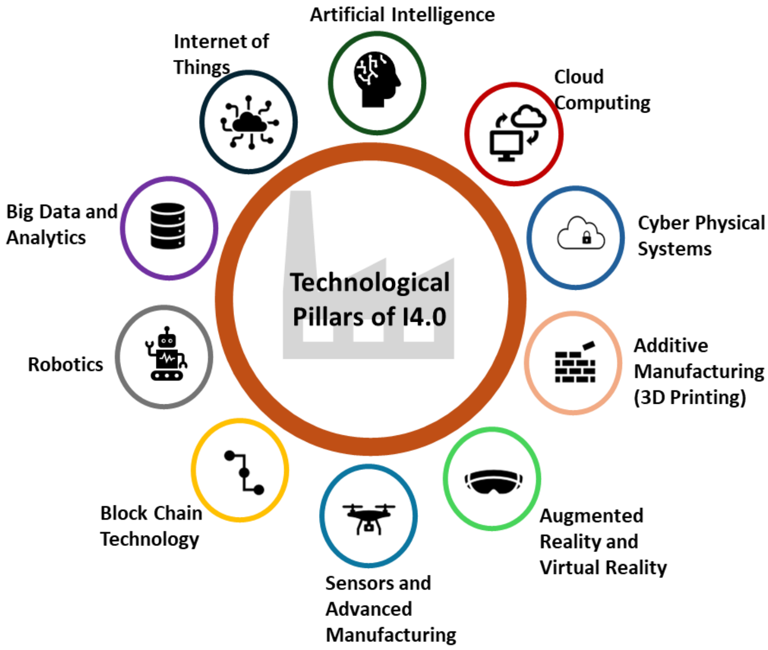


Figure 1: Technological pillars of I4.0

Technologies such as IoT and data analytics enable efficient resource management through real-time monitoring and analysis (Kumar & Shoghili, 2018; Javaid et al., 2022). Predictive maintenance, powered by these technologies, helps prevent costly equipment breakdowns (Agostinelli, 2023; Ferreiro et al., 2016). Optimised construction processes are achieved through Building Information Modelling (BIM), which minimises errors and wastage via 3D printing and simulations (Liu et al., 2015; Turner et al., 2020).

Construction projects can reduce waste by optimising material usage through real-time data collection, monitoring, and data analytics (Balasubramanian et al., 2021). Intelligent sensors monitor the number of resources used, while automated systems identify material recycling and reuse options (Costa et al., 2022). Energy efficiency is improved with smart HVAC systems, lighting, and renewable energy integration, optimising energy use based on real-time conditions (Newton, 2022; Minoli et al., 2017).

Achieving green building certification is simplified with tools that track energy use and sustainability indicators (Bonilla et al., 2018; Balasubramanian et al., 2021). Additionally, architects and engineers can produce highly customised and unique building designs using augmented reality and virtual reality technologies (Pech & Vrchota, 2022).

Regardless of the physical location, real-time collaboration technologies such as cloud computing enable all parties involved in construction projects to collaborate effectively (Erboz, 2017). These platforms facilitate better communication, faster decision-making, and rapid problem-solving (Saini et al., 2019).

Further, IoT sensors such as drones enhance construction site safety by tracking the real-time positions of workers, identifying hazardous situations, lowering risks, and ensuring the safety of both the public and workers (Javaid et al., 2022; Yasar & Gillis, 2024).

Improved safety procedures ensure the well-being of people and contribute to more sustainable construction projects (Oke & Arowoiya, 2021).

2.2 CHALLENGES OF IMPLEMENTING I4.0 FOR THE CONSTRUCTION INDUSTRY

Despite the substantial opportunities and promising sustainable and efficient construction practices offered by I4.0 technologies, several challenges hinder their full implementation.

One significant obstacle is the high initial cost associated with adopting I4.0 technologies. Integrating sensor systems, IoT devices, VR equipment, and customised automated machinery, as well as replacing outdated systems incompatible with I4.0 innovations, poses a substantial financial burden on construction companies, especially smaller ones (Sony & Aithal, 2020; Oesterreich & Teuteberg, 2016). Additionally, the lack of a skilled workforce proficient in digital technology operations, data analysis, and automation system troubleshooting is a major barrier (Huang et al., 2019).

Integrating advanced technologies while adhering to existing rules presents significant regulatory and compliance challenges. Building codes and standards often require updates to accommodate novel construction methods and materials introduced by I4.0 technologies which is a current challenge (Kozlovska et al., 2021).

The lack of standardised protocols in the construction industry further complicates I4.0 implementation. Establishing best practices is challenging without standard guidelines, necessitating collaboration with regulatory bodies to create standardised procedures (Kozlovska et al., 2021). Data security and privacy require significant attention. Construction firms must establish explicit privacy policies, ensure data encryption, and implement robust cybersecurity measures while adhering to data protection laws (Erboz, 2017).

Calculating the Return on Investment (ROI) for I4.0 investments is another challenge due to the time required for significant cost and efficiency reductions to materialise. Construction firms need precise parameters for calculating ROI and regular assessments of their technological expenditures (Demirkesen & Tezel, 2022).

The significant volume of data generated by I4.0 technologies complicates decision-making processes in construction. Advanced data analytics and visualisation tools are essential to streamline decision-making and accelerate the process (Erboz, 2017). Moreover, the unique nature of each construction project demands specialised solutions, which are often resource-intensive and time-consuming, underscoring the necessity for construction firms to exhibit adaptability (Maskuriy et al., 2019)

Lastly, cultural and organisational resistance further complicates the adoption of technologies. Traditional corporate cultures and practices can impede the transition to technology-driven processes, necessitating a deliberate change management approach, open communication, and leadership commitment (Muñoz-La Rivera et al., 2021). Ethical considerations also arise, particularly concerning employment displacement due to automation and robotics (Brown, 2018).

3. RESEARCH METHOD

This study employed a survey supported by a literature review and a questionnaire. The literature review enabled the identification of opportunities and challenges in implementing I4.0 technologies. These identified challenges and opportunities were incorporated into a five-point Likert scale (1=strongly disagree to 5=strongly agree), and respondents were asked to rate them accordingly.

Building professionals primarily involved in building and civil engineering projects within public and private sector construction organisations in Sri Lanka were targeted as respondents. The questionnaire survey was conducted online through Qualtrics software. The survey reached 60 professionals, resulting in 40 complete responses. Figures 2 and 3 illustrate the distribution of respondents and their work experience in the construction industry, respectively.

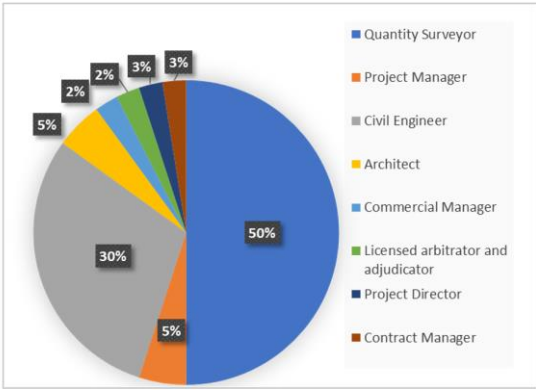


Figure 2: Distribution of respondents

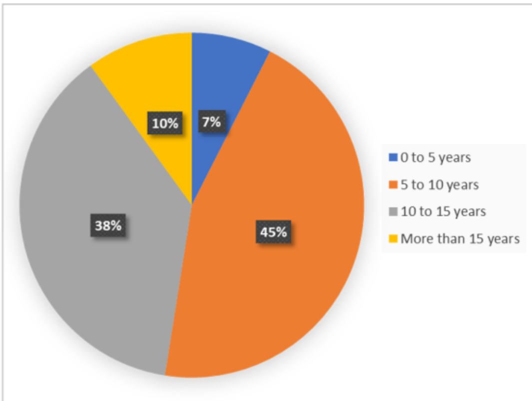


Figure 3: Work experience of respondents

The collected data were subsequently analysed using descriptive statistics and the Relative Importance Index (RII), enabling the systematic ranking of identified opportunities and challenges based on their perceived importance. This approach facilitated a clear understanding of the relative significance of each factor, guiding further discussions and strategic decision-making processes.

4. RESEARCH FINDINGS AND DATA ANALYSIS

Figures 4 and 5 illustrate the ranking of opportunities and challenges identified by respondents for implementing I4.0 in the Sri Lankan construction sector.

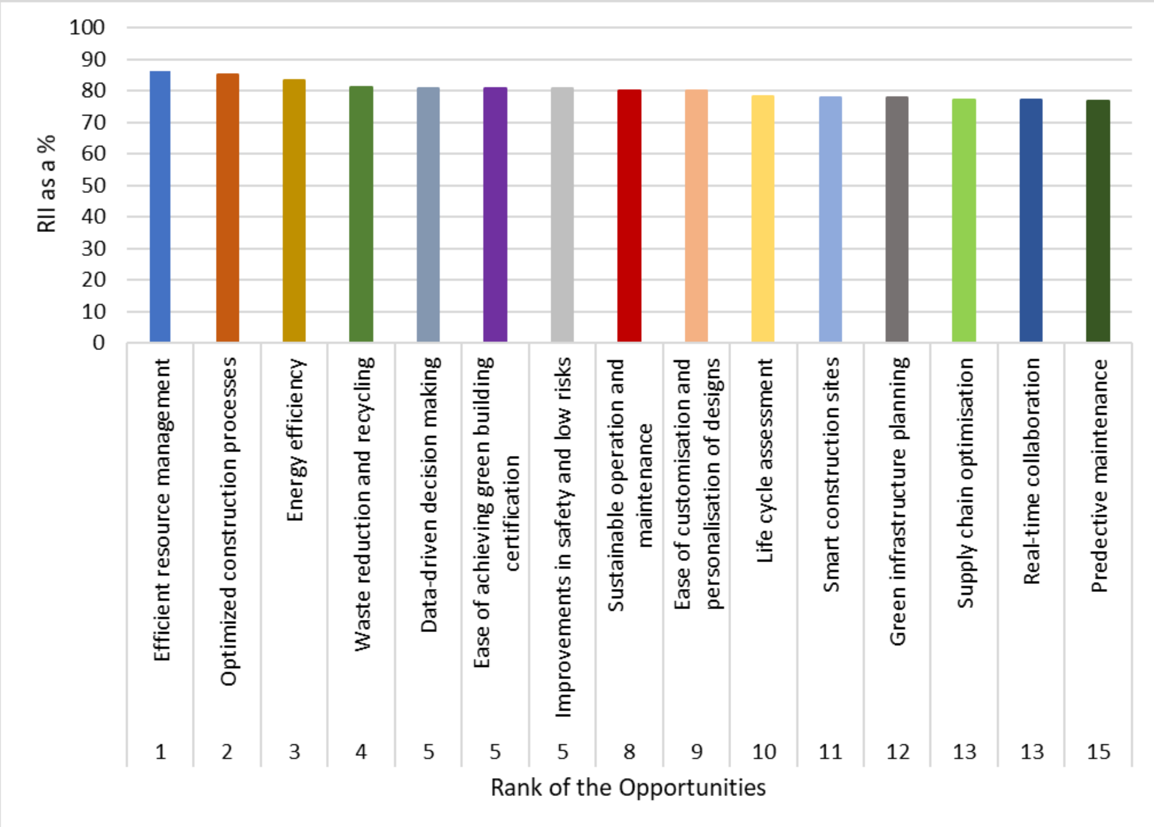


Figure 4: Opportunities for implementing Industry 4.0 in the construction sector in Sri Lanka

As depicted in Figure 4, the top three opportunities, in ascending order, include efficient resource management (86.1%), optimised construction processes (85.0%), and energy efficiency (83.3%). On the other hand, supply chain optimisation (77.20%), real-time collaboration (77.20%), and predictive maintenance (76.70%) were perceived as the least important opportunities.

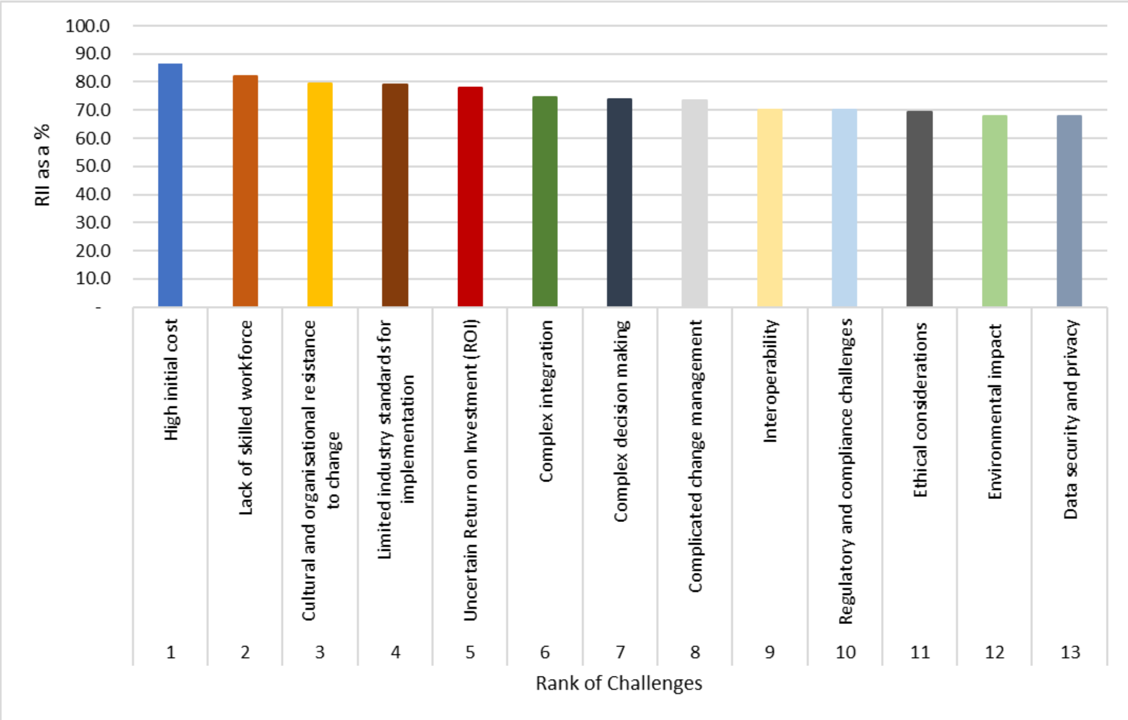


Figure 5: Challenges for implementing I4.0 in Sri Lankan construction industry

According to Figure 5, the top three challenges for implementing Industry 4.0 in the Sri Lankan construction industry are high initial cost (86.6%), lack of skilled workforce (82.2%), and resistance to change (79.4%). Conversely, ethical considerations (69.5%), environmental impact (67.70%), and data security (67.70%) were identified as the least significant challenges associated with adopting Industry 4.0 technologies.

5. DISCUSSION

Efficient resource management emerged as the foremost opportunity in Sri Lanka's adoption of I4.0. Implementation of IoT sensors and related technologies promises meticulous tracking of materials and equipment usage, thereby offering substantial reductions in waste generation and operational costs while enhancing overall sustainability (Al-Garadi et al., 2020). Following closely, respondents highlighted optimisation of construction processes as the second most significant opportunity. Unsurprisingly, optimisation is anticipated to lead to reductions in resource consumption, waste, errors, and project timelines (Maskuriy et al., 2019).

Energy efficiency ranked third among opportunities, highlighting how I4.0 technologies enable adjustments in building temperature and lighting based on occupancy, thereby enhancing overall energy efficiency (Minoli et al., 2017). The ability of construction professionals to make informed decisions on waste minimisation under sustainable practices was recognised as the fourth most important opportunity. Data-driven decision-making, ease in achieving green building certifications, and improvements in safety and risk management ranked fifth among opportunities. These aspects leverage massive data sets generated by I4.0 to support informed decision-making and streamline certification processes (Arowoiya et al., 2020; Balasubramanian et al., 2021). Moreover, IoT sensors integrated as wearable technology further enhance worker safety on construction sites (Oke & Arowoiya, 2021).

Conversely, predictive maintenance was deemed the least important opportunity among the identified 15 opportunities. This finding likely reflects the predominant focus of the surveyed construction project professionals rather than building environment professionals involved in the operational stage of buildings. Surprisingly, real-time collaboration among stakeholders ranked as the second least important opportunity. This may stem from limited awareness of relevant technologies and insufficient proficiency in working in real-time collaboration platforms.

Yet, alongside these opportunities, significant challenges accompany the implementation of Industry 4.0 in Sri Lanka's construction sector. Foremost among the challenges identified is the high initial cost, which stands as a predominant barrier. The adoption of Industry 4.0 technologies involves substantial expenses due to the new high-tech equipment and software required (Kelber, 2020). This financial burden is not unique to Sri Lanka but is similarly observed in other comparable countries.

The next closely ranked challenge is the lack of a skilled workforce capable of effectively utilising and maintaining these novel technological advancements. Competent staff is essential for effective I4.0 adoption (Huang et al., 2019). The current construction workforce in Sri Lanka needs significant training and upskilling to seamlessly integrate these technologies into their operations. Moreover, entrenched resistance to change within organisations and the industry itself poses another significant hurdle. Many experienced professionals in Sri Lanka are accustomed to legacy systems, intensifying their reluctance to adopt new technologies.

Further, respondents highlighted the limited industry standards for implementing Industry 4.0 in Sri Lanka as the fourth-highest challenge. This lack of standardisation complicates the integration of different technologies, necessitating closer engagement between technology experts, IT specialists, and the construction industry (Kozlovska et al., 2021).

Additionally, uncertain ROI, complex integration and decision-making, complicated change management processes, interoperability issues, and regulatory and compliance issues were identified as further challenges of implementing I4.0 in the Sri Lankan construction sector.

Ethical considerations such as job displacement due to technological transformation, environmental impacts such as high energy consumption for these technologies, and data security and privacy were rated as the least impactful challenges for the Sri Lankan construction industry. This is unsurprising for Sri Lanka, where many other pressing issues must be resolved first.

6. RECOMMENDATIONS FOR POLICYMAKERS AND INDUSTRY STAKEHOLDERS

It is evident that the implementation of I4.0 technologies significantly improves the efficiency, productivity, and sustainability of the construction sector. However, for the Sri Lankan construction industry to fully capitalise on these opportunities, it is crucial to address the associated challenges. Policymakers and industry stakeholders must collaborate closely to mitigate these challenges effectively.

Firstly, addressing the high initial costs associated with I4.0 technologies requires strategic investments, funding, government grants, and partnerships with technology providers. Additionally, it is essential to implement robust training and upskilling programs for the current workforce to ensure they are proficient in the use of these technologies.

Policymakers need to establish industry standards for the implementation of Industry 4.0 technologies. Developing clear guidelines and best practices will ensure smooth integration and compliance with existing regulations.

Furthermore, developing and executing robust change management plans will help address resistance within organisations. Fostering a culture that embraces technological advancements by demonstrating the long-term benefits of I4.0 is essential for overcoming resistance to change.

7. CONCLUSIONS

I4.0 presents a transformative opportunity to fully integrate humans and digitally controlled machinery, thereby enhancing the efficiency, productivity, safety, and sustainability of the construction sector. The technological pillars of I4.0 such as artificial intelligence, cloud computing, cyber-physical systems, augmented reality and virtual reality, 3D printing, robotics, and big data support the realisation of these opportunities. However, alongside these opportunities, numerous challenges arise, particularly for developing countries.

This study focused on Sri Lanka, aiming to investigate the opportunities for improvement and the challenges associated with implementing I4.0 in its construction sector. The findings revealed that to fully harness opportunities such as efficient resource management, optimised construction processes, energy efficiency, waste reduction and recycling, and improvements in safety and risk management, several critical challenges must be addressed. These challenges include high initial costs, a lack of skilled workforce, resistance to change, and limited industry standards.

Addressing these challenges will require a concerted effort from policymakers and industry stakeholders, including strategic investments, robust training programs, and the establishment of clear industry standards. By overcoming these barriers, Sri Lanka's construction sector can effectively leverage I4.0 technologies, leading to a more efficient, sustainable, and competitive industry.

8. REFERENCES

Agostinelli, S. (2023). COGNIBUILD: Cognitive digital twin framework for advanced building management and predictive maintenance. In E. Arbizzani et al. (Eds.), *Technological Imagination in the Green and Digital Transition*. *CONF.ITECH 2022. The Urban Book Series*. Springer, Cham. https://doi.org/10.1007/978-3-031-29515-7_8.

Alaloul, W. S., Liew, M. S., & Zawawi, N. A. B. W. A. (2016). A framework for coordination process into construction projects. In S. N. B. Kamaruzzaman, A. S. B. Ali, N. F. B. Azmi, & S. J. L. Chua (Eds.), *MATEC Web of Conferences* (Vol. 66, p. 00079). https://doi.org/10.1051/matecconf/20166600079

Al-Garadi, M. A., Mohamed, A., Al-Ali, A. K., Du, X., Ali, I., & Guizani, M. (2020). A survey of machine and deep learning methods for internet of things (IoT) security. *IEEE Communications Surveys & Tutorials*, *22*(3), 1646–1685. https://doi.org/10.1109/COMST.2020.2988293

Arowoiya, V. A., Oke, A. E., Aigbavboa, C. O., & Aliu, J. (2020). An appraisal of the adoption of internet of things (IoT) elements for sustainable construction. *Journal of Engineering, Design and Technology*, *18*(5), 1193–1208. https://doi.org/10.1108/JEDT-10-2019-0270

Balasubramanian, S., Shukla, V., Islam, N., & Manghat, S. (2021). Construction Industry 4.0 and sustainability: An enabling framework. *IEEE Transactions on Engineering Management*, *33*, 1–19. https://doi.org/10.1109/TEM.2021.3110427

Bonilla, S.H., Silva, H.R., Terra da Silva, M., Franco Gonçalves, R. and Sacomano, J.B., (2018) Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges. *Sustainability*, *10*(10), 3740. https://doi.org/10.3390/su10103740

Bortolini, M., Ferrari, E., Gamberi, M., Pilati, F., & Faccio, M. (2017). Assembly system design in the Industry 4.0 era: A general framework. *IFAC-PapersOnLine*, *50*(1), 5700–5705. https://doi.org/10.1016/j.ifacol.2017.08.1121

Brown, R. (2018). Robots, new technology, and industry 4.0 in changing workplaces: Impacts on labor and employment laws. *American University Business Law Review*, *7*, 349-360. https://heinonline.org/HOL/LandingPage?handle=hein.journals/aubulrw7&div=19&id=&page

Costa, M. M., Neto, J. F. B., Alberte, E. P. V., & Carneiro, A. P. (2022). Blockchain-based framework for improving waste management and circular economy in construction. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1101, No. 6, p. 062009). IOP Publishing. https://doi.org/10.1088/1755-1315/1101/6/062009

Daribay, A., Serikova, A., & Ukaegbu, I. A. (2019). Industry 4.0: Kazakhstani industrialization needs a global perspective. *Procedia Computer Science*, *151*, 903-908. https://doi.org/10.1016/j.procs.2019.04.127

Demirkesen, S., & Tezel, A. (2022). Investigating major challenges for industry 4.0 adoption among construction companies. *Engineering, Construction and Architectural Management*, *29*(3), 1470-1503. https://doi.org/10.1108/ECAM-12-2020-1035

Erboz, G. (2017). How to define Industry 4.0: Main pillars of Industry 4.0. In *Managerial trends in the development of enterprises in globalization era* (pp. 761-767).

Ferreiro, S., Konde, E., Fernández, S., & Prado, A. (2016). Industry 4.0: Predictive intelligent maintenance for production equipment. In *PHM Society European Conference* (Vol. 3, No. 1). https://doi.org/10.36001/phme.2016.v3i1.1667

Gálvez-Martos, J.-L., Styles, D., Schoenberger, H., & Zeschmar-Lahl, B. (2018). Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling*, *136*, 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016

Huang, C. J., Talla Chicoma, E. D., & Huang, Y. H. (2019). Evaluating the factors that are affecting the implementation of Industry 4.0 technologies in manufacturing MSMEs, the case of Peru. *Processes*, *7*(3), 161. https://doi.org/10.3390/pr7030161

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustainable Operations and Computers, 3,* 203–217. https://doi.org/10.1016/j.susoc.2022.04.001.

Kelber, J. (2020, April 21). *Is Industry 4.0 technology worth the cost?.* Flexis [blog]. Retrieved April 20, 2023, from https://blog.flexis.com/is-industry-4.0-technology-worth-the-cost

Kozlovska, M., Klosova, D., & Strukova, Z. (2021). Impact of Industry 4.0 platform on the formation of construction 4.0 concept: A literature review. *Sustainability*, *13*(5), 2683. https://doi.org/10.3390/su13052683

Kumar, A., & Shoghli, O. (2018). A review of IoT applications in supply chain optimization of construction materials. In ISARC. *Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 35, pp. 1–8). IAARC Publications.

Liu, Z., Osmani, M., Demian, P., & Baldwin, A. (2015). A BIM-aided construction waste minimisation framework. *Automation in Construction*, *59*, 1–23. https://doi.org/10.1016/j.autcon.2015.07.020.

Maskuriy, R., Selamat, A., Ali, K. N., Maresova, P., & Krejcar, O. (2019). Industry 4.0 for the construction industry—how ready is the industry?. *Applied Sciences*, *9*(14), 2819. https://doi.org/10.3390/app9142819

Minoli, D., Sohraby, K., & Occhiogrosso, B. (2017). IoT considerations, requirements, and architectures for smart buildings—Energy optimization and next-generation building management systems. *IEEE Internet of Things Journal*, *4*(1), 269-283. https://doi.org/10.1109/JIOT.2017.2647881

Moshood, T. D., Adeleke, A. Q., Nawanir, G., Ajibike, W. A., & Shittu, R. A. (2020). Emerging challenges and sustainability of Industry 4.0 era in the Malaysian construction industry. *International Journal of Recent Technology and Engineering (IJRTE)*, *9*(1), 1627-1634. https://doi.org/10.35940/ijrte.A3007.099120

Muñoz-La Rivera, F., Mora-Serrano, J., Valero, I., & Oñate, E. (2021). Methodological-technological framework for Construction 4.0. *Archives of Computational Methods in Engineering*, *28*, 689-711. https://doi.org/10.1007/s11831-020-09421-6

Newton, E. (2022, May 26). *Industry 4.0 can make commercial HVAC sustainable*. Insights for Professionals. Retrieved October 22, 2023, from https://www.insightsforprofessionals.com/management/compliance/industry-4-0-make-hvac-sustainable

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, *83*, 121-139. https://doi.org/10.1016/j.compind.2016.09.006

Oke, A. E., & Arowoiya, V. A. (2021). Evaluation of internet of things (IoT) application areas for sustainable construction. *Smart and Sustainable Built Environment, 10*(3), 387-402. https://doi.org/10.1108/SASBE-08-2019-0107

Pech, M., & Vrchota, J. (2022). The product customization process in relation to Industry 4.0 and digitalization. *Processes*, *10*(3), 539. https://doi.org/10.3390/pr10030539

Popkova, E. G., Ragulina, Y. V., & Bogoviz, A. V. (Eds.). (2019). *Industry 4.0: Industrial revolution of the 21st century* (p. 249). Cham: Springer. https://doi.org/10.1007/978-3-319-94310-7

Saini, H., Upadhyaya, A., & Khandelwal, M. K. (2019). Benefits of cloud computing for business enterprises: A review. In *Proceedings of International Conference on Advancements in Computing & Management (ICACM) 2019*. pp. 1003-1007. https://dx.doi.org/10.2139/ssrn.3463631

Sony, M., & Aithal, P. S. (2020). Developing an Industry 4.0 readiness model for Indian engineering industries. *International Journal of Management, Technology, and Social Sciences (IJMTS), 5*(2), 141-153. https://ssrn.com/abstract=3684688

Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N. A., Tan, M. J., & Leong, K. F. (2017). 3D printing trends in the building and construction industry: A review. *Virtual and Physical Prototyping, 12*(3), 261-276. https://doi.org/10.1080/17452759.2017.1326724

Turner, C. J., Oyekan, J., Stergioulas, L., & Griffin, D. (2020). Utilizing Industry 4.0 on the construction site: Challenges and opportunities. *IEEE Transactions on Industrial Informatics, 17*(2), 746-756. https://doi.org/10.1109/TII.2020.3002197

World Economic Forum. (2016). *Shaping the future of construction: A breakthrough in mindset and technology*. WEF Cologny: Geneva, Switzerland.

Yang, J., Yuan, H., & Zhang, L. (2020). Influence factors on general contractor capability in the context of transforming China. *Advances in Civil Engineering, 2020*, 1–18. https://doi.org/10.1155/2020/8874579

Yasar, K., & Gillis, A. S. (2024, June). *Internet of things (IoT)*. TechTarget. Retrieved July 18, 2024, from https://www.techtarget.com/iotagenda/definition/Internet-of-Things-IoT

Rajapaksha, E.G.L.S., Rathnayake, U. and Karunarathna, A.S.W., 2024. Feasibility assessment of smart grid technology for the Sri Lankan urban areas. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 481-494. DOI: https://doi.org/10.31705/WCS.2024.38. Available from: https://ciobwcs.com/papers/

FEASIBILITY ASSESSMENT OF SMART GRID TECHNOLOGY FOR THE SRI LANKAN URBAN AREAS

E.G.L.S. Rajapaksha[1], U. Rathnayake[2] and A.S.W. Karunarathna[3]

ABSTRACT

This study examines the viability of using smart grid technology in the urban areas of Sri Lanka as a solution to the electricity sector's challenges. Considering the elevated energy costs and reliance on costly fossil fuels, there is an urgent require for inventive alternatives. Smart grids have the potential to yield several advantages, including enhanced efficiency, seamless integration of renewable energy sources, and improved control of demand-side operations. The article assesses the viability and constraints of smart grids by conducting expert interviews and reviewing relevant existing literature. The development of an implementation framework is guided by insights provided by ten professionals from diverse sectors of the power sector. This study aims to identify the essential elements of smart grid systems that can be related to the Sri Lankan context including Advanced Metering Infrastructure (AMI), distributed energy resources, and demand response systems. Challenges including initial capital expenditures and risks related to cybersecurity are highlighted, with experts providing solutions for mitigation. A staged strategy for implementation, focusing on cost-effectiveness and cross-border cooperation is advocated. Methodologically, the study utilises qualitative analytic tools and semi-structured interviews to collect and analyse data. Findings from this study underscore the possibilities of smart grid technologies to enhance grid stability, reduce fossil fuel consumption, and improve dependability. Despite challenges, the study shows the necessity of smart grid deployment for attaining a more efficient, dependable, and sustainable energy system in Sri Lanka's urban areas.

Keywords: *Electricity; Feasibility Assessment; Renewable Energy; Smart Grid.*

1. INTRODUCTION

Sri Lanka is experiencing industrialisation, urbanisation, and rapid growth, resulting in a continuous increase in energy demand, and consequently, power consumption is rising every year (Asalanka, 2017). “Ceylon Electricity Board (CEB) is the government-owned electricity provider in Sri Lanka, which is struggling to cater to the increasing demand at an affordable cost. Overall, 10%-15% of electricity is wasted due to technical and non-technical losses in the national grid in Sri Lanka as in CEB Annual Reports 2013–2017”

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, lahirusampath1522@gmail.com
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, rmnuthpala@gmail.com
[3] Junior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, karunarathnasanduni1998@gmail.com

(Jayaratne et al., 2021). Farmanbar et al. (2019) argue that the current energy distribution system is one-way, with static consumer rates and simple meters that cannot transmit data in both directions. This limits utilities' ability to collect real-time data and provide consumers with information about their energy usage, hindering efficient grid management and personalised services.

In developing countries, recurrent electricity failures result in extended periods without power, limiting utilisation and benefits for industries, businesses, and households. This unreliable service poses a greater risk as dependency on electricity grows (Nduhuura et al., 2021). However, Sri Lanka is regarded as one of the least urbanised countries in the world. The majority of people in the nation about 81.7% remain concentrated in rural and plantation areas supported by the agricultural and Agri-based industries (Gasimli et al., 2019). Still, smart energy solution requirements have arisen in Sri Lanka aiming for the Colombo district as it acts as the heart of the Sri Lankan economy, and most of the socially and economically important places are located in the Colombo district (Asian Development Bank, 2023; Hamilton et al., 2010). Because energy is becoming more and more essential to modern living, complex distribution systems that provide two-way power flow and enhanced communication across microgrid components are required (Suryadevara & Biswal, 2019). The need for a smart grid emerges from this point, and it can deliver power in more effective ways and respond to a wide range of conditions and events by using two-way flows of electricity and information to create an automated and distributed advanced energy delivery network (Fang et al., 2012).

Within the Sri Lankan context, the pressing issue of electricity supply reliability and efficiency emerges, epitomised by technical and non-technical losses within the national grid (Amarasinghe & Perera, 2021; Jayaratne et al., 2021). Witharama et al. (2023) identified several factors that influencing the challenges of electricity market in Sri Lanka. This includes the high capital cost required to develop the necessary infrastructure, technical incapability, regulatory restraints, and limited infrastructure and resources within the country. As the country struggles to overcome these obstacles, the research question becomes clear as to how smart grid integration can be feasibly realised in Sri Lankan urban areas to improve smart city features, optimise energy consumption, and address the special difficulties associated with a developing country's urbanisation process. This research attempts to pave the path for supporting energy efficiency goals by examining the applicability, advantages, and limitations of smart grid adaption within Sri Lanka's urban fabric. Thus, this research aims to assess the feasibility of application of smart grid technology to Sri Lankan urban areas to contribute to energy efficiency approaches.

2. LITERATURE REVIEW

2.1 SMART GRID TECHNOLOGY

Hertzog and Stuart (2010) defines Smart Grid as a “bi-directional electric and communication network that improves the reliability, security, and efficiency of the electric system for small to large-scale generation, transmission, distribution, and storage”. In order to comprehensively monitor and regulate energy consumption on an extensive level, the Smart Grid system smoothly merges power system architecture and cutting-edge computer technology. Khan et al. (2020) and Jaber et al. (2023) identified that the concept of a smart grid refers to an evolving electrical network that encompasses many components including transmission lines, switches, transformers, protective equipment, sensors, and information technologies. Therefore, to make the most of the available resources, the smart grid network employs a transactive power structure together with techniques for predicting the medium- and short-term electricity demand (Haq et al., 2023).

2.2 SMART GRID TECHNOLOGY AND ARCHITECTURE

The key mechanism that allows smart grids is smart meters which are also referred to as AMI, enabling bi-directional, two-way communication between the consumer and the utility (Abrahamsen et al., 2021). Power Quality (PQ) monitoring features on AMI smart meters allow for quick detection, diagnosis, and resolution of PQ issues (National Energy Technology Laboratory, 2008). Demand response (DR) is a crucial feature of smart grid technology that helps utilities manage peak demand and reduce energy consumption through mechanisms like dynamic pricing, direct load control, and incentive programs (Bakare et al., 2023). Renewable energy sources are gaining popularity due to the potential to meet half of global energy demands by 2050, with smart grid systems offering energy security, environmental benefits, and conservation (Islam et al., 2014). The integration of renewable energy sources into the grid requires a more flexible and responsive system, which can be achieved through smart grid technology, enabling real-time power flow management and better supply-demand balance (Pragash et al., 2023). Smart grid dependability relies on control and communication systems, necessitating increased network connectivity and advanced security mechanisms to address cyber security flaws and breaches (Ghelani, 2022). Here it will require a proactive threat identification automated security analysis and dynamic measures should be taken to provide security and resilience for the system (Faquir et al., 2021).

2.3 NEED OF SMART GRID FOR SRI LANKA

The Sri Lankan power generation infrastructure has struggled to keep up with the nation's peak electrical consumption for the past 20 years (Nagahawatte, 2020). Kataray et al. (2023) identified that nearly 8% of the output of the conventional electrical grid is lost due to transmission lines, and 20% of its capacity is mostly used to fulfil peak demand. Sri Lanka's electricity distribution system has inefficiencies causing power outages, high bills, and environmental issues. CEB generates electricity from thermal, hydro, and renewable sources however the outdated distribution system lacks the infrastructure to meet growing demand (Asian Development bank, 2022). The current system faces high transmission and distribution losses in Sri Lanka, estimated at 10% in 2019. These losses result from technical inefficiencies (outdated equipment, poor maintenance) and non-technical issues (theft, illegal connections) (Hansika et al., 2021). Smart grid technology enables the active participation of both producers and consumers in network operation. Producers engage by utilising methods like time of use rate, real-time pricing, and direct load control to minimise energy usage and incentivise consumers to do the same (Young, 2017).

2.4 TECHNOLOGICAL, ECONOMIC, AND ENVIRONMENTAL ASPECTS OF IMPLEMENTING SMART GRID TECHNOLOGY

2.4.1 Technological Feasibility

As underlined by Alotaibi et al. (2020) the integration of smart grid technologies improves system resilience, improves energy efficiency, and facilitates real-time control and monitoring. However, as highlighted by Moreno Escobar et al., (2021) the deployment of such advanced technology demands a meticulous assessment of technical complexity, cybersecurity risks, and thorough legal frameworks. Fernando et al., (2017) declare that while Sri Lanka has made achievements in upgrading its energy infrastructure, concerns such as grid stability, interoperability, and workforce skill development still require special attention.

2.4.2 Economic Feasibility

The widespread adaption of Information and Communication Technology (ICT) in both the economic and social sectors has generated optimistic expectations regarding the potential reduction of energy consumption and emissions (Lange et al., 2020). On the contrary, Dorji et al., (2023) argue that the deployment of smart grid technologies encounters notable economic limitations, encompassing substantial initial expenditures, regulatory restrictions, and uncertainty regarding the profitability of the initiative. Here The economic feasibility of smart grids is contingent upon the capacity of stakeholders to effectively navigate the complicated socio-technical systems associated with them (Kumar, 2019).

2.4.3 Environmental Aspects

The environmental feasibility of implementing a smart energy system in Sri Lanka is crucial for sustainable energy development (Fernando, 2020). Smart grids can integrate renewable energy sources, reducing greenhouse gas emissions (Erickson & Brase, 2019). Ministry of Environment (2012) highlights that Sri Lanka's abundant renewable energy potential, including solar and wind resources, aligns with the country's commitment to climate change. Balancing intermittent renewable sources requires sophisticated grid management strategies. The life cycle environmental impact of smart grid components, such as advanced metering infrastructure, requires careful consideration (Aleksic & Mujan, 2016).

2.5 TECHNOLOGICAL INNOVATIONS AND INTERNATIONAL BEST PRACTICES IN SMART GRID APPLICATION

Table 1 illustrates the technology innovations and best practices in smart grid applications. It further discusses the usage of each innovation technology and best practice.

Table 1: Technology innovations and best practices in smart grid applications

Innovation/ Best Practice	Usage
Self-Healing Ability	Self-healing in smart grids involves distinguishing normal and abnormal functioning, enabling prompt fault detection through real-time monitoring. Objectives include swift fault detection, resource redistribution for reduced

Innovation/ Best Practice	Usage
	congestion, service continuity assurance under any condition, and minimising service restoration time (Thentral et al., 2019).
Integration of Electrical vehicle with SG	The rise of electric vehicles (EVs) necessitates a shift in the Transmission Network (TN) and Power Distribution Network (PDN) to manage dynamic charging demands, requiring smart grids for optimal load distribution and synchronised management in the evolving energy distribution landscape (Majeed Butt et al., 2021).
Distributed energy resources (DERs)	Distributed energy resources (DERs) are small-scale energy resources commonly positioned near areas of electricity demand, such as rooftop solar panels and battery storage. Their rapid expansion is revolutionising not merely the way electricity is generated, but the way it is traded, distributed, and utilised (International Energy Agency, 2022).
Usage of Big Data	Big data is crucial for smart grid decisions and autonomy, overcoming challenges in storage, visualisation, and security. Using diverse data, algorithms predict power patterns, enhancing smart energy management (Majeed Butt et al., 2021).
Use of data analytics and AI techniques	Data analytics and AI techniques, including machine learning and deep learning, optimises smart grid operations by analysing large datasets and automating tasks like load forecasting, demand response, fault detection, and grid stabilisation (Pullum et al., 2017).

2.6 IMPLEMENTATION CHALLENGES

The implementation of Smart Grid technology encounters various obstacles, such as the absence of regulatory frameworks, the vulnerability to cyber-attacks, the substantial expenses associated with installation, and the volatility and congestion within the network (Abdullah & Hassan, 2022). Technical limitations comprise an important factor in the implementation of smart grids, presenting issues (Voima & Kauhaniemi, 2012). Dhara et al. (2022) and Faquir et al. (2021) highlighted the importance of cybersecurity in smart grids, highlighting the vulnerability of their interconnected structure to cyber-attacks.

3. METHODOLOGY

A thorough investigation using the literature review was carried out in order to examine the smart grid technology, its application, suitability, and limitations using journals, books, conference proceedings, reports, government publications magazines, and dissertations. This study has used semi-structured interviews for the data collection process to allow the experts in the field to provide in-depth conversations for preset questions. Semi-structured interviews allowed to adapt questions based on the respondent’s context and experiences. It makes the interview encouraging respondents to share more openly. This qualitative research method involves in-depth discussions with specialised experts in a specific field or subject area, chosen based on their expertise, professional background, and familiarity with the subject matter under investigation. Hence, this study used purposive sampling method to select experts to get the data on their specified filed. Here mainly ten experts in the electricity fields have been interviewed to gather data. There are limited people who has experienced the real smart grid initiation. As a result, this study limited to ten expert interviews and respondents were selected based on their experience and contribution in Smart grid sector. These experts cover mainly three areas of the profession including experts from the electricity supply side (CEB), researchers, and energy consultants. The selection of these professions is based on the fact that CEB is the primary licensed entity in Sri Lanka responsible for supplying power. In the energy industry, researchers have opted to explore innovative concepts and characteristics that may be included in the SG system. Energy consultants must decide and select the aforementioned technology to obtain the necessary instructions for its actual implementation. When determining the years of service, individuals with over 10 years of competence are interviewed, presuming that they have accumulated a significant level of ability and knowledge in the relevant subject. The profiles of experts are shown in Table 2. To conduct a comprehensive analysis process Nvivo 12 has been used and based on the inputs gained from the expert's feasibility of implementing smart grid features within the Sri Lankan context and areas that need to be developed have been discussed and an implementation guide has been developed accordingly.

Table 2: Profiles of experts

Code of the Expert	Current Designation	Experience
E01	Grid System Analyst & Researcher	12 Years
E02	Deputy General Manager– Training	32 Years
E03	Post Doctoral Researcher	10 Years
E04	Project Director Power System Reliability Strengthens Project	22 Years
E05	Renewable Energy Consultant	11 Years
E06	Senior Power System Engineer & Researcher	12 Years
E07	Electrical Consultant	17 Years
E08	Electrical Engineer	11 Years
E09	Lead Electrical Engineer	12 Years
E10	Senior Electrical Engineer	14 Years

4. DATA ANALYSIS AND FINDINGS

4.1 CURRENT STATUS OF POWER SECTOR

A significant number of respondents perceived that the present energy supply system as having several favourable attributes, despite its expensive generation costs. Additionally, E01 and E04 stated that the main underlying issue is lagging in the implementation of low-cost or cost-efficient power plants. E01 further elaborated that *"this results in a significant gap between electricity demand and supply, making electricity supply in Sri Lanka most expensive"*. Accordingly, Sri Lankan electricity consumers bear a heavy burden due to the increased electricity price and inadequate low-cost electricity generation methods must be the underlying causes for current power sector issues.

4.2 ALTERNATIVE SOLUTIONS FOR CURRENT POWER FAILURES

The responses taken from the interviews mainly highlighted that the prime solution is to the achieve least cost generation and fill electricity demand enabling novel technologies. Using existing power plants for improved power generation is the main solution according to E04 and E02. Expert E04 proposes liquified natural gas (LNG) as a possible alternative to coal due to its reduced environmental effect and low cost. As the second solution experts underlined the potential of renewable energy sources. To support this E03 highlighted that solar power incorporated microgrid with battery storage is an optimal alternative. Moreover, E02 stresses that pump storage hydroelectricity is another viable option for load balancing that storing energy in the form of water gravitational potential. While these alternatives provide promise, experts also note that effective management of electricity infrastructure will be required to deliver the generation, transmission, and distribution capabilities. E03 stated that the smart grid will be a solution with their superior communication and control capabilities allowing integration of renewable energy and efficient distribution.

4.3 SMART GRID AS A VIABLE OPTION

E02 stated that "*Smart grids enable greater flexibility in managing electricity flows and balancing supply and demand"*. E01 highlighted that with economic constraints developing new power plants is infeasible and "*we can achieve a solution based on implementing a smart grid to utilise available energy generation options and infrastructure to gain efficient energy distribution and consumption using smart features"*. Furthermore, E05 elaborated the way smart grid features can be used to address the highlighted issues in the previous chapter by stating "*through technologies like demand response and distributed energy resources (DERs), such as solar panels and battery storage, utilities can dynamically adjust electricity generation and consumption to maintain grid stability, especially during periods of high demand using renewable energy output"*. Further, E02 highlighted that smart grids facilitate interconnectedness between different parts of the grid, enabling electricity to flow between regions and reducing dependency on specific generation sources or transmission lines. Accordingly, this interconnection promotes grid stability by giving backup options in localised power disruptions.

4.4 FEASIBLE SMART GRID FEATURES IN SRI LANKA

4.4.1 Advanced Metering Infrastructure

AMI is one of the most important components of any smart grid system. E02 stated, *"AMI is another feature that can be used in urban areas and some pilot projects are testing its feasibility in the present"*. Both E02 and E04 established that AMI has a role in reducing power theft, one of the persistent issues in electricity distribution. Furthermore, E04 highlighted that *"Smart metering does not just provide metering capabilities, it works like a smartphone where we can obtain individual voltage profiles, current profile load curve consumption, drop time, and fail time proving controllability over the system"*. E05 presented an alternative option that can be implemented along with the AMI to facilitate a prepaid metering system where that eliminates the use of the meter readers and allows consumers to use electricity according to their prepaid balance and shut the electricity down until they top-up their account.

4.4.2 Distributed Energy Resources

In the foreign renewable energy sector, consumers increasingly choose solar and battery projects, becoming independent from grid connections. They prioritise solar, and battery while using the grid supply as a backup. E05 elaborated that this can be comprehensively achieved within the Sri Lankan context and P01 confirms this by stating *"DER makes customers energy independent using solar and battery storage systems"*. Further, the respondent declared that the integration of renewable energy sources is a significant challenge, as many PV and solar systems operate independently of the national grid. To effectively monitor and manage this supply, it is crucial to integrate solar project supply with the national control system.

4.4.3 Demand Response and Load Management

E09 mentioned that *"DR initiatives encourage users to shift their power usage during peak demand periods. Smart grids can convey real-time grid status to end-users, allowing them to get involved in DR programs by moving non-critical energy usage to off-peak hours"*. E05 further highlighted that building management systems with automation technologies integrated with demand response initiatives offer further benefits by automating lighting HVAC and other systems, enhancing power quality and system security within the buildings.

4.4.4 Other Features

Peer-to-peer energy sharing feature was revealed by the E01 and he mentioned "*one option includes scheduling and sharing surplus loads generated by PV systems with other neighbour buildings. This needs connection with building management systems, to optimise energy distribution and consumption"*. E05 presented the power wheeling practice where customers can buy electricity from alternative generators and pay only for government-provided transmission line supply, which can be implemented in Sri Lanka with the right policy framework. E02 and E06 described the self-healing grid operations as smart grids that enable interconnectedness across the grid, allowing electricity to flow across regions and reducing dependence on specific sources or transmission lines. Experts highlighted cyber security as another required feature in the smart grid system for the security and integrity of the system. As a result, it was introduced as a necessary evil to protect consumer data and against cyber-attacks.

4.5 FEASIBILITY ASSESSMENT

4.5.1 Technological Assessment

According to E02 as the basic adaptation, it may follow a comprehensive guide including, equipping current grid components with new metering and communication technologies to enable real-time data collecting. Second, integrating distribution automation will boost grid control and efficiency. Third, incorporating renewable energy sources like solar into the grid would diversify the energy mix and encourage sustainability. Lastly, increasing cybersecurity measures is vital to defend against future cyber-attacks. As the smart grid is a wide concept including different segments E03 introduced a divisional procedure for integration as follows,

- **Generation -** Achieving 70% renewable energy generation is already a target at the national level. To get their solar systems, wind turbines can be used and create a microgrid using the projects.
- **Storage -** Batteries, flywheels, and thermal storage mechanisms can be used here.
- **Delivery & Transmission -** The communication network should be strengthened. Different types of sensors should be used to detect faults and grid management.

- **Consumption level -** AMI initiation and demand response and load scheduling practices.

Enabling these features is based on the financial and economic capabilities of the country and E04 stated that *"smart grid initiation should be started in a region where mostly smart features are required. For industrial zones, airport zones, hospital zones, etc. from there, we can expand the system to other areas as well"*.

4.5.2 Economic Assessment

Most of the experts held that the main barrier to the smart grid initiation lies in the economic constraints. E07 stated that "*while most smart technologies are available in commercial-level projects, the primary concerns rise from economic viability and adaptability issues"*. Focusing on regions with higher energy usage provides the greatest economic advantage for the initial launch of smart grid technology in Sri Lanka. According to E05, it is recommended to prioritise areas including Central Business Districts (CBDs), industrial zones, and high-density residential regions. E01 presented the main categorisation and areas where cost can be accumulated. This includes, Designing & Planning, Equipment purchasing, Architecture development, IT and software integration, labour and interest or financing cost project loans. As aforementioned the early expenses related to the adoption of smart grids can be substantial, and many experts argue that the long-term economic advantages may surpass these initial financial outlays. According to E01 *"quantifying the benefits of smart grid implementations can have challenges, However, the possibility of achieving long-term economic benefits by implementing smart grid technology is undeniable"*. It is evident that the Sri Lankan government with its economic capabilities cannot bear the investment value of a mega project. As a solution, experts have provided many options including, public private partnership, grants, and loans from the Asian Development Bank and World Bank, USAID, and foreign investors.

4.5.3 Regulatory Assessment

As the smart grid is a continuously evolving system, regulatory policies should be updated to accommodate new changes and trends. E05 highlighted that the current system discourages renewable energy investments due to limitations in selling excess electricity back to the grid at a fair price. Further, he elaborated on the necessity of policy revisions for the power wheeling mechanism, allowing surplus renewable energy to be purchased by other users. E03 introduced the Energy Independence and Security Act 2007 as a guiding regulation to improve the Sri Lankan regulatory framework on the energy sector. Furthermore, E01 and E06 identified that robust security and confidentiality of data policies are necessary to preserve customer details against cyberattacks and illegal access in modernised grid.

4.6 IMPLEMENTATION PRACTICES

As the first step, E10 advised to conduct a detailed feasibility analysis to evaluate the alternative options based on available technologies, funding options and legal considerations. And as the next step it is required to select the most financially and technically feasible option from them after conducting cost benefit analysis. According to E01 "*we need to prioritise considering the available features in the industry*". Before starting with a large-scale project E02, E09 and E04 explained conducting a pilot project as the initial step. E07 stated that, as the next step "*we have to obtain relevant institutional* *approvals, legal approvals and permits, before proceeding with project implementation*". According to E02, tendering and contractor selection and identifying potential funders and investors is a major step of the implementation process. Further to E02, the next step action plan is required in expansion processes and needs to gather information and observe the new trends in the global context for upgrades. E10 highlighted the equipment design based on the scope and scale and executed the project with the proper project team. E03 expressed that in each stage of the project continuous monitoring and evaluation is an essential step.

5. DISCUSSION

Sri Lanka's power industry confronts issues, including high energy rates and dependence on expensive fossil fuels. The literature study highlighted smart grids as a viable option, including benefits such as higher efficiency, greater renewable energy inclusion, and improved demand-side management. Interviews with specialists support these potential advantages, stressing the possibilities of smart grids to increase grid stability, and dependability, and minimise dependency on fossil fuels. Experts question smart grids' ability to reduce energy expenses directly, however their long-term economic benefits through improved efficiency and reduced losses appear promising.

Expert interviews revealed numerous smart grid aspects especially applicable to Sri Lanka's urban setting. These include AMI, distributed energy resources, peer-to-peer energy sharing, demand response and load management, power wheeling, self-healing grids, real-time grid monitoring, and interaction with electric car technology. Additionally, experts offered possibilities including prepaid billing mechanisms, smart meter connection with building management systems, and microgrids for energy-independent clients.

In the smart grid adaptation, a layered approach that includes integration is suggested, focusing on generation by boosting renewable energy sources like solar and wind through microgrids. Storage alternatives should be considered through batteries, flywheels, and thermal storage devices Delivery and transmission enhancements require upgrading the communication network and employing multiple sensors for real-time grid management. At the consumption level, AMI deployment alongside demand response and load scheduling strategies will be required.

Economic feasibility is crucial because experts underline the necessity to prioritise low-cost electricity production and manage energy consumption and delivery through smart features. International financial help from agencies like the World Bank, ADB, and USAID can be sought, along with possible partnerships with organisations like NREL for specialist technical assistance. Adapting the legal framework to support smart grids is necessary. This involves modifications to the power wheeling process to promote renewable energy integration. Robust data security and confidentiality standards are necessary to secure customer information. Additionally, implementing interoperability standards would guarantee compliance with the current grid code and PUCSL general policy guidelines. Figure 1 illustrates the guideline that can be used to implement the SG technology in Sri Lanka.

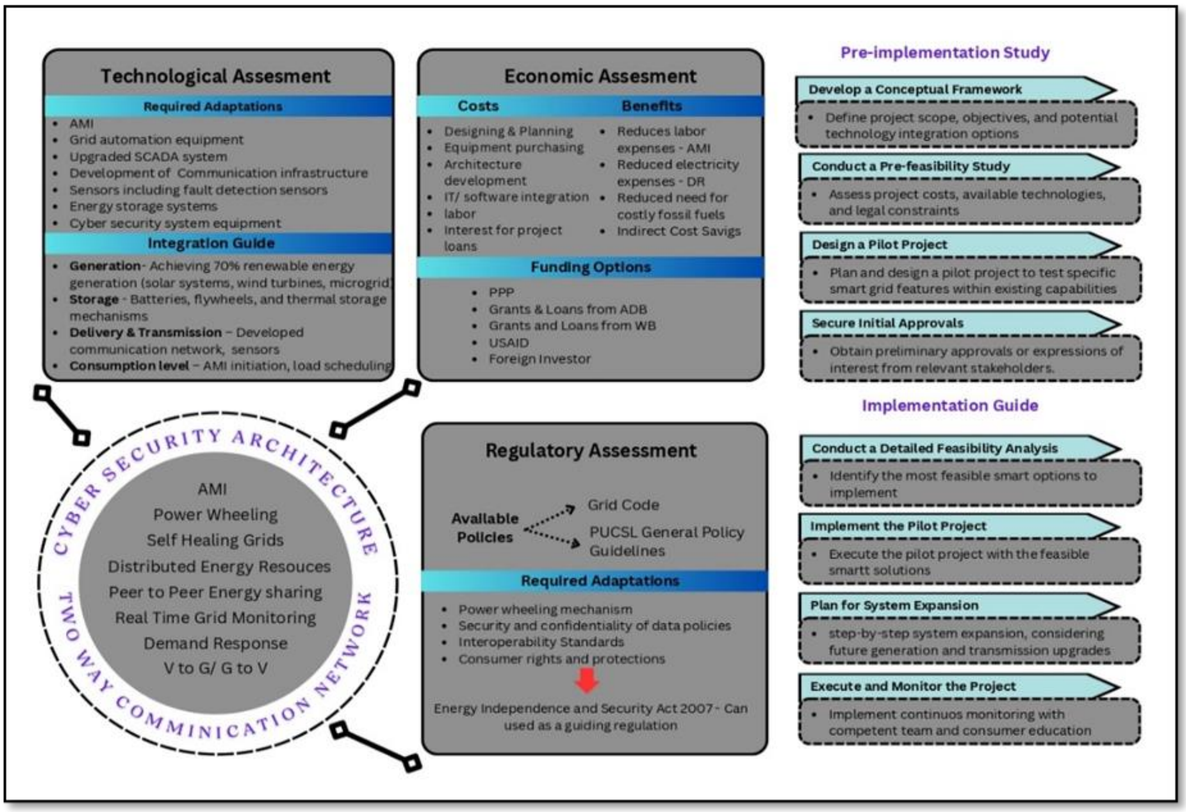


Figure 1: Feasibility assessment and implementation guide

6. CONCLUSIONS

Study aim was achieved by conducting literature review in the initial stage and then conducted semi-structured interviews with the experts in the electricity filed to gather the data relevant to Sri Lankan context. Literature findings identified smart grids as a viable option for Sri Lanka and it provides benefits such as higher efficiency, greater renewable energy inclusion, and improved demand-side management. The literature information for the Sri Lankan context was validated through expert interviews. Further, key benefits of smart grids were identified during the expert interviews. Findings emphasised how smart grids can reduce reliance on fossil fuels and improve grid stability and dependability. Considering the economic background, it was notable that experts have considered the initial investment involved with the smart grid adaptation including infrastructure changes, smart meter installations, and communication networks. Further, it was identified that economic feasibility is crucial due to the necessity of low-cost energy production. As the funding options, International financial agencies like the World Bank, ADB, and USAID can be supportive. When considering the technological background, it was identified that technological constraints can be overcome through a proper financial investment and the use of IT and other available technical expertise. Considering the limitations, focus area of this research is limited to Sri Lankan context because of the lack of smart features in power distribution sector. And it is suggested to conduct further researches on the effect of smart grid integration with building energy systems. Ultimately this research has provided feasible guide for the implement.

7. REFERENCES

Abdullah, A. A., & Hassan, T. M. (2022). Smart grid (SG) properties and challenges: an overview. *Discover Energy*, *2*(1), 8. https://doi.org/10.1007/s43937-022-00013-x

Abrahamsen, F. E., Ai, Y., & Cheffena, M. (2021). Communication technologies for smart grid: A comprehensive survey. *Sensors*, *21*(23), 8087. https://doi.org/10.3390/s21238087

Aleksic, S., & Mujan, V. (2016). Exergy-based life cycle assessment of smart meters. *2016 ELEKTRO*, 248–253. Slovakia: IEEE. https://doi.org/10.1109/ELEKTRO.2016.7512075

Alotaibi, I., Abido, M. A., Khalid, M., & Savkin, A. V. (2020). A comprehensive review of recent advances in smart grids: A sustainable future with renewable energy resources. *Energies*, *13*(23), 6269. https://doi.org/10.3390/en13236269

Amarasinghe, A. G., & Perera, E. N. C. (2021). Modelling predictive suitability to determine potential areas for establishing wind power plants in Sri Lanka. *Modelling Earth Systems and Environment*, *7*(1), 443–454. https://doi.org/10.1007/s40808-020-00868-w

Asalanka, D. (2017). Predictive analysis of electrical power failures in Sri Lanka using big data technologies. *International Journal of Robotics and Information Technology*, *1*(2), 65–73. https://www.researchgate.net/publication/323772636

Asian Development Bank. (2022). *The story of Lanka Electricity Company*. https://doi.org/http://dx.doi.org/10.22617/TCS220258-2

Asian Development Bank. (2023). *On the road to achieving full electrification in Sri Lanka*. https://doi.org/10.22617/TCS230011-2

Bakare, M. S., Abdulkarim, A., Zeeshan, M., & Shuaibu, A. N. (2023). A comprehensive overview on demand side energy management towards smart grids: challenges, solutions, and future direction. *Energy Informatics*, *6*(1), 4. https://doi.org/10.1186/s42162-023-00262-7

Dhara, S., Kumar Shrivastav, A., & Kumar Sadhu, P. (2022). Smart grid modernization: opportunities and challenges. In M. Ghofrani (Ed.), *Electric Grid Modernization*. IntechOpen. https://doi.org/10.5772/intechopen.97892

Dorji, S., Stonier, A. A., Peter, G., Kuppusamy, R., & Teekaraman, Y. (2023). An extensive critique on smart grid technologies: Recent advancements, key challenges, and future directions. *Technologies*, *11*(3), 81. https://doi.org/10.3390/technologies11030081

Erickson, L. E., & Brase, G. (2019). Smart Grid. In L. E. Erickson & G. Brase (Eds.), *Reducing greenhouse gas emissions and improving air quality* (1st ed., pp. 71–78). CRC Press. https://doi.org/10.1201/9781351116589-7

Fang, X., Misra, S., Xue, G., & Yang, D. (2012). Smart grid — The new and improved power grid: A survey. *IEEE Communications Surveys & Tutorials*, *14*(4), 944–980. https://doi.org/10.1109/SURV.2011.101911.00087

Faquir, D., Chouliaras, N., Sofia, V., Olga, K., & Maglaras, L. (2021). Cybersecurity in smart grids, challenges and solutions. *AIMS Electronics and Electrical Engineering*, *5*(1), 24–37. Retrieved from https://www.aimspress.com/article/doi/10.3934/electreng.2021002?viewType=HTML

Farmanbar, M., Parham, K., Arild, O., & Rong, C. (2019). A widespread review of smart grids towards smart cities. *Energies*, *12*(23), 4484. https://doi.org/10.3390/en12234484

Fernando, W. (2020). A feasibility study of development and implementation of smart energy system for 100% renewable energy and transport solutions in Sri Lanka [Doctor of Philosophy, Edinburgh Napier University]. https://napier-repository.worktribe.com/output/2707187/a-feasibility-study-of-development-and-implementation-of-smart-energy-system-for-100-renewable-energy-and-transport-solutions-in-sri-lanka

Fernando, W., Gupta, N., & Ozveren, C. S. (2017). The electricity infrastructure in Sri Lanka then, now and hereafter. *2017 52nd International Universities Power Engineering Conference (UPEC)*, (pp. 1–6). IEEE. https://doi.org/10.1109/UPEC.2017.8231986

Gasimli, O., Haq, I. U, Gamage, S. K. N., Shihadeh, F., Rajapakshe, P. S. K., & Shafiq, M. (2019). Energy, trade, urbanization and environmental degradation nexus in Sri Lanka: Bounds testing approach. *Energies*, *12*(9), 1655. https://doi.org/10.3390/en12091655

Ghelani, D. (2022). Cyber security in smart grids, threats, and possible solutions. *CC-BY American Journal of Applied Scientific Research*. https://doi.org/10.22541/au.166385207.71655799/v1

Hamilton, B., Pullins, S., Miller, J., & Hanley, M. (2010). *Smart grid principal characteristic enables new products, services, and markets* (Publication No. DOE/NETL-2010/1401). U.S. Department of Energy. https://netl.doe.gov/sites/default/files/Smartgrid/Appendix-A6---Enables-Markets-v3_0.pdf

Hansika, S., Subasinghe, S. M. I. K., Ahmed, M. S. I., Weesinghe, P., & Siyambalapitiya, T. (2021). Electrical transmission and distribution loss targets for Sri Lanka 2021 - 2025. *SLEMA Journal*, *24*(2), 14. https://doi.org/10.4038/slemaj.v24i2.31

Haq, E. U., Pei, C., Zhang, R., Jianjun, H., & Ahmad, F. (2023). Electricity-theft detection for smart grid security using smart meter data: A deep-CNN based approach. *Energy Reports*, *9*, 634–643. https://doi.org/10.1016/j.egyr.2022.11.072

Hertzog, C., & Stuart, D. (2010). *Smart Grid Dictionary* (3rd ed.). Greenspring Marketing LLC.

International Energy Agency. (2022). *Unlocking the potential of distributed energy resources: Power system opportunities and best practices*. https://iea.blob.core.windows.net/assets/3520710c-c828-4001-911c-ae78b645ce67/UnlockingthePotentialofDERs_Powersystemopportunitiesandbestpractices.pdf

Islam, M. A., Hasanuzzaman, M., Rahim, N. A., Nahar, A., & Hosenuzzaman, M. (2014). Global renewable energy-based electricity generation and smart grid system for energy security. *Scientific World Journal*, *2014*, 1–13. https://doi.org/10.1155/2014/197136

Jaber, M. M., Ali, M. H., CB, S., Asaad, R. R., Agrawal, R., Bizu, B., & Sanz-Prieto, I. (2023). Future smart grids creation and dimensionality reduction with signal handling on smart grid using targeted projection. *Sustainable Computing: Informatics and Systems*, *39*, 100897. https://doi.org/10.1016/j.suscom.2023.100897

Jayaratne, W., Dasanayaka, S. W. S. B., & Mudalige, D. M. (2021). Model for measuring the effect of incentive schemes, tariff regimes and technological innovations on change of consumer behaviour on energy savings: A study based on Sri Lankan electricity consumers in the domestic sector. *International Journal of Engineering Management and Economics*, *6*(4), 272–291. https://doi.org/10.1504/IJEME.2021.120099

Kataray, T., Nitesh, B., Yarram, B., Sinha, S., Cuce, E., Shaik, S., Vigneshwaran, P., & Roy, A. (2023). Integration of smart grid with renewable energy sources: Opportunities and challenges – A comprehensive review. *Sustainable Energy Technologies and Assessments*, *58*, 103363. https://doi.org/10.1016/j.seta.2023.103363

Khan, Z. A., Adil, M., Javaid, N., Saqib, M. N., Shafiq, M., & Choi, J.-G. (2020). Electricity theft detection using supervised learning techniques on smart meter data. *Sustainability*, *12*(19), 8023. https://doi.org/10.3390/su12198023

Kumar, A. (2019). Beyond technical smartness: Rethinking the development and implementation of sociotechnical smart grids in India. *Energy Research & Social Science*, *49*, 158–168. https://doi.org/10.1016/j.erss.2018.10.026

Lange, S., Pohl, J., & Santarius, T. (2020). Digitalization and energy consumption. Does ICT reduce energy demand? *Ecological Economics*, *176*, 106760. https://doi.org/10.1016/j.ecolecon.2020.106760

Majeed Butt, O., Zulqarnain, M., & Majeed Butt, T. (2021). Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Engineering Journal*, *12*(1), 687–695. https://doi.org/10.1016/j.asej.2020.05.004

Ministry of Environment. (2012). *National climate change policy of Sri Lanka*. https://cdn.climatepolicyradar.org/navigator/LKA/2012/national-climate-change-policy-of-sri-lanka_a3287a87ec3f542a37cc40ac49e7e7e5.pdf

Escobar, J. J. M., Matamoros, O. M., Padilla, R. T., Reyes, I. L., & Espinosa, H. Q. (2021). A comprehensive review on smart grids: Challenges and opportunities. *Sensors*, *21*(21), 6978. https://doi.org/10.3390/s21216978

Nagahawatte, R. (2020, April). Sri Lankan power crisis and future energy management. *The Official E-Newsletter of the Institution of Engineers Sri Lanka*, *47*. pp. 1-5. https://iesl.lk/SLEN/47/Energy%20Management.php

National Energy Technology Laboratory, (2008). *Advanced metering infrastructure*. https://netl.doe.gov/sites/default/files/Smartgrid/AMI-White-paper-final-021108--2--APPROVED_2008_02_12.pdf

Nduhuura, P., Garschagen, M., & Zerga, A. (2021). Impacts of electricity outages in urban households in developing countries: A case of Accra, Ghana. *Energies*, *14*(12), 3676. https://doi.org/10.3390/en14123676

Pragash, S. M., Vinoth, K., & Karthik, P. (2023). Smart grid technology and its impact on renewable energy integration. *IEEE Access*. https://doi.org/10.13140/RG.2.2.25508.14722

Pullum, L. L., Jindal, A., Roopaei, M., Diggewadi, A., Andoni, M., Zobaa, A., Alam, A., Bani-Ahmed, A., Ngo, Y., Vyas, S., Kumar, R., Robu, V., Flynn, D., Caputo, P., & Rajski Parashis, A. (2017). *Big data analytics in the smart grid: big data analytics, machine learning and artificial intelligence in the smart grid: introduction, benefits, challenges and issues*. IEEE. https://smartgrid.ieee.org/images/files/pdf/big_data_analytics_white_paper.pdf

Suryadevara, N. K., & Biswal, G. R. (2019). Smart plugs: Paradigms and applications in the smart city-and-smart grid. *Energies*, *12*(10), 1957. https://doi.org/10.3390/en12101957

Thentral, T.M.T., Semwal, P., Pandey, P.K., Raju, A., Mukherjee, U., & Ganguly, U. (2019). Recent trends in smart grid technology – A review paper. *International Journal of Innovative Technology and Exploring Engineering (IJITEE)*, *8*(8), 858-862. https://www.ijitee.org/wp-content/uploads/papers/v8i8/G5319058719.pdf

Voima, S., & Kauhaniemi, K. (2012). Technical challenges of smart- and microgrids. *Renewable Efficient Energy II Conference, Finland,* 21-22 March 2012. (pp. 1–8). https://www.researchgate.net/publication/268205830_Technical_Challenges_of_Smart-and_Microgrids

Witharama, W. M. N., Bandara, K. M. D. P., Azeez, M. I., Adhikari, M., Bandara, K., Logeeshan, V., & Wanigasekara, C. (2023). Optimal scheduling of a solar-powered microgrid using ml-based solar and load forecasting. *2023 IEEE World AI IoT Congress (AIIoT), U.S.A*, 07-10 June 2023, (pp. 447–453). https://doi.org/10.1109/AIIoT58121.2023.10174588

Young, J. R. (2017, June 02). *Smart grid technology in the developing world*. Seattle Pacific Library. https://digitalcommons.spu.edu/honorsprojects/68/

Dalugoda, T.P., Gallage, S.D. and Bandaranayake, D.M.L.N., 2024. Feasibility of web-based microservices architecture for contract document drafting. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 495-505. DOI: https://doi.org/10.31705/WCS.2024.39. Available from: https://ciobwcs.com/papers/

FEASIBILITY OF WEB-BASED MICROSERVICES ARCHITECTURE FOR CONTRACT DOCUMENT DRAFTING

T.P. Dalugoda[1], S.D. Gallage[2] and D.M.L.N. Bandaranayake[3]

ABSTRACT

This study investigates the feasibility of utilising web-based microservices architecture (MSA) for contract document drafting in the construction industry. The research aims to identify essential selection parameters for contracts, address challenges in manual drafting, and determine necessary features for MSA integration. Through interviews with industry professionals and a comprehensive literature review, the study uncovered key parameters such as project size, type, procurement method, and design responsibility, with jurisdiction emerging as a significant factor. Challenges in manual drafting included human errors, stakeholder delays, and inefficiencies in existing tools, particularly regarding document tracking and security. Desired features for a microservices-based solution included version control, real-time collaboration, machine learning capabilities, and customisable data validation. Current technologies are often fragmented and lacking cohesive integration, which MSA could address by modularising features and improving overall efficiency. The findings suggest that MSA could enhance contract management by offering a more integrated, secure, and efficient solution. This study provides valuable insights for construction industry practitioners seeking to improve document handling and offers a foundation for further research into MSA applications and their impact on legal drafting processes.

Keywords: *Contract Drafting; Construction Industry; Document Management; Microservices Architecture; Technology Integration.*

1. INTRODUCTION

Contracts are crucial in the construction industry, acting as binding agreements that define roles, responsibilities, and expectations among stakeholders, thus ensuring the smooth progression of projects (Hughes & Murdoch, 2007). Over the years, contract drafting has evolved significantly, from manual processes involving extensive paper documentation to the adoption of digital formats. The advent of digital contracts, including Smart Contracts, has introduced automation and efficiency in contract management, potentially reducing fraud and enhancing transparency in construction projects (Ahmadisheykhsarmast et al., 2023).

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, dalugoda.19@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sasankag@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, lakshithab@uom.lk

However, despite these advancements, conventional contract drafting practices still face significant challenges. The integration of various technologies often lacks cohesion, leading to communication breakdowns, information silos, and inconsistencies in contractual terms (Abdallah et al., 2023). This disjointed approach can result in disputes, delays, and increased costs, undermining project success (Vilkonis & Antuchevičienė, 2024).

Microservices architecture presents a promising solution to these issues. This architectural style, characterised by the deployment of independently functioning services, allows each microservice to handle a specific business function, enhancing modularity and scalability (Jamshidi et al., 2013). Unlike traditional monolithic applications, where a single issue can affect the entire system, microservices can be updated and scaled individually, facilitating more efficient management of complex tasks like contract drafting (Ren et al., 2018). The use of lightweight HTTP protocols for communication ensures high concurrency and reliability, essential for the dynamic and high-stakes environment of construction projects (Ren et al., 2018).

Studying the potential of microservices architecture in contract drafting is crucial for addressing the current inefficiencies and promoting more cohesive and reliable contract management practices. This study aims to explore the feasibility of utilising microservices architecture for contract document drafting within the construction industry. It seeks to identify essential selection parameters for contract types, address challenges and issues related to manual contract drafting and document preparation and determine the necessary features for integrating microservices. By examining these aspects, the study aims to provide insights into how microservices can streamline contract drafting processes, enhance real-time collaboration, and improve overall efficiency, thereby reducing the risk of disputes and contributing to the success of construction projects.

2. LITERATURE REVIEW

2.1 CONTRACTS IN CONSTRUCTION

Before the Industrial Revolution, construction projects were managed by a "master builder" responsible for both design and construction (Turner, 2009). Contracts in construction, emerging around this period, allowed for specialised roles, giving owners the freedom to employ multiple professionals rather than relying on a single individual (Eenmaa & Schmidt, 2019). Modern construction contracts have evolved into complex agreements involving financers, architects, suppliers, and insurance companies, with clearly defined tasks and responsibilities for each party (Nadar, 2023; Wautelet et al., 2012). Quantity Surveyors now play a crucial role in maintaining these contractual links, serving as Commercial Managers, Contract Administrators, and Contract Managers (Australian Institute of Quantity Surveyors [AIQS], 2024). Construction contracts are essential for addressing issues like professional pride, stage overlaps, extended project participation, and potential conflicts among stakeholders and teams (Hughes & Murdoch, 2007).

2.2 DIFFERENT CLASSIFICATIONS OF CONTRACTS

Construction contracts are categorised based on the parties involved and project circumstances (Hinze, 2010). Various sources offer different classifications. Traditional

Contracts, such as the General Contract Method and Design-Bid-Build, are widely recognised (Clough et al., 2015; Hinze, 2010). The Separate Contracts Method, where the owner acts as the general contractor, includes Direct Contracting (Bailey, 2016). The Design-Build Method integrates design and construction, often under one contract, providing a streamlined approach (Godwin, 2013). Construction Management approaches, such as Professional Construction Management and Construction Management at Risk, involve separate entities managing the construction process (Bailey, 2016; Hinze, 2010). Collaborative Contracting, similar to Joint Venturing, involves shared risks and rewards among parties (Hughes & Murdoch, 2007). Public/Private Partnerships (PPP) and Turnkey Contracts/EPC are specialised for large-scale projects (Kelley, 2012; Robinson, 2011). The MDB edition contracts, offered by FIDIC, are used for projects funded by international agencies like the World Bank and Islamic Development Bank (Robinson, 2011). These diverse classifications, also known as procurement routes, cater to various project needs, offering flexibility and specificity (Bailey, 2016; Chappell, 2021).

2.3 SELECTION PARAMETERS OF MAIN CONTRACT TYPES

The selection of contract types in construction projects depends on various parameters. Traditional Contracts often involve the architect taking design responsibility, with the contractor selected through competitive bidding. These contracts are suitable for projects with a well-defined scope, budget, and timeline, typically in commercial construction (Chappell, 2021; Clough et al., 2015; Surahyo, 2018).

The Design-Build Method consolidates design and construction responsibilities under a single entity, which can streamline processes, reduce conflicts, and shorten project timelines (Surahyo, 2018). This method is particularly effective for projects needing expedited delivery.

Construction Management Contracts involve a construction manager overseeing all project aspects, including design, providing a centralised approach and often used for complex projects requiring detailed coordination (Hinze, 2010).

Public/Private Partnerships (PPP) are ideal for long-term infrastructure projects, where the private sector assumes significant design, construction, and financial responsibilities, offering economic benefits to the public sector (Surahyo, 2018).

Joint Venturing is selected when multiple firms collaborate, often necessitated by legal requirements or the need to combine different expertise and resources (Surahyo, 2018).

Turnkey Contracts/EPC assign all project responsibilities, from design to completion, to the contractor, making them suitable for large-scale industrial projects such as petrochemical plants (Bailey, 2011; Hinze, 2010).

2.4 STANDARD TYPES OF CONTRACTS USED IN CONSTRUCTION

Contract documents in construction typically include several essential components, often referred to as "boilerplate" provisions, which are consistent across various forms such as FIDIC (Godwin, 2013). These documents, including tender documents, conditions of contract, specifications, schedules, construction drawings, and bills of quantities, provide a comprehensive legal framework between the contractor and the employer (Clough et al., 2015; Surahyo, 2018). Additionally, forms like the project manual, performance bonds, and insurance certificates are critical to the contract's structure (Hinze, 2010).

In construction, standard contracts are essential for defining the roles and responsibilities of parties involved, and several recognised forms are widely used globally. The FIDIC suite, for instance, includes the Red Book for employer-designed projects and the Yellow Book for contractor-designed works, offering a comprehensive legal framework adaptable to various jurisdictions (Fédération Internationale des Ingénieurs – Conseils [FIDIC], 2022). The JCT contracts are prevalent in the UK, providing options from minor works to complex projects, ensuring clarity in roles, timelines, and payment structures (Eggleston, 2001). The NEC contracts are known for their flexibility and clarity, facilitating smooth project management through standard forms like the Engineering and Construction Contract (ECC). Similarly, IChemE contracts cater specifically to the process industries, and DBIA contracts are tailored for design-build projects, integrating design and construction responsibilities. These standard forms help streamline the contractual process, reduce ambiguity, and promote fair and efficient project execution (Hillig et al., 2010).

2.5 PROBLEMS ASSOCIATED WITH DRAFTING CONTRACTS

Drafting construction contracts presents numerous challenges that can lead to disputes and litigation, despite adhering to best practices. A primary issue is the use of complex and ambiguous language. Adams (2018) points out that long sentences, syntactic ambiguity, and jargon can result in misinterpretation, often leading to disputes. To combat these issues, best practices recommend using simple language, avoiding jargon, and maintaining clarity through concise sentences (Paris, 2015).

Another significant problem is the failure to review and update contract documents adequately. Fox (2008) notes the importance of collecting and integrating information from related documents to ensure comprehensiveness. Yet, failure to do so can lead to incomplete or outdated contract terms, contributing to conflicts. Furthermore, as advised by Stark (2014), reliance on templates and precedents can sometimes perpetuate outdated practices or overlook unique project requirements.

Despite following best practices, contracts are inherently imperfect. Soo and Cheng (2022) argue that even the most carefully drafted contracts are prone to disputes, as highlighted in the Arnold vs. Britton case, conflicts can arise even from well-drafted agreements. This underscores the reality that while best practices can minimise issues, they cannot completely eliminate the potential for disputes.

2.6 USE OF TECHNOLOGY IN CONSTRUCTION CONTRACT DRAFTING

The evolution of technology in construction contract drafting has introduced various tools to enhance accuracy and efficiency. Initially, basic software like MS Word facilitated the creation of documents, while grammar checkers and find-and-replace tools improved drafting quality (Espenschied, 2020). Modern advancements include Natural Language Processing (NLP) for drafting and interpreting contract clauses and smart contracts for automating and securing transactions (Aggarwal et al., 2021; Ibba, 2022). These innovations address specific challenges such as complex clause management and transaction automation (Safa et al., 2017; Pierro et al., 2020).

Despite these advancements, technologies often tackle discrete tasks without cohesive integration. For example, while NLP aids in drafting, software like AutoCAD and MS Project supports drawing preparation and scheduling, respectively (Parfitt et al., 1993;

Tereso et al., 2014). Additionally, e-tendering systems and Decision Support Systems (DSS) are used for submitting tenders and negotiating contract terms (Eadie et al., 2012; Mohemad et al., 2010). However, the lack of a unified system means these tools operate independently, potentially limiting their effectiveness in streamlining the entire contract lifecycle (Vukomanović et al., 2012).

2.7 USE OF MICROSERVICE ARCHITECTURE IN CONSTRUCTION CONTRACTS

Microservice architecture (MSA) has evolved from service-oriented architectures and web services, offering a modular approach to application development (Barros & Dumas, 2006; Richardson & Ruby, 2007). Unlike traditional monolithic applications, which deploy all components together, MSA breaks applications into smaller, independently deployable services, each handling a specific function (Ren et al., 2018). This approach supports diverse technology stacks and independent updates, utilising lightweight HTTP protocols for communication (Jamshidi et al., 2013).

Popular microservices include Single Page Applications (SPAs) for seamless user experiences, Multi Page Applications (MPAs) for traditional browsing, and Progressive Web Apps (PWAs) that combine modern features with offline capabilities (Al-Fedaghi, 2011). Each offers unique advantages in performance and user interaction.

In construction contracts, MSA can significantly enhance software solutions by improving integration and efficiency. To fully leverage MSA, it is crucial to identify and connect specific features that address various aspects of contract management. For instance, integrating legal drafting tools with contract management systems, risk assessment platforms, and document storage solutions can streamline the contract lifecycle and ensure cohesive output (Jamshidi et al., 2013).

Additionally, connecting features such as real-time updates, centralised data storage, and modular risk assessment tools can enhance overall contract management processes (Gorín et al., 2011). Despite these advantages, current solutions lack comprehensive MSA applications for legal drafting, indicating a need for further development to fully exploit microservices' benefits (Gorín et al., 2011).

3. RESEARCH METHOD

A well-structured research design is essential as it serves as the blueprint for the research project, integrating all its components. Research designs are generally categorised into experimental, quasi-experimental, descriptive, and correlational types, although classification methods can vary (Dulock, 1993).

The choice of research approach significantly influences the study's design, findings, and interpretations (Prescott & Conger, 1995). Approaches can be broadly classified into quantitative, qualitative, or a mixed approach that combines elements of both (Choudrie & Dwivedi, 2005). Quantitative research focuses on numerical data and statistical relationships, suitable for controlled environments but limited in capturing subjective experiences and complexities (Quick & Hall, 2015; Savela, 2018). In contrast, qualitative research delves into social phenomena and subjective experiences, making it more suitable for exploring nuanced issues like contract drafting challenges and technology integration (Teherani et al., 2015; Cleary et al., 2014). This approach allows for in-depth theory development and discovery, which is crucial for understanding specific requirements in the context of microservices architecture (Berg & Struwig, 2017).

Expert interviews are employed to identify contract selection parameters and challenges that microservices architecture should address. Eighteen experts were purposively sampled based on their extensive experience in contract management and technology integration, ensuring practical and relevant insights. Their diverse backgrounds, detailed in Table 1, provide a comprehensive understanding of current practices and challenges essential for developing effective microservices solutions.

Table 1: Interviewee profile

Respondent	Designation	Experience	Countries	Exposure
R1	Academic	9	Sri Lanka, Australia	Sri Lankan and Australian construction industries
R2	Academic	24	Sri Lanka	BIM technology
R3	Commercial manager	29	Dubai, Sri Lanka	Contract drafting, ADR, Road construction
R4	Commercial manager	16	Sri Lanka	Commercial and contracts manager
R5	Consultant	30	Sri Lanka, Qatar	contract administration, ADR
R6	Academic	15	UK, Sri Lanka	Contract law
R7	Consultant/Academic	15	Australia, Sri Lanka	Procurement and contract law
R8	Consultant/Chief Qs	12	New Zealand, pacific islands, Sri Lanka	Business law, Procurement
R9	Consultant Qs	6	Dubai, Sri Lanka	Infrastructure projects
R10	Contractor	5	Sri Lanka	ERP system, Cubicost
R11	Consultant	6	Sri Lanka	ADR and BOI projects.
R12	Contractor/ Academic	25	Dubai, Sri Lanka	academics.
R13	Consultant	14	UAE, Sri Lanka, Australia	Specialties in Pre-contract, post-contract Quantity Surveying and Contract Management
R14	Contractor	20	UAE	Precontract and post-contract administrations from the contractor
R15	Consultant	18	Dubai	Contract administration
R16	Consultant	10	Sri Lanka	Commercial projects.
R17	Procurement executive/planning engineer	7	Sri Lanka	Project Management
R18	Consultant Quantity Surveyor	10	Sri Lanka, Dubai, Australia	BOI projects, Bridge projects and Cubicost

The data collected from these interviews were systematically analysed using NVivo software, which facilitated the identification of key themes and patterns. This method provided a comprehensive understanding of current practices and challenges, essential for developing effective microservices solutions to enhance contract drafting processes.

4. RESEARCH FINDINGS

4.1 SELECTION PARAMETERS OF CONTRACT TYPES IN CONSTRUCTION PROJECTS

From the interviews, several main findings emerged. The project's size was widely recognised as a valid parameter, with respondents like R3, R4, R6, R8, R12, R13, R15, and R1 highlighting its importance, though there were calls for clearer definitions, such as distinguishing between monetary and time-based size (R6). The type of project was deemed crucial, with respondents such as R3, R7, R12, R15, and R18 highlighting that different contracts are suitable for specific project types, like road construction projects in Qatar (R12). The procurement type was universally acknowledged as critical by all 14 respondents, with examples like the FIDIC Red Book being used for employer-designed projects. However, the complexity of a project was largely dismissed as too vague by respondents like R1, R2, R3, R4, R6, R7, R8, R11, R12, R13, R15, and R18, with several suggesting its removal as a selection parameter (R3, R13). Design responsibility was considered essential, as noted by respondents such as R1, R3, R4, R7, R8, R12, R13, R15, and R18, as different forms of contracts specify usage based on who holds design responsibility. The source of funding was highlighted as crucial by all 14 respondents, especially when contracts are tailored for specific funding agencies like the Asian Development Bank (ADB) or the World Bank (R11). Jurisdiction was emphasised by R1, R3, R4, R8, R11, and R18 as a necessary consideration due to varying legal requirements in different regions. Lastly, project duration was noted as important by respondents such as R3, R7, R8, R11, R12, and R13 for aligning contract types with project timelines and budgets.

The literature supports the importance of project size, type, procurement method, and design responsibility in contract selection. For instance, traditional contracts often involve architects in design roles, while the Design-Build method consolidates design and construction responsibilities (Chappell, 2021; Surahyo, 2018). Public/Private Partnerships (PPP) and Turnkey Contracts/EPC, which allocate comprehensive project responsibilities, align with the interview findings on funding sources and contract comprehensiveness (Bailey, 2011; Hinze, 2010). However, the interviews highlighted jurisdiction more prominently than the literature, suggesting it is a critical factor often overlooked. Additionally, the feedback suggested removing complexity as a parameter, a point of deviation from some literature that includes it as a significant factor (Chappell, 2021).

4.2 CHALLENGES IN MANUAL DRAFTING AND DOCUMENT PREPARATION

Interviews highlighted several challenges in manual drafting and document preparation, categorised into issues related to document preparation, stakeholder involvement, and existing tools. Document preparation challenges were notably attributed to human errors, such as data transfer mistakes, as emphasised by respondents like R12 and R15. Delays in information provision from stakeholders were also a significant issue, affecting the timeliness of drafting (R7). Additionally, repetitive tasks increased the likelihood of errors, with respondents like R14 pointing out the time-consuming nature of the process.

Stakeholder-related challenges included difficulties in managing undue influence and changing requirements, complicating the drafting process (R5, R9). Security concerns were another major issue, with respondents like R11 stressing the need to protect sensitive information, a sentiment echoed by R7 regarding current communication methods' inadequacies.

Existing tools also posed challenges, particularly email chains, which were criticised for their inefficiency in document tracking and collaboration (R6, R4). Another highlighted issue was the inability to restrict document access and pass on knowledge effectively, making it difficult to manage information securely and consistently (R14, R6).

Comparing these findings with the literature, there is significant alignment, particularly regarding the issues of syntactic ambiguity and the importance of clarity in contract language, as noted by Adams (2018) and Paris (2015). However, the interviews provided additional insights into the practical challenges of using email and existing tools for document management, which are not extensively covered in the literature. The issue of stakeholder influence is more vividly illustrated in the interviews. The literature also emphasises the need for regular contract updates and the risks of relying on outdated templates (Fox, 2008; Stark, 2014). This correlates with the challenges noted in passing knowledge and managing stakeholder inputs in the interviews.

4.3 FEATURES REQUESTED IN CONTRACT DRAFTING TOOLS AND INTEGRATION WITH MICROSERVICES ARCHITECTURE

Based on the interviews, several key features emerged as necessary for an effective contract drafting application. Respondents highlighted the need for version control (R2), access to project data from any location (R1, R3, R4, R6, R7, R8, R10, R14, R15), the ability to create and save templates (R4), and real-time collaboration (R4, R7, R8, R9, R10, R11, R13, R14, R15, R16, R17). Additionally, features like document tracking (R1, R2, R3, R6, R8, R12, R14, R15), grammar correction (R2), and machine learning capabilities (R9) were also emphasised. Other suggested features included exporting in various file formats (R2, R3, R4, R6, R8, R11, R13, R14, R15, R16, R17), and customisable data validation (R2, R3, R6, R7, R13, R14, R18).

Current technologies, including basic text editors and standalone tools, often fall short in delivering these requested features. For instance, while platforms like Google Docs offer version control and real-time collaboration (Espenschied, 2020), they lack advanced document tracking and integration capabilities across different applications (Aggarwal et al., 2021; Ibba, 2022). Tools like MS Word provide grammar correction but are limited in offering integrated solutions for machine learning or comprehensive document management (Parfitt et al., 1993; Tereso et al., 2014). The problem lies in the fragmented nature of existing technologies which handle discrete tasks without cohesive integration (Vukomanović et al., 2012).

MSA offers a promising approach to address these limitations. By modularising the application into independent, deployable services, MSA can integrate diverse features such as version control, real-time collaboration, and machine learning capabilities. For instance, a microservice could handle version tracking, another could manage access to project data, and yet another could facilitate real-time updates and collaborative drafting

(Barros & Dumas, 2006; Richardson & Ruby, 2007). This modular approach allows for seamless integration of various features, enhancing overall efficiency and user experience. MSA can also support real-time data validation and grammar correction by incorporating specialised services (Jamshidi et al., 2013; Gorín et al., 2011). However, existing solutions often lack comprehensive MSA applications for legal drafting, indicating a gap that needs addressing to fully leverage microservices' benefits (Gorín et al., 2011).

5. CONCLUSIONS

This study aimed to explore the feasibility of utilising microservices architecture for contract document drafting in the construction industry by identifying essential selection parameters, addressing associated challenges, and determining necessary features for integration. The research effectively achieved its objectives by employing a qualitative approach, which prompted conducting interviews with 18 industry practitioners. However, the findings are limited by the focus on qualitative data from interviews, which may not fully represent all industry perspectives, and the exclusion of quantitative analysis of existing tools' performance.

The key findings indicate that project size, type, procurement method, design responsibility, and funding source are critical parameters in contract selection, with jurisdiction being highlighted more in interviews than in existing literature. Challenges identified include human errors, stakeholder delays, repetitive tasks, inefficiencies with existing tools such as email chains, and significant concerns over security and document tracking. The features most desired for a microservices-based solution include version control, real-time collaboration, machine learning capabilities, and customisable data validation. Current tools are fragmented and lack comprehensive integration, highlighting the need for an advanced, modular approach.

Implementing microservices architecture can address these issues by modularising features and improving integration, leading to more efficient and secure document management. For construction industry practitioners, this translates to enhanced workflow and better document handling. Academia can further investigate the detailed implementation of MSA in legal drafting, evaluating its impact on efficiency and exploring its integration with AI and machine learning technologies. Future research should focus on practical application strategies and the broader implications of MSA in contract drafting.

6. REFERENCES

Abdallah, A. A., Shaawat, M. E., & Almohassen, A. S. (2023). Causes of miscommunication leading to project delays and low work quality in the construction industry of Saudi Arabia. *Ain Shams Engineering Journal*, *15*(3), 102447. https://doi.org/10.1016/J.ASEJ.2023.102447

Adams, K.A. (2018). *A Manual of style for contract drafting* (4th ed.). American Bar Association.

Aggarwal, V., Garimella, A., Srinivasan, B. V., Anandhavelu, N., & Jain, R. (2021). CLAUSEREC: A clause recommendation framework for ai-aided contract authoring. *Proceedings of the 2021 conference on empirical methods in natural language processing, Punta Cana, Dominican Republic,* November 2021. (pp. 8770–8776*)*. Association for Computational Linguistics. https://doi.org/10.18653/v1/2021.emnlp-main.691

Ahmadisheykhsarmast, S., Senji, S. G., & Sonmez, R. (2023). Decentralized tendering of construction projects using blockchain-based smart contracts and storage systems. *Automation in Construction*, *151*, 104900. https://doi.org/10.1016/J.AUTCON.2023.104900

Australian Institute of Quantity Surveyors. (2024, July). *Roles and titles of Quantity Surveying professionals: Buildings - AIQS*. Australian Institute of Quantity Surveyors. https://www.aiqs.com.au/roles-and-titles-quantity-surveying-professionals-buildings

Al-Fedaghi, S. (2011). Developing Web Applications. *International Journal of Software Engineering and Its Applications, 5*(2), 57–68. https://www.earticle.net/Article/A147973

Bailey, J. (2016). *Construction law Volume I* (2nd ed.). Informa Law from Routledge.

Barros, A. P., & Dumas, M. (2006). The rise of web service ecosystems. *IT Professional*, *8*(5), 31–37. https://doi.org/10.1109/MITP.2006.123

Berg, A, V. D., & Struwig, M. (2017). Guidelines for researchers using an adapted consensual qualitative research approach in management research. *Electronic Journal of Business Research Methods, 15*(2), 109-119. https://academic-publishing.org/index.php/ejbrm/article/view/1361

Chappell, D. (2021). *Construction Contracts* (4th ed.). Routledge

Choudrie, J., & Dwivedi, Y. K. (2005). Investigating the research approaches for examining technology adoption issues. *Journal of Research Practice*, *1*(1), 1–12. https://core.ac.uk/download/pdf/268475979.pdf

Cleary, M., Horsfall, J., & Hayter, M. (2014). Qualitative research: Quality results? *Journal of Advanced Nursing*, *70*(4), 711–713. https://doi.org/10.1111/JAN.12172

Clough, R. H., Sears, G. A., Sears, S. K., Segner, R. O., & Rounds, J. L. (2015). *Construction contracting: A practical guide to company management* (8th ed). Wiley.

Dulock, H. L. (1993). Research design: Descriptive research. *Journal of Pediatric Oncology Nursing*, *10*(4), 154–157. https://doi.org/10.1177/104345429301000406

Eadie, R., Millar, P., Perera, S., Heaney, G., & Barton, G. (2012). E-readiness of construction contract forms and e-tendering software. *International Journal of Procurement Management*, *5*(1), 1–26. https://doi.org/10.1504/IJPM.2012.044151

Eenmaa, H., & Schmidt, M. (2019). Creating markets in no-trust environments: The law and economics of smart contracts. *Computer Law & Security Review*, *35*(1), 69–88. https://doi.org/10.1016/J.CLSR.2018.09.003

Eggleston, B. (2001), *The ice conditions of contract (7th ed.)*. Wiley-Blackwell.

Espenschied, L. (2020). *Contract drafting: Powerful prose in transactional practice (aba fundamentals)* (3rd ed.). American Bar Association.

Fédération Internationale des Ingénieurs – Conseils (2022). *FIDIC contracts guide* (2nd ed.). Fédération Internationale des Ingénieurs - Conseils.

Fox, C. M. (2008). *Working with contracts: What law school doesn't teach you* (2nd ed.). Practicing Law Institute.

Godwin, W. (2013). *International construction contracts: A handbook* (1st ed.). Wiley-Blackwell.

Gorín, D., Mera, S., & Schapachnik, F. (2011). A software tool for legal drafting. In E. Pimentel, & V. Valero (Eds.), *Electronic proceedings in theoretical computer science*, *68*, (pp. 71–86). https://doi.org/10.4204/EPTCS.68.7

Hillig, J.-B., Dan-Asabe, D., Donyavi, S., Dursun, O., & Thampuratty, A. (2010). FIDIC's Red Book 1999 edition: A study review. *Proceedings of the institution of civil engineers - Management, procurement and law*, *163*(3), (pp. 129–133). https://doi.org/10.1680/mpal.2010.163.3.129

Hughes, W., & Murdoch, J. (2007). *Construction contracts: Law and management* (4th ed.). Routledge. https://doi.org/10.4324/9780203965740

Jamshidi, P., Ahmad, A., & Pahl, C. (2013). Cloud migration research: A systematic review. *IEEE Transactions on Cloud Computing*, *1*(2), 142–157. https://doi.org/10.1109/TCC.2013.10

Hinze, J. (2010). *Construction contracts* (3rd ed.). McGraw-Hill.

Kelley, G. (2012). *Construction law: An introduction for Engineers, Architects, and Contractors*. RSMeans

Mohemad, R., Hamdan, A.R., Othman, Z. A., Maizura, N., & Noor, M. (2010). Decision support systems (DSS) in construction tendering processes. *International Journal of Computer Science Issues*, *7*(1). https://doi.org/10.48550/arXiv.1004.3260

Nadar, A. (2023, October 12). *The contract: The foundation of construction projects - global arbitration review*. Global Arbitration Review. https://globalarbitrationreview.com/guide/the-guide-construction-arbitration/fifth-edition/article/the-contract-the-foundation-of-construction-projects

Parfitt, M. K., Syal, M. G., Khalvati, M., & Bhatia, S. (1993). Computer-integrated design drawings and construction project plans. *Journal of Construction Engineering and Management*, *119*(4), 729–742. https://doi.org/10.1061/(ASCE)0733-9364(1993)119:4(729)

Paris, C.E.C. (2015), *Drafting for corporate finance: Concepts, deals, and documents* (2nd ed.). Practicing Law Institute.

Pierro, G. A., Tonelli, R., & Marchesi, M. (2020). An organized repository of Ethereum smart contracts' source codes and metrics. *Future Internet*, *12*(11), 197. https://doi.org/10.3390/fi12110197

Prescott, M. B., & Conger, S. A. (1995). Information technology innovations: A classification by IT locus of impact and research approach. *SIGMIS Database, 26*(2–3), 20–41. https://doi.org/10.1145/217278.217284

Quick, J., & Hall, S. (2015). Part three: The quantitative approach. *Journal of Perioperative Practice*, *25*(10), 192–196. https://doi.org/10.1177/175045891502501002

Ren, Z., Wang, W., Wu, G., Gao, C., Chen, W., Wei, J., & Huang, T. (2018). Migrating web applications from monolithic structure to Microservices Architecture. In *Proceedings of the 10th asia-pacific symposium on internetware, China,* 16 September 2018. (pp. 1–10). Association for Computing Machinery.

Richardson, L., & Ruby, S. (2007). *RESTful web services* (1st ed,). O'Reilly Media.

Robinson, M.D. (2011). *A contractor's guide to the FIDIC conditions of contract* (1st ed.). Wiley-Blackwell.

Safa, M., Shahi, A., Haas, C. T., & Hipel, K. W. (2017). Construction contract management using value packaging systems. *International Journal of Construction Management, 17*(1), 50–64. https://doi.org/10.1080/15623599.2016.1167369

Savela, T. (2018). The advantages and disadvantages of quantitative methods in schoolscape research. *Linguistics and Education*, *44*, 31–44. https://doi.org/10.1016/J.LINGED.2017.09.004

Soo, G. & Cheng, P. (2022). *Essentials of contract drafting and negotiation for construction professionals*. Hong Kong University Press

Stark, T. L. (2014). *Drafting contracts: How and why lawyers do what they do* (2nd ed.). Aspen Publishing.

Surahyo, A. (2018). *Understanding construction contracts*. Springer International Publishing AG

Teherani, A., Martimianakis, T., Stenfors-Hayes, T., Wadhwa, A., & Varpio, L. (2015). Choosing a qualitative research approach. *Journal of Graduate Medical Education*, *7*(4), 669–670. https://doi.org/10.4300/JGME-D-15-00414.1

Tereso, A. P., Guedes, A., & Cascais, A. C. P. (2014). A computer application for scheduling in MS project. *Computer Science and Applications, 1*(5), 309-318. https://hdl.handle.net/1822/36893

Turner, J. R. (2009). *Handbook of project-based management: Leading strategic change in organizations* (3rd ed.). McGraw-Hill Education.

Vilkonis, A., & Antuchevičienė, J. (2024). Price recalculation model of construction contracts. *Mokslas – Lietuvos Ateitis / Science – Future of Lithuania, 16*. https://doi.org/10.3846/mla.2024.19221

Vukomanović, M., Radujković, M., & Dolaček-Alduk, Z. (2012). The use of project management software in construction industry of Southeast Europe. *Tehnički Vjesnik*, *19*(2), 249–258. https://urn.nsk.hr/urn:nbn:hr:133:558801

Wautelet, P., Kruger, T., & Coppens, G. (Eds.). (2012). *The practice of arbitration: Essays in honour of Hans van Houtte* (UK ed.). Bloomsbury Publishing.

Berawi, M.A., Wicaksono, P.L., Saroji, G., Sari, M. and Miraj, P., 2024. Financing scheme for the transit-oriented development projects in Indonesia. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 506-517. DOI: https://doi.org/10.31705/WCS.2024.40. Available from: https://ciobwcs.com/papers/

FINANCING SCHEME FOR THE TRANSIT-ORIENTED DEVELOPMENT PROJECTS IN INDONESIA

Mohammed Ali Berawi[1], Pradhana Listio Wicaksono[2], Gunawan Saroji[3], Mustika Sari[4], and Perdana Miraj[5]

ABSTRACT

Transit-Oriented Development (TOD) is expected to increase public use of mass transportation and reduce private vehicle usage. However, its development entails a high financial investment. This paper determines a financing scheme to boost private sector investment in TOD projects, considering the TODs in Indonesia's Jabodebek Light Rail Transi (LRT) as the case study. Simulation of cost-sharing scenarios between public and private sectors was simulated to form the financing scheme, along with the benchmarking study to establish the institutional scheme. The findings reveal that an optimal Internal Rate of Return (IRR) of 14.92%, indicates that the project is financially viable. The optimal distribution of initial cost, operational and maintenance cost, and revenue incurred to the private sector are 39.86%, 66.02%, and 72.02%, respectively. The government is responsible for developing and operating the proposed institutional scheme's LRT and other supporting infrastructure, while the private sector handles the development and operation of TOD mixed-used properties.

Keywords: *Financing Scheme, Light Rail Transit (LRT); Public-Private Partnership (PPP); Transit-Oriented Development (TOD).*

1. INTRODUCTION

Though many cities in developing countries are growing at a staggering rate, cities in Indonesia are growing at an average of 4.1% per year, relatively faster than other Asian cities (Abiad et al., 2019). In 2030, over 73% of Indonesia's population is predicted to live in cities (Narieswari et al., 2019). If not equipped with sufficient urban infrastructure, this rapid urbanisation often brings about urban issues, primarily when most of the population relies heavily on private vehicles, which could vary from congestion and air pollution to social inequality of accessibility (Berawi et al., 2021; Suzuki et al., 2015).

Due to rapid urbanisation, Jakarta, the capital city, has faced traffic congestion problems caused by ever-increasing private automotive use (Hidayati et al., 2019). To tackle this

[1] Professor, Department of Civil Engineering, Universitas Indonesia, Indonesia, maberawi@eng.ui.ac.id
[2] Researcher, Center for Sustainable Infrastructure Development, Universitas Indonesia, Indonesia, csid@eng.ui.ac.id
[3] Associate Professor, Department of Civil Engineering, Politeknik Negeri Bengkalis, Indonesia, gunawan@polbeng.ac.id
[4] Lecturer, Department of Civil Engineering, Universitas Indonesia, Indonesia, mustika.sari01@ui.ac.id
[5] Ph.D. Researcher, Delft University of Technology, Netherlands, perdana.miraj@gmail.com

problem, it has now developed an immense infrastructure with new mass transit networks, such as Mass Rapid-Transit (MRT), Light Rapid Transit (LRT), and the extension of the commuter line. The development of these transportation systems is expected to shift the paradigm of private vehicle use in favour of public transportation (Mudigonda et al., 2014; Ma et al., 2018; Berawi et al., 2020).

However, as the development of this transportation infrastructure entails substantial financial investment, a built environment intervention focused on the availability of mass transportation, called Transit-Oriented Development (TOD), should also be proposed as a part of the transit system. TOD is undoubtedly one of the most effective strategies for tackling the challenges faced by car-dependent cities by developing a compact, mixed-use, pedestrian-friendly development organised around a transit station (Berawi et al., 2020; Suzuki et al., 2013). It is believed to improve the feasibility of transit projects by developing real estate around transit stations and increasing public interest in using public transportation (Cervero & Murakami, 2009; Gunawan et al., 2020).

Due to insufficient funds for necessary infrastructure investments, the Indonesian government must seek alternative financing by involving the private sector through Public-Private Partnership (PPP) schemes. To boost private sector participation in infrastructure development, the government needs to enhance the attractiveness of these investments. Economic viability is a critical success factor for implementing PPP (Zhang, 2005). A previous study conducted by Berawi et al. (2019) calculated the financial analysis of a TOD area development for LRT Jabodebek’s Phase I project, the results of which show that the Internal Rate of Return (IRR) for the development of TOD LRT Jabodebek was estimated to be 9.75%. The Net Present Value (NPV) was projected to be around 190 trillion Rupiahs. The result might look promising at first glance. However, suppose the IRR was compared with the Weighted Average Cost of Capital (WACC) for Indonesia's construction and materials sector, which is around 11.01%. In that case, the project could be deemed financially unattractive to private investors.

Therefore, this study aims to develop a feasible PPP-based financing scheme that could attract more private investors to participate in the TOD projects. Several successful TOD projects have implemented PPP financing schemes. The innovative integration of transportation infrastructure with urban development is exemplified by these initiatives, which promote the development of economically viable and sustainable communities. The TOD in Hong Kong is a prime example of this, which has seamlessly incorporated its extensive metro system with real estate development (Musil, 2020).

2. LITERATURE STUDY

2.1 TRANSIT-ORIENTED DEVELOPMENT

TOD is a concept of urban area development that arises as a solution to resolve urban problems caused by uncontrolled rapid urbanisation, such as environmental pollution, resource deficiency, unreasonable land use, traffic congestion, and unrestrained urban sprawl (Habibi & Asadi, 2011; Petrova & Prodromidou, 2019). Per Wey and Chiu (2013), TOD integrates urban land use and public transportation, allowing city residents to meet all their daily needs without relying on private vehicles. Moreover, TOD is a medium- to high-density housing equipped with public facilities, retail facilities, and strategic workplaces, emphasising the strategic development areas around the transit area

(Calthorpe, 2022). The mixed-use area comprises various building functions, such as residential, offices, malls, hotels, etc.

Commonly the developments of TOD in various countries have primarily relied on conventional construction and mortgage financing schemes, with banks as the primary sources of lending (Venner & Ecola, 2007). However, it is important to consider that mixed-use schemes entail several uncertainties and risks associated with the TOD, ultimately leading to higher required rates of return. Mixed-use developments pose significant challenges that are amplified by the intricate design and construction processes, resulting in heightened financial obstacles for TOD. Effective strategies to overcome these obstacles include aligning structures with established product categories, securing patient, high-equity investments, utilising alternative construction methods and materials, adopting advanced information management systems, collaborating with seasoned stakeholders, and employing value engineering.

2.2 PUBLIC-PRIVATE PARTNERSHIP (PPP)

PPP involves collaboration between the government and the private sectors in the financing, developing, and operating of public projects in any or all phases of the projects, starting from design and construction, capacity building/rehabilitation, to operation and maintenance (Wilhelm et al., 2009; Engel et al., 2019). ADBI (2000) defines PPP as the collaborative activities among interested groups and actors based on mutual recognition of respective strengths and weaknesses, working towards commonly agreed objectives developed through effective and timely communication. The long-term contract provides a balanced service in facilities received by the government and the benefits received by the private sector.

PPP can be used to sustainably meet funding needs by mobilising private funds, increasing quantity, quality, and efficiency of service through healthy competition, improving the quality of management and maintenance in infrastructure facilities, and considering the users' ability to pay. While PPP emphasises mutually beneficial cooperation between the public and private sectors, it is also crucial to share risks and responsibilities between the parties involved (Mohd-Rahim et al., 2018).

PPP schemes enable knowledge transfer and innovation in design, construction, maintenance, and operation, as well as fill financing voids, thereby providing superior value for money (Berawi, 2019). The implementation of PPPs is based on the distribution of responsibilities between the public and private sectors, which varies by country (Viegas, 2010). Thus, various types of PPP implemented in worldwide infrastructure projects have shown mixed results.

2.3 FINANCIAL FEASIBILITY ANALYSIS

Financial feasibility analysis is conducted in the pre-investment phase of a prospective project to ensure that the project's investment is profitable and attractive for the investors by meeting their objectives and interests (Halil et al., 2016). Several approaches with diverse characteristics can be used in the investment feasibility analysis, as it is carried out based on the institution or individual who invests in the project or has a direct interest in it. The key principle of financial feasibility assessments is to maintain positive cash flow at all project stages (Dikareva & Voytolovskiy, 2016). Several indicators, such as NPV and IRR can be used in the financial feasibility analysis.

NPV and IRR are considered the standard Life Cycle Cost (LCC) approach for evaluating a project's economic feasibility over its life cycle and estimating the profitability of the investments by considering the time value of money (Fouche & Crawford, 2017). NPV is calculating the cost invested by estimating the value in a particular period. The formula can be expressed as follows (Equation 01):

$$NPV = \sum_{t=0}^{n} \frac{(R_t)}{(1+i)^t} \qquad \textit{(Eq. 01)}$$

Where:
R_t = net cash flow during a time t
i = discount rate
t = number of cash flow time

With the criteria:
NPV>0, investment is feasible
NPV=0, the investment returns the same amount of value as the money invested
NPV<0, investment is not feasible

Meanwhile, IRR is a method to evaluate the level of interest in potential project investment, depending on whether the value reaches the Rate of Return (RoR) set or not. The IRR of the investment rate is the prevailing interest rate, which shows that the NPV is equal to the project's total investment. The formula for the IRR calculation is as in Equation 02:

$$IRR = i_1 + \frac{NPV_1}{(NPV_1 - NPV_{2})}(\, i_2 - i_1) \qquad \textit{(Eq. 02)}$$

Where:
i_1 = lower discount rate chosen
i_2= higher discount rate chosen
NPV_1 = NPV at i_1
NPV_2 = NPV at i_2

3. METHODS

The development of the LRT Jabodebek project was planned to be conducted in two phases, with a total length of 83.6 km track that consists of six corridors i.e. (i) Cawang-Cibubur corridor, (ii) Cawang-Kuningan-Dukuh Atas corridor, (iii) Cawang-Bekasi Timur corridor, (iv) Dukuh Atas-Senayan corridor, (v) Cibubur-Bogor corridor, and (vi) Palmerah-Bogor corridor. The first phase of the development comprises a 14.5 km long Cawang-Cibubur corridor with four stations, an 11.5 km long Cawang-Kuningan-Dukuh Atas corridor, and an18.5 km long Cawang-Bekasi Timur corridor with that have seven stations each. Hereinafter, Cibubur-Bogor, Dukuh Atas-Senayan, and Palmerah Bogor corridors will be developed in the second phase. The length of each track would be around 25 km, 7.8 km, and 5.7 km, respectively.

This study will determine the financing scheme for developing TOD concepts for four stations of LRT Jabodebek developed in a previous study by Berawi et al. (2019), including Bekasi Timur, Cibubur, Ciracas, and Jaticempaka stations, with a total length of 42.1 km LRT rail track. According to the results of the LCC analysis conducted previously, the initial cost for the development of TOD LRT Jabodebek was estimated at IDR 57 trillion (USD 3.95 million), while the OM cost was projected at IDR 152 trillion

(USD 10.52 million) with the revenue of around IDR 562 trillion (USD 38.95 million) for 40 years. Furthermore, its cash flow projection will also be used as the basis of the calculation conducted in this study to develop a more optimal financing scheme that can improve the investment attractiveness from the private sector's point of view. Table 1 presents the proposed TOD design concepts in the four stations.

Table 1: TOD conceptual design for four stations of LRT Jabodebek
Source: Berawi et al. (2019)

Category	TOD Location			
	Bekasi Timur Station	**Cibubur Station**	**Ciracas Station**	**Jaticempaka Station**
Land Area (m^2)	50,000	14,075	122,678	53,574
Building Area (m^2)	45,000	12,300	109,700	47,830
Gross Floor Area (m^2)	357,500	98,760	769,280	390,554
Building Coverage Ratio (BCR)	90%	87%	89%	89%
Floor-Area Ratio	7.15	7.02	6.27	7.29
Residential Area (m^2)	162,000	45,360	233,280	171,481
Offices (m^2)	65,000	18,000	127,500	69,678
Hotel (m^2)	40,500	10,800	80,000	46,867

Afterwards, the financing scheme was then developed by dividing the financial responsibility-sharing scenarios based on the project life cycle, which can potentially improve the delivery of each project stage since the responsible parties are encouraged to optimise the economics of their investments in the project stage (Eldrup & Schutze, 2013). Several types of cost-sharing scenarios combine the initial cost, OM cost, and revenue, where the optimum IRR generated from a sharing scenario will be considered for developing an institutional scheme for the PPP implementation of the project.

There are four financing options developed in this study, i.e., (i) initial cost-sharing, (ii) OM cost-sharing, (iii) initial cost and OM cost-sharing, and (iv) costs and revenue sharing. The IRR and NPV resulting from the main financing options would be evaluated to obtain the most optimal financing scheme. Subsequently, only scenarios that produced IRR surpassing the WACC value of 11.01% would be considered.

In the initial cost-sharing scheme, the project's financial feasibility would be evaluated if the government and the private sector share only the initial cost burden. The private sector would entirely incur the OM cost, and the revenue would be fully entitled to the private sector. The government would have no obligation to manage the project. The three options on which the evaluation for the initial cost-sharing scheme would be based are as follows: the first scenario is where the government's share of the initial cost is at 60% while the private sector bears the other 40%. The second scenario is where the government and private sector bear the same initial cost-sharing, each at 50%. In the third scenario, the government's share of the initial cost is 40%, while the private sector bears 60%.

The project's financial feasibility would be evaluated in the OM cost-sharing scheme if the government and private sector share only the OM cost burden. This means that the private sector would incur the initial cost entirely, and the revenue would be fully entitled to the private sector. The share of the OM cost would follow the cost-sharing percentage used in initial cost-sharing scenarios.

Furthermore, the initial cost and OM cost-sharing scheme will simulate the potential IRR and NPV generated from the financing scenario where the government and private sector share the burden for initial cost and OM cost. The private sector would be fully entitled to the revenue in these sharing schemes. There are nine scenario options where the evaluation would be based: the first three scenarios are where the government's share of the initial cost is at 60%, and the share of OM cost is each varied from 40-60%, while the second three scenarios are where the government's share of the initial cost is at 50%, and the share of OM cost is each varied from 40, 50, and 60%. Furthermore, the last three scenarios are where the government's share of the initial cost is at least 40%, and the share of OM cost each varied from 40, 50, and 60%.

In the costs and revenue sharing scheme, the government and the private sector are simulated to share both initial and OM costs and the revenue. There are 27 scenario options for this sharing scheme, where each of the scenarios from the nine scenarios in the previous Initial Cost and OM Cost Sharing has three different options for the government's share of revenue, consisting of 40%, 30%, and 20%.

The results of the cost-sharing scheme evaluation were used to determine the distribution of responsibility between the public and private entities in the project. The cost and revenue distribution between the government and private sector were further adjusted based on the benchmark of best practices of PPP implementation in TOD projects, such as the one in the Hong Kong MTR project (Suzuki et al., 2015) and Beijing No. 4 Metroline MRT (Chang, 2013).

An institutional scheme for PPP implementation in the TOD project was then developed by conducting the following steps:

- Reference study to the institutional schemes in transit infrastructure projects
- Benchmark study to the governance of infrastructure systems in other countries
- Identify the internal and external stakeholders in the TOD LRT Jabodebek projects
- Evaluate the roles and responsibilities of the government
- Determine the sharing of responsibilities among stakeholders in the concession
- Determine the concession duration
- Determine the relationship between the concession and the lender
- Determine the mechanism of the monitoring and evaluation processes

The proposed financing and institutional scheme resulted from this study were then validated through in-depth interviews with the experts from the National Development Planning Agency (Bappenas) and PT Sarana Multi Infrastruktur (SMI), a special mission vehicle (SMV) under the Ministry of Finance engaged in financing and preparing infrastructure project.

4. RESULTS AND DISCUSSION

4.1 COST-SHARING FINANCIAL SCHEMES

This research evaluates 42 sharing options, including three initial cost-sharing scenarios, three OM cost-sharing scenarios, nine initial cost+OM cost-sharing scenarios, and 27 initial cost+OM cost+revenue sharing scenarios. Each type of these sharing schemes generates an optimal IRR and NPV result. For the initial cost-sharing scheme, the scenario that produces the optimal IRR and NPV is when the government provides 60% of the initial cost. The IRR is approximately 18.15%, while the NPV is around IDR 92.29 trillion (USD 6.39 million). The evaluation of the OM cost-sharing scheme produces a similar result. The scenario that results in the most optimal IRR and NPV is when the government provides 60% of the OM cost, which equals 11.44% and IDR 90.07 trillion (USD 6.24 million), respectively. In the financing scheme where both initial and OM costs are shared between the government and private sector, the scenario that produces the optimal IRR and NPV is where the government covers 60% of the initial cost and operational and maintenance costs. This scenario results in an IRR of 21.40% and an NPV of IDR 119.3 trillion (USD 8.26 million).

As for the financing scheme in which both parties share the initial and OM costs and the revenue, the most optimum scenario is where the government covers 60% of the initial and OM costs and gets 20% of the revenue. The private sector could expect an IRR value of 17.84% and an NPV of IDR 87.96 trillion (USD 6.09 million) from this scenario.

The study shows that the most profitable scenarios for private investors involve significant government contributions to costs and minimal revenue sharing. While these scenarios attract private investors, other factors, such as risk-sharing, should be considered for optimal financing. Higher risks for private investors typically drive efficiency in cost and time management, affecting their return on investment and payback periods. Although a scenario with the government covering 60% of costs and receiving no revenue offers the highest IRR for investors, it is not recommended.

A financing scheme that involves the government covering a part of the initial and operational costs and receiving a revenue share is preferred. This approach reduces the risk of a private sector monopoly and facilitates the transfer of knowledge, including technological and management innovations, from the private sector to the government (Delmon, 2015). Sharing costs and revenues enables the government to recoup a portion of its expenditures, rendering this scenario advantageous.

The share of costs and revenue was then adjusted, referring to the result of a benchmark study on the Hong Kong MTR project (Suzuki et al., 2015). Responsibility in the financing scheme was determined based on the literature study, where the government is the responsible party for the land acquisition, land and building permits, and the development and operation of rail infrastructure and other supporting infrastructures, such as Water Treatment Plant (WTP) and Sewage Treatment Plant (STP). On the other hand, the private sector is responsible for developing and operating mixed-use properties surrounding the transit stations (e.g., hotels, apartments, malls, offices, etc.). As for the revenue, the government would be entitled to the revenue from the apartment sales transaction, farebox revenue, and utility revenues (WTP and STP). The private investors would be entitled to the revenue from other mixed-use properties (e.g., hotel, mall, office, park and ride facilities, etc.). The details of the division of responsibility between the government and the private sector are shown in Figure 1.

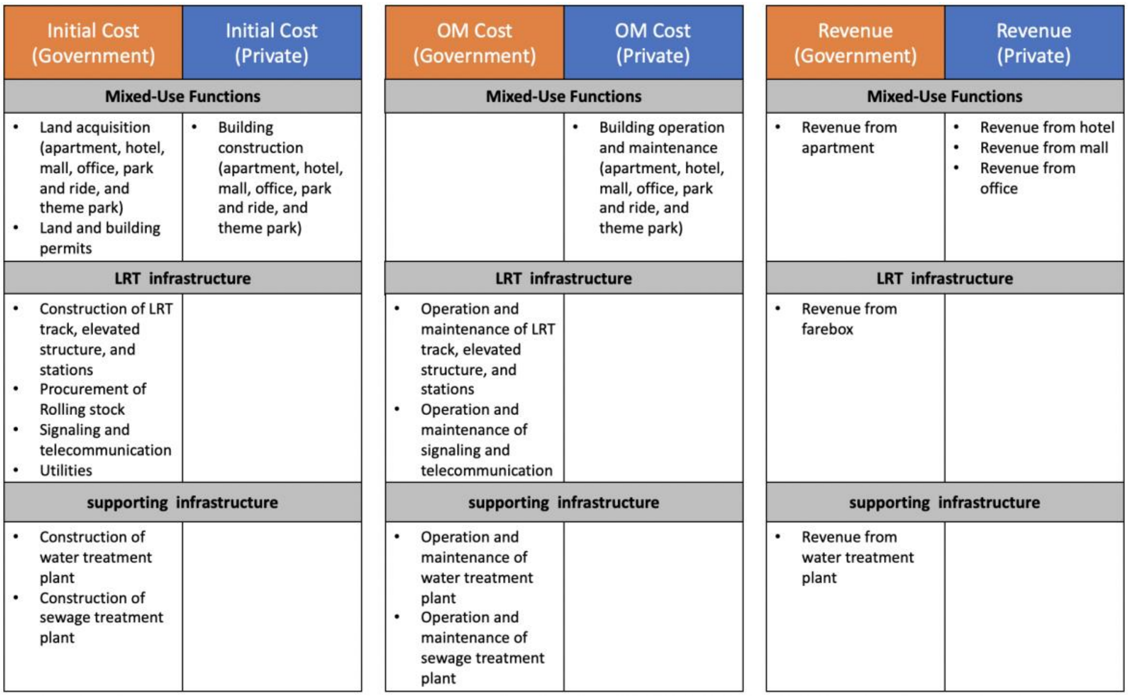


Figure 1: Division of responsibility between the government and private sector

The NPV for each cost and revenue component was calculated based on this distribution of costs and revenue. The share of cost and revenue was then calculated based on the total NPV to which both entities are responsible and entitled. The result is shown in Table 2.

Table 2: Share of costs and revenue between government and private investors

Financial Component	Net Present Value (in millions)		Share (%)	
	Private	Government	Private	Government
Initial Cost	-USD 1,410	-USD 2,127	39.86%	60.14%
OM Cost	-USD 2,550	-USD 1,312	66.02%	33.98%
Revenue	USD 7,480	USD 3,700	72.02%	27.98%

The financing scheme mentioned above generates an IRR of 14.92% for the private sector, which is higher than the WACC for Indonesia's construction and materials sector, indicating the project's financial feasibility. The estimated IRR from this financially engineered scheme is also higher by 5.17% than the original IRR estimation for the TOD LRT Jabodebek project estimated by Berawi et al. (2019).

4.2 INSTITUTIONAL SCHEMES

An institutional scheme was then developed to implement the PPP scheme throughout the project life cycle, from planning, construction, and operational and maintenance. It determines all the stakeholders' respective roles and responsibilities throughout the project. The visual representation of the proposed institutional scheme for PPP implementation in the TOD LRT Jabodebek projects can be seen in Figure 2.

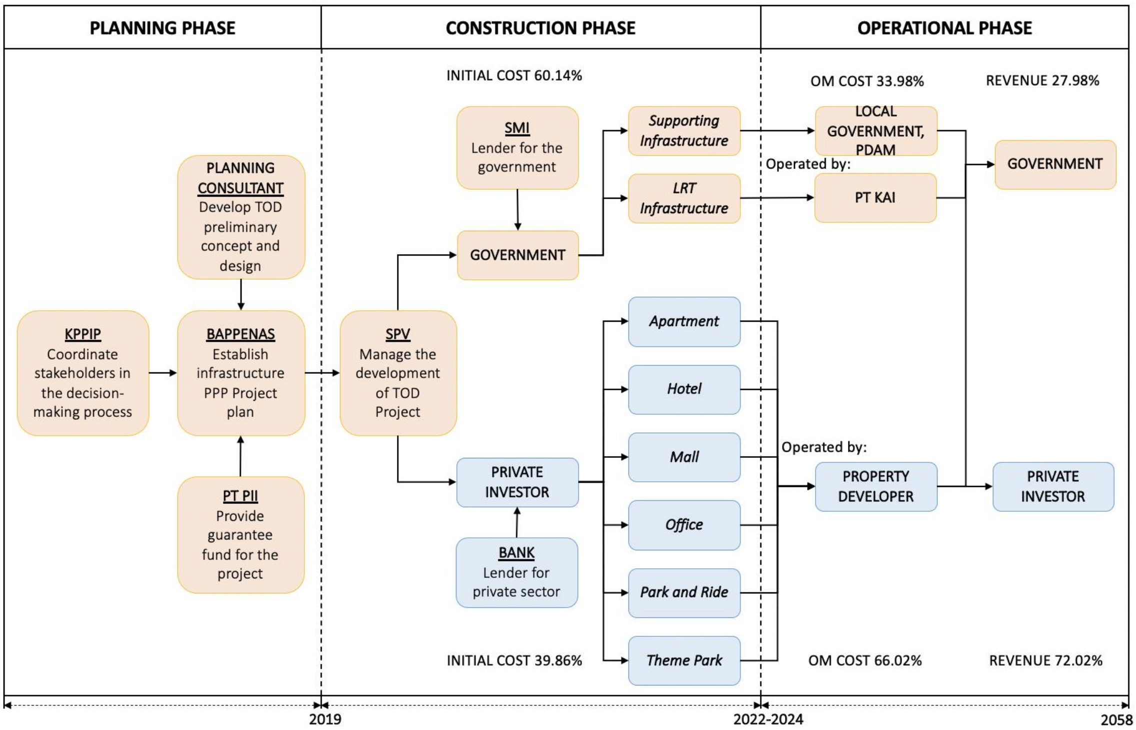


Figure 2: Institutional scheme for TOD LRT Jabodebek projects

During the planning stage, the stakeholders involved are Bappenas, the Indonesia Infrastructure Guarantee Fund (IIGF), the Committee for Acceleration of Priority Infrastructure Delivery (KPPIP), and the planning consultant. Bappenas would establish the plan for infrastructure PPP projects, assess the project's feasibility, sign the PPP contract, confirm the guarantee, and close the financial close. Meanwhile, IIGF would provide a guarantee fund for LRT Jabodebek, which could increase the project's creditworthiness and the private investor's interest in the project investment. Furthermore, the problems in Indonesia's infrastructure development process are due to the ineffective coordination between government and private stakeholders that might have different interests and responsibilities; thus, the role of KPPIP is to coordinate with involved stakeholders throughout the decision-making processes. KPPIP also facilitates the capacity building of the relevant government agencies and institutions at the planning stage to accelerate the development of the TOD LRT Jabodebek LRT projects. Moreover, the planning consultant would provide the TOD LRT Jabodebek project development design, such as project structure designs, building function designs developed in the TOD area, project budget plan calculations, and environmental impact analysis.

At the construction stage, a Special Purpose Vehicle (SPV) responsible for managing the project would be formed through an agreement between the government and private investors. Both the government and private investors will play key roles as shareholders for the SPV, ensuring a robust and balanced ownership structure. As per the result of the financing scheme, the government is encouraged to cover the initial cost for the LRT infrastructure and supporting infrastructure, while the private sector should cover the initial cost for the mixed-use functions. Apart from the shareholders' investment through equity, the SPV might also need other financing sources, such as loans from SMI to the government or banks to the private sector.

For the operational stage of the project, the infrastructure components would be operated by these respective parties. In this case, the LRT would be operated by PT KAI (Indonesia's railway company), and the supporting infrastructure would be operated by a local government company responsible for distributing clean water called PDAM. The mixed-use properties would be operated and maintained by a property developer.

The result of this study is in line with research by Bhagwati and Kumar (2024). The authors discovered that although implementing TOD regulations such as mixed-land use zoning, density control, limited parking, Public-Private Partnership (PPP) financing, and encouraging public-private collaboration near transit stations is essential, financial frameworks are even more crucial for the success of TOD. This makes it feasible on a global scale.

5. CONCLUSIONS

Developing TOD areas around transit stations requires substantial funding, necessitating private sector involvement through PPP schemes. This study proposes an optimal financing model where private investors cover 39.86% of initial costs, 66.02% of operational and maintenance costs, and receive 72.02% of revenue, resulting in a 14.92% IRR, which exceeds the sector's WACC.

This financing structure enhances TOD project feasibility and contributes to the knowledge of transportation financing. It offers a model adaptable to other TOD projects in Indonesia and developing countries. The proposed institutional scheme involves a special-purpose vehicle for managing construction and operations, with revenue-sharing between the government and private investors, promoting sustainable development.

6. ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Research, Technology and Higher Education Republic of Indonesia for the support given to this research.

7. REFERENCES

Abiad, A., Farrin, K., & Hale, C. (2019). *Sustaining Transit Investment in Asia's Cities: A Beneficiary-Funding and Land Value Capture Perspective*. Asian Development Bank. https://doi.org/http://dx.doi.org/10.22617/ARM190085-2

ADBI. (2000). *Public-Private Partnerships in the Social Sector: Issues and Country Experiences in Asia and the Pacific*. ADBI Publishing.

Berawi, M. A. (2019). Public-private partnership: Generating mutual benefits for stakeholders. *International Journal of Technology*, *10*(1), 1–4. https://doi.org/10.14716/ijtech.v10i1.2835

Berawi, M. A., Aprianti, L., Saroji, G., Sari, M., Miraj, P., & Kim, A. A. (2020). Land value capture modeling in residential area using big data approach method. *Engineering Journal*, *24*(4), 249–259. https://doi.org/10.4186/ej.2020.24.4.249

Berawi, M. A., Suwartha, N., Salim, A. V., Saroji, G., & Sari, M. (2021). Developing mobile application for land value capture scheme to finance urban rail transit projects. *International Journal of Technology*, *12*(7), 1448–1457. https://doi.org/10.14716/ijtech.v12i7.5332

Berawi, M. A., Wicaksono, P. L., Gunawan, Miraj, P., & Rahman, H. A. (2019). Life cycle cost analysis of the transit-oriented development concept in Indonesia. *International Journal of Technology*, *10*(6), 1184–1193. https://doi.org/10.14716/ijtech.v10i6.3621

Bhagwati, P., & Kumar, M. (2024). Transit-oriented development: learnings from global examples. *LOGI - Scientific Journal on Transport and Logistics*, *15*(1), 1–12. https://doi.org/10.2478/logi-2024-0001

Calthorpe, P. (2022). The next American Metropolis: From the next American Metropolis: Ecology, community, and the American dream (1993). *The Sustainable Urban Development Reader* (3rd ed., pp. 119–128). https://doi.org/10.4324/9781003288718-28

Cervero, R., & Murakami, J. (2009). Rail and property development in Hong Kong: Experiences and extensions. *Urban Studies*, *46*(10), 2019–2043. https://doi.org/10.1177/0042098009339431

Chang, Z. (2013). Public-private partnerships in China: A case of the Beijing No.4 Metro line. *Transport Policy*, *30*(4), 153–160. https://doi.org/10.1016/j.tranpol.2013.09.011

Delmon, J. (2015). *Private Sector Investment in Infrastructure: Project Finance, PPP Projects and PPP Frameworks* (3rd ed). Wolters Kluwer.

Dikareva, V., & Voytolovskiy, N. (2016). The efficiency and financial feasibility of the underground infrastructure construction assessment methods. *Procedia Engineering*, *165*, 1197–1202. https://doi.org/10.1016/j.proeng.2016.11.839

Eldrup, A., & Schutze, P. (2013). *Organization and financing of public infrastructure projects: a path to economic growth and development of the Danish welfare model*. Copenhagen, Denmark: Offentligt- Private Partnerskab.

Engel, E. M. R., Fischer, R., & Galetovic, A. (2019). Soft budgets and endogenous renegotiations in transport PPPs: An equilibrium analysis. *Economics of Transportation*, *17*, 40–50. https://doi.org/10.1016/j.ecotra.2018.12.003

Fouche, M., & Crawford, R. H. (2017). Towards an integrated approach for evaluating both the life cycle environmental and financial performance of a building: A review. *Procedia Engineering*, *180*, 118–127. https://doi.org/10.1016/j.proeng.2017.04.171

Gunawan, Berawi, M. A., & Sari, M. (2020). Optimizing property income in transit oriented development: A case study of Jakarta TOD. *Civil Engineering and Architecture*, *8*(2), 136–143. https://doi.org/10.13189/cea.2020.080211

Habibi, S., & Asadi, N. (2011). Causes, results and methods of controlling urban sprawl. *Procedia Engineering*, *21*, 133–141. https://doi.org/10.1016/j.proeng.2011.11.1996

Halil, F. M., Nasir, N. M., Hassan, A. A., & Shukur, A. S. (2016). Feasibility study and economic assessment in green building projects. *Procedia - Social and Behavioral Sciences*, *222, 56-64*. https://doi.org/10.1016/j.sbspro.2016.05.176

Hidayati, I., Yamu, C., & Tan, W. (2019). The emergence of mobility inequality in Greater Jakarta, Indonesia: A socio-spatial analysis of path dependencies in transport-land use policies. *Sustainability*, *11*(8), 5115. https://doi.org/10.3390/su11185115

Ma, X., Chen, X., Li, X., Ding, C., & Wang, Y. (2018). Sustainable station-level planning: An integrated transport and land use design model for transit-oriented development. *Journal of Cleaner Production*, *170*, 1052–1063. https://doi.org/10.1016/j.jclepro.2017.09.182

Mohd-Rahim, F. A., Abd-Rahim, M. S., Zainon, N., Chuing, L. S., & Abd-Samad, Z. (2018). Project life cycle risk of public-private partnership (PPP) projects for construction sustainability. *Journal of Design and Built Environment*, 39–53. https://doi.org/10.22452/jdbe.sp2018no1.4

Mudigonda, S., Ozbay, K., Ozturk, O., Iyer, S., & Noland, R. B. (2014). Quantifying transportation benefits of transit-oriented development in New Jersey. *Transportation Research Record*, *2417*(1), 111–120. https://doi.org/10.3141/2417-12

Musil, C. (2020). Hong Kong's "Rail-plus-Property" Development: A Model for Financing Public Transportation in Developing Cities in Southeast Asia? *Future Challenges of Cities in Asia*, 243–276. https://doi.org/10.2307/j.ctvs32qp6.12

Narieswari, L., Sitorus, S. R. P., Hardjomidjojo, H., & Putri, E. I. K. (2019). Multi-dimensions urban resilience index for sustainable city. *IOP Conference Series: Earth and Environmental Science*, *399*(1), 012020. https://doi.org/10.1088/1755-1315/399/1/012020

Petrova, S., & Prodromidou, A. (2019). Everyday politics of austerity: Infrastructure and vulnerability in times of crisis. *Environment and Planning C: Politics and Space*, *37*(8), 1380–1399. https://doi.org/10.1177/2399654419831293

Suzuki, H., Cervero, R., & Iuchi, K. (2013). *Transforming Cities with Transit: Transit and land-use integration for sustainable urban development*. World Bank Publications. https://doi.org/10.1596/978-0-8213-9745-9

Suzuki, H., Murakami, J., Hong, Y.-H., & Tamayose, B. (2015). *Financing transit-oriented development with land values: Adapting land value capture in developing countries*. The World Bank Publications. https://doi.org/10.1596/978-1-4648-0149-5

Venner, M., & Ecola, L. (2007). Financing transit-oriented development: Understanding and overcoming obstacles. *Transportation Research Record*, *1996*(1), 17-26. https://doi.org/10.3141/1996-03

Viegas, J. M. (2010). Questioning the need for full amortization in PPP contracts for transport infrastructure. *Research in Transportation Economics*, *30*(1), 139–144. https://doi.org/https://doi.org/10.1016/j.retrec.2010.10.014

Wey, W. M., & Chiu, Y. H. (2013). Assessing the walkability of pedestrian environment under the transit-oriented development. *Habitat International*, *38*, 106–118. https://doi.org/10.1016/j.habitatint.2012.05.004

Wilhelm, H., Kalidindi, S. N., Ogunlana, S., ShouQing, Wang, Martinus P. Abednego, Andrea Frank-Jungbecker, Y.-C. A., & Jan, Yongjian Ke, YuWen Liu, L. Boeing Singh, G. Z. (2009). *Public-Private Partnership in Infrastructure Development - Case Studies from Asia and Europe*. Verlag der Bauhaus-Universität, Weimar. https://nbn-resolving.de/urn:nbn:de:gbv:27-20100922-160114-1

Zhang, X. (2005). Critical success factors for public-private partnerships in infrastructure development. *Journal of Construction Engineering and Management*, *131*(1), 3–14. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:1(3)

Nadarajah, S., Kulatunga, U., Weerasooriya, D. and Rathnasinghe, A.P., 2024. Fire under control: Enhancing warehouse safety through strategic fire prevention and risk management. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 518-531. DOI: https://doi.org/10.31705/WCS.2024.41. Available from: https://ciobwcs.com/papers/

FIRE UNDER CONTROL: ENHANCING WAREHOUSE SAFETY THROUGH STRATEGIC FIRE PREVENTION AND RISK MANAGEMENT

S. Nadarajah[1], U. Kulatunga[2], D. Weerasooriya[3], and A.P. Rathnasinghe[4]

ABSTRACT

Warehouse fires represent a global challenge, inflicting economic losses, damaging reputational integrity, disrupting business operations, leading to job losses, and negatively impacting the environment. Despite strict fire regulations and codes of practice aimed at safeguarding warehouse facilities, the prevalence of catastrophic fires persists globally, including notable incidents in Sri Lanka. This persistence prompts an inquiry into the adequacy and appropriateness of current protective measures. This research addresses the urgent need to discern the root causes of warehouse fires and the consequent damages to devise effective preventative strategies. Through a combination of literature review and semi-structured interviews with ten experts, this study employs manual content analysis to explore underlying factors. Key findings indicate that failures often stem from the absence, inadequacy, or improper maintenance of fire detection and protection systems, the specific nature of storage configurations, the size of the facilities, and the combustible characteristics and volume of stored goods. The study proposes adhering to the Construction Industry Development Authority (CIDA) fire regulations, which mandate the provision and maintenance of active and passive fire protection measures. It further recommends the regular execution of fire risk assessments, the enforcement of stringent housekeeping protocols, the strategic separation of commodities based on their class and compatibility, and the isolation of battery re-charging operations from storage areas as critical steps to mitigate fire risks in warehouses. These insights guide warehouse owners, tenants, fire risk assessors, and other professionals who enhance fire safety in warehouse settings.

Keywords: *Fire Hazard; Fire Safety; Sri Lanka; Warehouse.*

1. INTRODUCTION

Warehouse fires represent a persistent global challenge that damages property, disrupts supply chains, inflates downtime, and tarnishes corporate reputations. Such incidents result in significant economic losses due to direct damage to buildings and contents and incur additional costs related to interrupted operations and third-party claims (Ronken, 2019; Spieler, 2016). For instance, notable incidents in Sri Lanka include fires at a Bata

[1] Chief Fire Officer, Port fire brigade, Sri Lanka Ports Authority, Sri Lanka, nadaasel@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dilanw@uom.lk
[4] PhD candidate, Faculty of Engineering and Environment, Northumbria University, England, akila.rathnasinghe@northumbria.ac.uk

warehouse in Rathmalana in 2004, at a Sri Lanka Ports Authority facility in 2013 (Kavirathna et al., 2021), and at a private textile firm in Lansiyahena in 2018 (Pabasara et al., 2019), which collectively underscore the severity of these events.

Despite frequent warehouse fires, only large-scale, disastrous fires receive significant attention. This focus overshadows the smaller fires that collectively pose a substantial risk (Ren, 2012; Twigg et al., 2017). This discrepancy highlights the need for a comprehensive approach to fire safety that encompasses emergency response and preventive strategies. The current fire safety regulations, while extensive, often fall short of effectively mitigating the risk of large-scale fires, particularly in oversized and densely stocked warehouse environments where fires can escalate rapidly due to high temperatures and abundant combustible materials (Alvarez et al., 2013; Hakes et al., 2017; Islam & Hossain, 2018; Qin et al., 2016).

Moreover, the environmental and health hazards posed by fire effluents, such as toxic gases and contaminated runoff, further complicate the impact of warehouse fires, affecting the immediate vicinity and the broader ecosystem (Perez, 2020). Considering the above, this paper argues for a critical revaluation of fire safety practices in Sri Lankan warehouses, emphasising the necessity of integrating modern technologies and revising existing guidelines under the CIDA fire regulation framework to enhance the efficacy of fire prevention and mitigation strategies. To achieve this, the remainder of this study is structured as follows: Section 2 synthesises the literature on factors influencing fire development in warehouses and existing fire safety regulations. Section 3 describes the methodology employed in this study, involving interviews with experts. Section 4 discusses the findings from these interviews. The conclusion reflects on the implications of this research and suggests avenues for future investigation.

2. LITERATURE REVIEW

2.1 FACTORS THAT ARE INFLUENCING THE FIRE DEVELOPMENT IN WAREHOUSES

Various factors influence the development and spread of fires in warehouses. Firstly, the size and layout of the warehouse play a crucial role (Lawson, 2001). According to Dinaburg and Gottuk (2012), large, undivided spaces allow fires to spread rapidly, as firefighters may struggle to reach the seat of the fire quickly due to increased distances and time spent laying out hoses. Moreover, the configuration of storage areas, especially in height and aisle width, impacts fire development. As storage heights increase (Overholt et al., 2011), so does the fire risk, with fire patterns transitioning from horizontal to vertical spread (Neale, 2017). Flue spaces, which provide ventilation and aid sprinkler effectiveness, become critical factors in fire control (Abdulrahman et al., 2021).

Additionally, the types of commodities stored, and their arrangement contribute significantly to fire hazards (Gollner et al., 2011). For example, certain materials may burn more rapidly when their surface area is maximised, and packing materials such as plastic films can hinder sprinkler effectiveness (Ebeling, 1990). Categorising commodities based on their burning and spread rates is essential for designing appropriate fire suppression systems (Overholt et al., 2011). Furthermore, the configuration of storage areas, including flue spaces, influences fire behaviour by providing pathways for air supply. According to Moran and Knight (2021), creating fire breaks between storage racks or piles can help slow the spread of fire, while open areas allow sprinklers to control the blaze (Security, 2019) effectively. Understanding and mitigating these factors are pivotal for effectively preventing and managing warehouse fires.

2.2 CONTRIBUTING CAUSES FOR FIRES IN WAREHOUSES

A combination of oxygen, fuel, and heat often initiates fires in warehouses. Once ignited, they can spread rapidly, fuelled by various sources within the warehouse environment. Electrical malfunctions are a significant contributor, with arc faults and electrostatic sparks being familiar ignition sources (Baalisampang et al., 2018). Exposed wires, overheating, and faulty connections are frequent culprits, highlighting the importance of regular maintenance and predictive techniques like thermography to detect potential faults (Yang et al., 2024). Ground faults and static electricity buildup pose risks, emphasising the need for ground-fault circuit interrupters and proper grounding programs. Mechanical equipment, such as mixers and elevators, can generate frictional heat or sparks during operation, while exhaust systems from diesel engines may ignite nearby combustibles. Battery charging operations present another hazard due to the release of hydrogen gas, necessitating proper ventilation or dedicated charging areas with fire-rated construction (Murphy et al., 2023).

Self-ignition can occur in materials stored for extended periods, especially during hot and moist conditions, while improper storage of chemicals can lead to unexpected reactions and fires (Saffarinia, 2021). Smoking materials and arson are additional causes, with reckless disposal of cigarettes and intentional fires being significant risks. Implementing designated smoking areas, security measures, and surveillance systems can help mitigate these risks. Therefore, warehouse fires result from various factors, including electrical faults, mechanical operations, battery charging processes, self-ignition of stored materials, chemical reactions, smoking, and arson. Preventative measures such as regular maintenance, proper storage practices, and enhanced security protocols are essential for reducing the likelihood and severity of warehouse fires.

2.3 FIRE PROVISIONS GIVEN FOR THE WAREHOUSES

Fire regulations, standards, and codes of practice, both locally and internationally, are crucial for ensuring the safety of warehouses. These guidelines cover various aspects such as fire alarm systems, access to fire service appliances, compartment sizes, structural fire resistance, and fire protection systems. Fire alarm systems are required in storage occupancies, but exemptions apply based on factors such as fire hazard level and the presence of automatic sprinkler systems (Meacham, 2023). Manual alarm systems and video image fire detection may be required for larger or unmanned storage areas. Access roads for fire service appliances must be broad enough to ensure effective response (Zhou & Zhang, 2020). Further, compartment sizes are regulated to limit fire spread, with considerations for sprinkler protection and building height. Fire protection systems including sprinklers, portable extinguishers, and hose reels are mandated based on warehouse size and hazard level (Bag & Ganguly, 2023). External fire hydrants may be required for larger areas.

Smoke ventilation systems or smoke control measures may be necessary depending on compartment size and fire protection systems in place (Short et al., 2006). Structural materials must have specified fire-resistance periods, with requirements varying based on building height and sprinkler protection (Kallianiotis et al., 2022). Signage is essential for indicating maximum storage heights and maintaining clearance below sprinkler heads.

Regular maintenance and testing of active and passive fire protection systems ensure their effectiveness over time (Hsiao & Hsieh, 2023). Fire regulations, standards, and codes of practice provide comprehensive guidance for mitigating fire risks in warehouses, encompassing various aspects of fire prevention, detection, suppression, and structural resilience. Compliance with these regulations is essential for safeguarding life and property in warehouse environments.

2.4 THE CURRENT FIRE REGULATIONS RELATED TO WAREHOUSES IN SRI LANKA

The current fire regulations related to warehouses in Sri Lanka encompass local and international standards to ensure safety and prevent fire incidents. According to the National Fire Protection Association (NFPA) guidelines, fire alarm systems are mandatory for all storage facilities, except when the content is of low fire hazard, or an automatic sprinkler system protects the warehouse. Additional measures include the requirement for manual alarm systems in single-story warehouses exceeding 400 m^2 and video image fire detection in unmanned storage areas with large open spaces or high ceilings. Furthermore, warehouses with floor areas over 800 m^2 must be equipped with manual call points and automatic fire detection systems, fire extinguishers, hose reels, landing valves, and automatic fire sprinklers.

Accessibility for fire service appliances is another crucial aspect of the regulations, mandating a clear path around warehouses. Roads leading to premises must have a minimum width of 3.7 meters between kerbs, with the actual width determined in consultation with local fire services. The storage building access should not be less than 4 meters in width. Compartment sizes are limited unless automatic fire sprinklers or similar protections are installed to prevent fire spread. For instance, in non-sprinkler warehouses with high fire hazards, compartment sizes are limited to 2,000 m^2 with a maximum height of 12 meters. The regulations also emphasise the importance of maintaining and periodically testing both active and passive fire protection systems and implementing control measures such as preventive maintenance of electrical equipment, proper storage practices, designated smoking areas, and installation of CCTVs to mitigate arson risks. While these regulations provide a robust framework for fire safety in warehouses, further study is still needed to address evolving risks and emerging technologies. Continuous research and updates to the fire safety codes are essential to ensure comprehensive protection and adapt to new challenges in warehouse management.

3. RESEARCH METHODOLOGY

The research problem is “Are the existing fire safety in warehouses in Sri Lanka adequate or improvement needed?”. Consequently, the research problem is subjective. A subjective presentation of the findings is required. Instead of attempting to prove a hypothesis about a phenomenon, such as "how many", it aims to examine and answer questions such as "what?" and "why?" As a result, the qualitative approach was used to perform this research. Therefore, this research was conducted using a qualitative approach. For this study, data was collected through semi-structured interviews, which helped the researcher conduct an in-depth inquiry into the study. The literature review helped identify fire causes, fire safety issues in warehouses in other countries and appropriate mitigating solutions. Qualitative content analysis is one of the methods used to analyse data (Hsieh, 2023). It starts with ideas about the hypotheses or issues that may arise and looks for them in the data that has been collected. Therefore, the qualitative content analysis method was selected to analyse data as it gains a rich, detailed understanding of a specific context and a more creative and flexible design in this study. Table 1 presents the profile of the experts.

Table 1: Profile of experts

Participants	Designation/field experience	Experience (years)
R1	Retired chief fire officer and fire consultant	40
R2	Retired chief fire officer and fire consultant	30
R3	Retired chief fire officer and fire consultant	28
R4	Chief fire officer	25
R5	Chief fire officer	15
R6	Fire consultant and fire incident investigator	35
R7	Fire consultant and fire system installer	15
R8	Fire consultant and fire system installer	20
R9	Fire risk assessor	22
R10	Fire officer and fire risk assessor	20

Ten non-random purposive samples were used to select the experts for this study. Palinkas et al. (2015) stated that purposive sampling is broadly used in qualitative research to obtain rich information from a limited resource. According to Gounder (2021), a larger sample size is needed for quantitative research, whereas for qualitative research, even a small sample size will be sufficient to obtain data saturation. After ten semi-structured interviews, the saturation level was reached.

4. DATA ANALYSIS AND RESULTS

4.1 CAUSES THAT CONTRIBUTE TO FIRES IN WAREHOUSES IN SRI LANKA

Six leading causes contributing to fires in warehouses were identified from the literature, and expert interviews were used to identify causes related to Sri Lanka. According to the experts, no proper investigation has been carried out in Sri Lanka to find the most common ignition source of fire. A summary of the causes of fires identified by each respondent is given in Table 2.

Table 2: Cause of fire

Causes of Fire	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Electrical source	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Unsafe hot work	✓	✓	✓	✓	✓	✓	✓	✓	✓	×
Incompatible materials	×	✓	✓	✓	×	×	×	✓	✓	✓
Battery charging inside the warehouses.	✓	✓	✓	✓	×	✓	✓	×	✓	✓
Deliberate acts	✓	✓	✓	✓	×	✓	✓	✓	×	✓
Smoking	✓	×	×	×	×	×	✓	×	✓	✓

Causes of Fire	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Storing flammable liquid inside the warehouse	×	×	×	✓	×	×	×	×	✓	×
Self–reactive materials	×	✓	✓	✓	×	×	×	×	×	×
Lightning	×	×	×	×	×	×	✓	×	✓	×

According to the table, all interviewees agreed that the electrical source was a cause of the warehouse fire in Sri Lanka. However, many respondents stated that unsafe hot work, auto ignition of some specific materials, chemical reactions of incompatible materials stored together, arson, and the battery charging inside the buildings cause fires other than the electrical source. Agreeing with that, R9 mentioned that even though the leading causes for warehouse fires are the electrical source and unsafe hot work, other sources such as the chemical reaction of incompatible materials stored, self-ignition of some materials, arson and careless smoking also initiate fires". However, R4 commented that *"even though battery charging causes a fire, battery charging operation inside the warehouses is rare in Sri Lankan context*". Similarly, three interviewees (R4, R6, R10) highlighted that arson causes warehouse fires; in Sri Lankan contexts, the probability is low.

According to R5, the fire-contributing factors of warehouses are electrical and hot work. Two responders agreeing with R5 added that lightning and the sparks from forklifts used in warehouses for loading and unloading purposes and smoking may also initiate a fire. R7 highlighted that lightning also initiates fires if no appropriate lightning protection is provided. In addition to that, two interviewees (R4, R9) stated that flammable liquids with points less than 320C 32 to the points are less than 320C 32 to the points are less than 320C 32 to the points are less than 32^{0C}. The regulation does not allow flammable liquids and reactive materials to be stored inside a warehouse as they initiate fire, yet many warehouse owners store them. Therefore, if any spark is introduced accidentally, it may form a flammable mixture and initiate fire.

4.2 Causes of Rapid-Fire Development in Warehouses in Sri Lanka

Respondents highlighted that numerous factors contribute to fire development in warehouses. Table 3 lists the leading causes of rapid-fire development in warehouses identified by respondents.

Table 3: Causes of rapid-fire development in warehouses

Causes of rapid-fire development	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Presence of a large amount of O_2	✓	×	✓	✓	✓	×	×	✓	✓	✓
High fire load	✓	✓	✓	✓	✓	✓	×	✓	✓	✓
No compartmentation to hold fire spread	✓	✓	✓	✓	✓	×	✓	✓	✓	✓
Storage Configuration	✓	✓	✓	✓	✓	✓	×	×	✓	✓
Delaying identifying the fire	✓	✓	✓	✓	✓	✓	✓	✓	×	✓
Lack/absence of fire protection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Most respondents pointed out that oxygen, the supporting agent for fire growth, is available sufficiently in warehouses as the warehouses have high volumes and large natural openings. Two respondents (R1, R3) explained that openings such as roller shutters/doors in warehouses also supply oxygen continually to the fire, as they are kept open to usual access and exit. R10 further added that the best practice of keeping the access and exit doors when not in use to prevent oxygen supply to the fire is not practised in Sri Lanka'. All experts pointed out that the absence of compartment walls to hold fire in large warehouses where the fire originates causes fire to spread.

Types of storage configurations play essential roles in fire spread and development. As with many respondents, R9 commented, "*Storage configuration and the tendency of hot smoke, gases, and flame travel upwards influence the fire spread*". According to R1, fire development is very high in rack storage rather than in big stacks as its ignitable surface is high. The distances between the stacks and the storage height can influence the fire spread. R4 stated that when the height of the rack storage increases and the gaps between racks narrow, it leads to rapid-fire development.

All experts agreed that the absence of fire detection systems to identify the fire in its early stage and the unavailability of firefighting equipment to control the fire in its early stage led to fire development in warehouses. Similarly, R9 highlighted that inadequate, inappropriate, and faulty conditions of the fire detection and extinguishing systems in existing warehouses are the major issues in Sri Lanka. Further, R10 commented, "*inadequate and improper maintenance of firefighting system in the existing warehouses also let the fire to burn until the firefighters intervene to control fire*". According to most respondents, many combustible materials, either material itself or packing materials stored in warehouses, can also lead to uncontrollable fire spread.

4.3 LEVEL OF EXISTING FIRE PROTECTION SYSTEMS IN WAREHOUSES IN SRI LANKA

The CIDA fire regulation, comparable to other international regulations and codes of practice, emphasises the provision of active and passive fire protection to warehouses. Installation of fire protection such as portable fire extinguishers, hose reels, landing valves, external hydrants, smoke extraction systems, and fire sprinklers depends on the floor area of the compartment or area of the warehouses and vice versa. Similarly, compartment size is limited unless it is protected with fire sprinklers. Table 4 summarises the requirements of the CIDA Fire Regulation to protect warehouses and the respondents' views.

Table 4: Requirements of CIDA fire regulation and views of respondents

CIDAFR Requirement	Respondents' Comments
Compartment size should be limited unless an auto fire protection system is provided.	It is not practical to follow the compartment limitation in warehouses. Most of the warehouses have not provided sufficient fire protection.
A fire detection system should be provided in warehouses.	Some warehouses belonging to multinational companies provided sufficient protection. Most of the warehouses have not provided sufficient fire detection systems.

CIDAFR Requirement	Respondents' Comments
Fire protection and detection systems should be maintained periodically.	Most warehouses have not been maintained periodically. Some warehouses belonging to multinational companies are maintained periodically.
Clear external access to warehouses shall be provided and maintained	Even though many warehouses provided access, it was found obstructed. The old warehouse, built before CIDA came into force, was not provided.

All respondents agreed that most warehouses in Sri Lanka have not been protected adequately, and most of the warehouses in Sri Lanka do not comply with the CIDA fire regulation. R9 further added that many warehouses in Sri Lanka found only portable fire extinguishers even though the requirements are higher than that. In addition, R1 stated that some other warehouses that maintain ISO standards have sufficient fire protection. R8 highlighted that providing passive fire protection in the warehouse is difficult due to its nature. For instance, "*We cannot limit the compartment size as the warehouse needs a large open area. Therefore, we have to consider only the active fire protection*", R8 further stated. According to R10, some warehouses exceeded the CIDA compartment limitation; nevertheless, there was no sprinkler system. CIDA fire regulation sets guidelines for installing fire sprinklers, hose reels, fire hydrants, and detection systems to protect the warehouse. As per most of the respondents, most of the warehouses in Sri Lanka do not comply with the CIDA fire regulation.

4.4 SUMMARY OF FINDINGS ON FIRE SAFETY MEASURES FOR WAREHOUSES IN SRI LANKA

Figure 1 presents the findings for fire safety measures for warehouses in Sri Lanka.

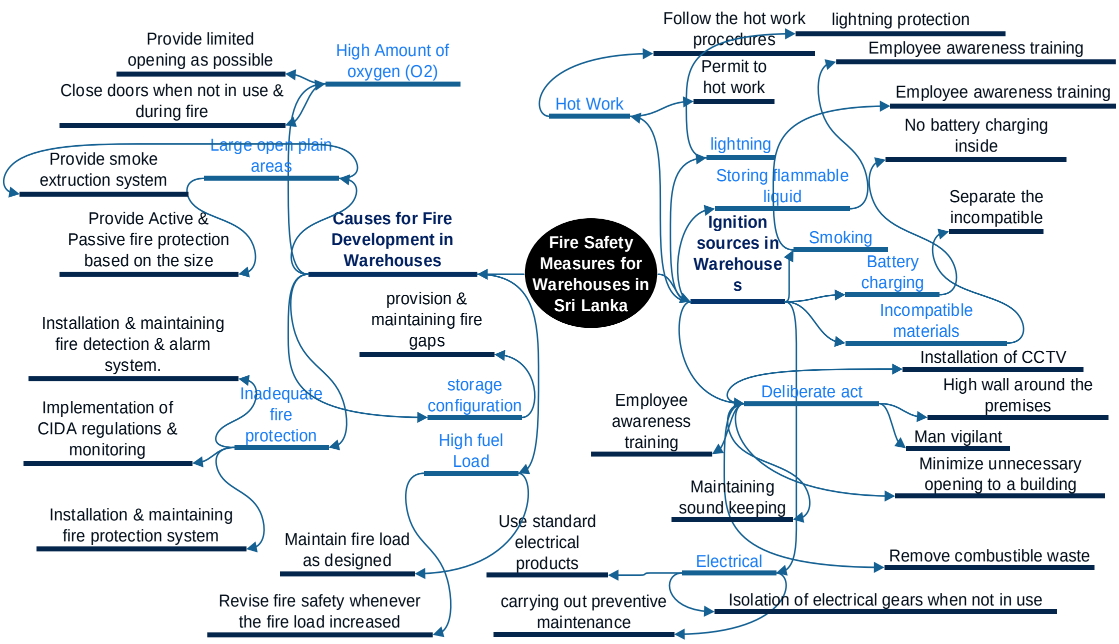


Figure 1: Summary of findings on fire safety measures for warehouses in Sri Lanka

According to most respondents, several factors contribute to warehouse fire development, including high fuel loads, ample oxygen supply, storage configurations, and inadequate or faulty fire protection and detection systems. Nine out of ten respondents emphasised that the high fuel load, due to the large amounts of combustible goods stored, is a leading cause of rapid-fire development. Additionally, high amounts of oxygen, facilitated by high roof levels and large open areas, create ideal conditions for fire growth. Respondents also highlighted that opening such as roller shutters and doors, often left open for access and exit, continuously supply Oxygen to the fire, exacerbating the situation. The absence of compartment walls in warehouses further allows the fire to spread unchecked from its origin.

Storage configurations play a crucial role in fire spread and development, with respondents noting that configurations like rack storage, with its high ignitable surfaces and narrow gaps between racks, can lead to rapid fire escalation. The storage height influences fire spread, as hot smoke, gases, and flames tend to travel upwards. Inadequate fire detection and protection systems significantly contribute to fire development in warehouses. Respondents pointed out that the absence of early fire detection systems and firefighting equipment allows fires to grow uncontrollably. Faulty or insufficient fire protection measures further delay the identification and response to fires, providing more time for the fire to develop and spread, underscoring the critical need for adequate fire safety measures in warehouses.

4.5 STRATEGIES TO MITIGATE FIRES AND FIRE DAMAGES IN WAREHOUSES IN SRI LANKA

This section analyses the primary data to find solutions to protect the warehouses and identify the parties responsible for implementing them. All respondents mentioned that the fire protection systems in existing warehouses in Sri Lanka are inadequate and need to be improved to mitigate the impact on the warehouses and save lives. R4 commented, *"The CIDA fire regulation guideline and code of practice are somewhat sufficient if implemented correctly. However, improvement should be made based on the content stored, structure, and storage height, which have not been addressed in the regulation".* Similarly, R10 argued that the CIDA regulation would be sufficient if implemented fully and monitored by the enforcement authority. However, R10 also agrees with improving fire safety in warehouses in Sri Lanka.

During semi-structured interviews, experts presented the findings of the Framework for Strategies to Mitigate Fire and Fire Damages. Figure 2 presents the findings.

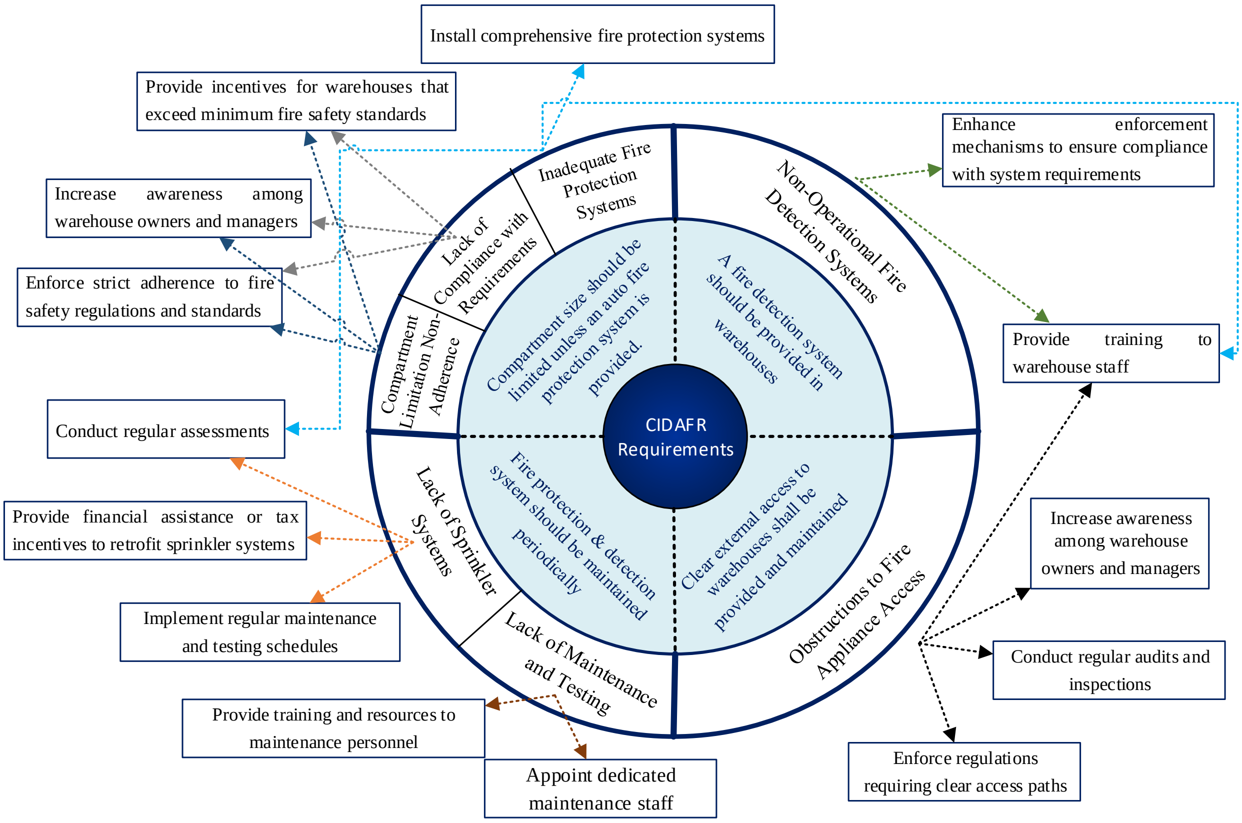


Figure 2: Framework for strategies to mitigate fires and fire damages

Many respondents agreed that the large areas used to store goods could be protected by providing sufficient fire gaps among storage stacks and walls to stacks as they can prevent fire spread due to flame impingement and radiant heat. Agreeing to the above, R1 added, *"maintaining fire gaps between storage piles and wall to racks, and ventilation arrangement such as smoke extraction system, and using a fire-rated structural material to build the warehouses could improve fire safety"*. Similarly, R8 stated that installing a smoke extraction system could mitigate fire spread and potential damages. According to R6, to improve fire safety in warehouses, *"the designers should analyse the risk and come up with the suitable protection"*. However, R4 mentioned that fire risk assessment should be carried out periodically to check whether the fire load and class of content have changed. This will help control the designed quantity and the type of goods unchanged and review the fire protection if any changes occur.

5. DISCUSSION

Fire safety in warehouses is a critical concern, and the findings of this research highlight several key areas that demand immediate attention and improvement. The inadequacy of current fire protection measures in many Sri Lankan warehouses exposes these facilities to significant risks, underscoring the urgent need for comprehensive fire safety strategies. A proactive approach to fire safety begins with the strategic design and layout of warehouses. Ensuring sufficient gaps between storage racks, stacks, and walls is fundamental in preventing the rapid spread of fire. This measure, supported by many respondents, is complemented by creating fire breaks and maintaining open areas to optimise sprinkler coverage (Security, 2019). Proper ventilation, achieved through transverse and longitudinal flue spaces within rack systems, enhances the dispersion of fire effluents and the effectiveness of sprinkler systems, a critical factor in fire mitigation.

Smoke extraction systems are another pivotal component of a robust fire safety strategy. These systems help control the spread of fire and ensure that clear escape routes are available for occupants, a recommendation strongly supported by some respondents. Additionally, incorporating fire risk analysis during the design phase and conducting periodic fire risk assessments are essential practices for adapting and updating fire protection measures as needed (Meacham et al., 2016). Early fire detection and rapid response are crucial for minimising damage. The widespread endorsement of fire detection systems among respondents highlights their importance, provided these systems are correctly installed and maintained. Installing fire sprinkler systems, specially tailored to specific storage configurations and commodity types, is widely recognised as a vital measure for controlling fire spread in warehouses (Meacham et al., 2016; Moran & Knight, 2021). The debate between the use of in-rack sprinkler systems versus ESFR systems reveals varying preferences based on storage types and configurations. While in-rack sprinklers are favoured for high-pile rack storage, ESFR systems, despite their limitations, offer rapid response capabilities that can be augmented with additional protections (NFPA, 2013).

Segregation of warehouse commodities according to their fire risk classes and implementing appropriate fire protection measures is another critical aspect respondents emphasise (Overholt et al., 2011). Controlling ignition sources, such as adequately maintaining electrical systems and equipment, is crucial for fire prevention. Additionally, precautions around battery charging operations and storing flammable liquids can significantly reduce fire risks (CIDA, 2018). Proper chemical storage practices, including maintaining safe distances between incompatible materials, are essential for preventing chemical-related fires (Saffarinia et al., 2021). Security measures, such as installing CCTV systems, employing security personnel, and rigorous housekeeping practices, prevent arson and unauthorised access (Meacham et al., 2016).

Finally, ensuring clear external fire access routes and conducting regular inspections are vital responsibilities for warehouse owners and fire departments. These measures ensure that in the event of a fire, emergency services can respond swiftly and effectively (Meacham, 2016). By addressing these findings and implementing comprehensive fire safety measures, warehouses in Sri Lanka can significantly mitigate the risk of fires and protect both property and human lives. The collective insights from this research provide a blueprint for enhancing fire safety protocols and fostering a safer working environment in warehouse facilities.

6. CONCLUSIONS

This study aims to devise strategies to diminish fire incidents and substantial damages in Sri Lankan warehouses. Employing a qualitative methodology, data was gathered via semi-structured expert interviews, supplemented by a rigorous content analysis of empirical findings. The literature review provided insights into the general construction attributes of warehouses, ignition sources, commodity types and their arrangements, fire behaviour, and existing fire protection measures. The interviews not only corroborated the literature but also tailored the findings to the Sri Lankan context, facilitating the development of a targeted fire safety framework. The results underscore the potential for this framework to increase awareness of fire causatives and enhance preventive actions. Crucially, the study underscores the role of governmental regulation in enforcing suitable fire protection standards, which is pivotal for the practical application of these findings.

Despite the comprehensive approach, this research acknowledges certain limitations. It excludes high-hazard categories such as chemical or liquid gas storage. It does not consider smaller storage facilities, focusing primarily on property protection rather than life safety due to the time constraints of the research team. However, these limitations inform further areas for research, suggesting that future studies could apply the developed framework in case study scenarios to test its effectiveness and scope. Overall, while this study contributes to the existing body of knowledge by identifying common causes of warehouse fires globally and within Sri Lanka, it also significantly establishes a novel framework to reduce fire-related losses in warehouse settings. Further investigation through case studies is recommended to validate and refine the proposed framework.

7. REFERENCES

Abdulrahman, S. A., Chetehouna, K., Cablé, A., Skreiberg, O., & Kadoche, M. (2021). A review on fire suppression by fire sprinklers. *Journal of Fire Sciences, 39*(6), 512-551. doi:10.1177/07349041211037436

Alvarez, A., Meacham, B. J., Dembsey, N. A., & Thomas, J. R. (2013). Twenty years of performance-based fire protection design: Challenges faced and a look ahead. *Journal of Fire Protection Engineering, 23*(4), 249-276. doi:10.1177/1042391513502386

Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., & Dadashzadeh, M. (2018). Review and analysis of fire and explosion accidents in maritime transportation. *Ocean Engineering, 158*, 350-366. doi: 10.1016/j.oceaneng.2018.04.021

Bag, S., & Ganguly, K. (2023). Mitigation of fire hazards in hospital. In A. Bag & K. Ganguly (Eds.), *A guide to hospital administration and planning* (pp. 193-229). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-4221-3_9

Construction Industry Development Authority (2018) Construction Industry Development Authority Fire Regulations (CIDAFR) (2018th ed.) Construction Industry Development Authority. https://www.scribd.com/document/452444487/CIDA-Fire-Regulation

Dinaburg, J., & Gottuk, D. T. (2012). *Fire detection in warehouse facilities*. Springer New York. https://doi.org/10.1007/978-1-4614-1185-3

Ebeling, C. (1990). *Integrated packaging systems for transportation and distribution*. USA: Marcel Dekker Inc.

Gollner, M. J., Overholt, K., Williams, F. A., Rangwala, A. S., & Perricone, J. (2011). Warehouse commodity classification from fundamental principles. Part I: Commodity & burning rates. *Fire Safety Journal, 46*(6), 305-316. Retrieved from https://doi.org/10.1016/j.firesaf.2011.04.004

Hakes, R. S., Caton, S. E., Gorham, D. J., & Gollner, M. J. (2017). A review of pathways for building fire spread in the wildland urban interface part II: Response of components and systems and mitigation strategies in the United States. *Fire Technology, 53*(2), 475-515. Retrieved from https://doi.org/10.1007/s10694-016-0601-y

Hsieh, S. H. (2023). Real-time fire protection system architecture for building safety. *Journal of Building Engineering, 67*, 105913. Retrieved from https://doi.org/10.1016/j.jobe.2022.105913

Hsiao, C. J., & Hsieh, S. H. (2023). Real-time fire protection system architecture for building safety. *Journal of Building Engineering, 67*, 105913. Retrieved from https://doi.org/10.1016/j.jobe.2022.105913

Kallianiotis, A., Papakonstantinou, D., Tolias, I. C., & Benardos, A. (2022). Evaluation of fire smoke control in underground space. *Underground Space, 7*(3), 295-310. Retrieved from https://doi.org/10.1016/j.undsp.2021.12.005

Koorsen Fire & Security. (2019, May 15). *Are the fire sprinklers protecting your high-piled storage areas?* Koorsen Fire & Security Headquarters. Retrieved August 01, 2024 from https://blog.koorsen.com

Short, C. A., Whittle, G. E., & Owarish, M. (2006). Fire and smoke control in naturally ventilated buildings. *Building Research and Information, 34*(1), 23-54. Retrieved from https://doi.org/10.1080/09613210500379667

Islam, M. Z., & Hossain, K. (2018). Fire hazards in Dhaka city: An exploratory study on mitigation measures. *IOSR Journal of Environmental Science, Toxicology and Food Technology, 12*(5), 46-56. Retrieved from https://doi.org/10.9790/2402-1205014656

Kavirathna, C. A., Hanaoka, S., Kawasaki, T., & Shimada, T. (2021). Port development and competition between the Colombo and Hambantota ports in Sri Lanka. *Case Studies on Transport Policy, 9*(1), 200-211.

Lawson, R. (2001). Fire engineering design of steel and composite buildings. *Journal of Constructional Steel Research, 57*(12), 1233-1247. Retrieved from https://doi.org/10.1016/s0143-974x(01)00051-7

Meacham, B. J., Charters, D., Johnson, P., & Salisbury, M. (2016). Building fire risk analysis. In M.J Hurley (Eds.) *SFPE Handbook of Fire Protection Engineering* (pp. 2941-2991). Springer New York. https://doi.org/10.1007/978-1-4939-2565-0_81

Meacham, B. J. (2023). Fire safety of existing residential buildings: Building regulatory system gaps and needs. *Fire Safety Journal, 140*, 103902. Retrieved from https://doi.org/10.1016/j.firesaf.2023.103902

Moran, C., & Knight, S. (2021, July 24). Four sprinkler options for warehouses with high combustible loads. *Daily eNews*. Retrieved from https://www.facilitiesnet.com/firesafety/article/Four-Sprinkler-Options-for-Warehouses-with-High-Combustible-Loads--17737

Murphy, J. F. (2017). Safety considerations in the chemical process industries. In J.A. Kent, B.V. Bommaraju, & S.D. Banicki (Eds.), *Handbook of Industrial Chemistry and Biotechnology* (pp. 1805-1887). Springer New York. https://link.springer.com/chapter/10.1007/978-3-319-52287-6_34

Murphy, B. P., Whitehead, P. J., Evans, J., Yates, C. P., Edwards, A. C., MacDermott, H. J., ... & Russell-Smith, J. (2023). Using a demographic model to project the long-term effects of fire management on tree biomass in Australian savannas. *Ecological Monographs, 93*(2), e1564. Retrieved from https://doi.org/10.1002/ecm.1564

National Fire Protection Association (NFPA) (2022). *NFPA 10: Standard for portable fire extinguishers*. National Fire Protection Association.

Neale, R. (2017, October 1). *High challenge: High piled storage fire protection - Part 1*. Gulf Fire. Retrieved August 01, 2024, from https://gulffire.mdmpublishing.com/high-challenge-high-piled-storage-fire-protection/

Overholt, K., Gollner, M., Perricone, J., Rangwala, A., & Williams, F. (2011). Warehouse commodity classification from fundamental principles. Part II: Flame heights and flame spread. *Fire Safety Journal*, *46*(6), 317-326. Retrieved from https://doi.org/10.1016/j.firesaf.2011.04.005

Palinkas, L., Horwitz, S., Green, C., Wisdom, J., Duan, N., & Hoagwood, K. (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and Policy in Mental Health and Mental Health Services Research, 42*(5), 533-544. Retrieved from https://doi.org/10.1007/s10488-013-0528-y

Pabasara, W. G. A., Nanayakkara, M. P. A., Samarasekara, A. M. P. B., Amarasinghe, D. A. S., & Karunanayake, L. (2019). Extraction and characterization of bio-based polymeric materials from traditional rice varieties in Sri Lanka. *Agricultural Research*, *30*(2), 47-54, Retrieved from https://tar.sljol.info/articles/10.4038/tar.v30i2.8308

Perez, C. (2020, October 05). *Preventing warehouse fires matters, now more than ever.* Xtralis Warehouse. Retrieved August 01, 2024, from https://www.linkedin.com/pulse/preventing-warehouse-fires-matters-now-more-than-ever-cesar-perez

Qin, Y., Huang, W., Xiang, Y., Zhang, R., Lu, P., & Tan, X. (2016). Feasibility analysis on natural smoke extraction for large space warehouse buildings. *Procedia Engineering, 135*, 495-500. Retrieved from https://doi.org/10.1016/j.proeng.2016.01.161

Ronken, L. (2019). *Warehouse fires - an underwriter's guide to containing the risks*. Cologne: Gen Re.

Saffarinia, N., Pouyakian, M., Zendehdel, R., & Ramezanian, R. (2021). Presenting a new method to evaluate the severity of the incompatibility of dangerous goods based on FTOPSIS: A case study of the 4.3 class. *ACS Chemical Health & Safety, 28*(5), 339–347. Retrieved from https://doi.org/10.1021/acs.chas.1c00017

Spieler, G. (2016, September 14). *The hidden costs of warehouse fires*. Supply Chain Dive. Retrieved August 01, 2024, from https://www.supplychaindive.com/news/hidden-cost-warehouse-fire/426281/

Twigg, J., Christie, N., Haworth, J., Osuteye, E., & Skarlatidou, A. (2017). Improved methods for fire risk assessment in low-income and informal settlements. *International Journal of Environmental Research and Public Health, 14*(2), 139. Retrieved from https://doi.org/10.3390/ijerph14020139

Yang, B., Zheng, R., Han, Y., Huang, J., Li, M., Shu, H., ... & Guo, Z. (2024). Recent advances in fault diagnosis techniques for photovoltaic systems: A critical review. *Protection and Control of Modern Power Systems, 9*(3), 36-59. Retrieved from https://doi.org/10.1186/s41601-023-00269-1

Zhou, K., & Zhang, X. (2020). Design of outdoor fire intelligent alarm system based on image recognition. *International Journal of Pattern Recognition and Artificial Intelligence, 34*(07), 2050018. Retrieved from https://doi.org/10.1142/S0218001420500181

Rahubadda, R.V.A.D. and Kulatunga, U., 2024. Harnessing nature's blueprint: Biomimicry in urban building design for sustainable and resilient cities. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 532-543. DOI: https://doi.org/10.31705/WCS.2024.42. Available from: https://ciobwcs.com/papers/

HARNESSING NATURE'S BLUEPRINT: BIOMIMICRY IN URBAN BUILDING DESIGN FOR SUSTAINABLE AND RESILIENT CITIES

Ashen Rahubadda[1] and Udayangani Kulatunga[2]

ABSTRACT

The increasing urban population and its associated activities significantly contribute to greenhouse gas emissions and exacerbate climate change impacts. Urban areas, particularly susceptible to extreme weather events, face challenges such as heat stress, flooding, air pollution, and water scarcity. In response, the concept of biomimicry, drawing inspiration from nature's functional principles, has gained traction as a viable approach for sustainable urban design. By emulating natural systems and processes, biomimetic solutions offer innovative strategies for addressing environmental challenges at various scales, from single buildings to entire urban areas. This study explores the potential of biomimicry in urban building design to mitigate environmental challenges associated with rapid urbanisation and climate change. Utilising a two-part methodology, the research includes a narrative literature review and a survey of practical case studies to evaluate the benefits of biomimetic concepts in architecture. The literature review provides a comprehensive, critical analysis of current knowledge on biomimicry, while the case studies showcase real-world examples of biomimetic design, such as the Eden Project and Eastgate Centre. Findings demonstrate that biomimicry enhances energy efficiency, reduces Carbon emissions, and increases resilience against extreme weather events. The study concludes that while biomimicry holds great promise for creating sustainable and resilient urban environments, widespread adoption is hindered by limited awareness and education among stakeholders. The research contributes to the field by highlighting the need for increased training and collaboration in biomimicry to fully harness its potential for sustainable urban design.

Keywords: *Biomimicry; Climate Change Mitigation; Resilient Urban Environments; Sustainable Architecture; Urban Built Environment.*

1. INTRODUCTION

Over half of the global population resides in urban areas, a figure expected to rise to 68% by 2050 (United Nations Department of Economic and Social Affairs Population Division, 2018). This rapid urbanisation significantly impacts climate change through direct CO_2 emissions and indirect effects such as pollution, waste production, and unsustainable consumption (Min et al., 2022). As urban populations expand, cities' influence on regional and global climates is likely to intensify (Emmanuel & Krüger, 2012). The swift growth of urban areas has led to microclimatic conditions, increasing

[1] Department of Building Economics, University of Moratuwa, Sri Lanka, rahubaddarvad.19@uom.lk
[2] Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

local air temperatures (Fahed et al., 2020). Consequently, urban areas are highly vulnerable to climate change impacts, facing risks including heat stress, flooding, landslides, air pollution, drought, and water scarcity (Stadler & Houghton, 2020). Urbanisation correlates with global population growth, exacerbating issues such as urban flooding, which affects larger populations and causes extensive damage costing billions of dollars (Zu Ermgassen et al., 2019). Global warming, driven by fossil fuel combustion since the Industrial Revolution, has resulted in increased CO_2 emissions (Musah et al., 2021). Especially urban building construction, identified as one of the least sustainable areas, significantly contributes to the climate crisis (Sijakovic & Peric, 2021).

In response, many cities have implemented measures to combat climate change. Networks such as the C40 Cities Climate Leadership Group (C40) and Local Governments for Sustainability (ICLEI) facilitate collaboration to address climate challenges (Musah et al., 2021). The European Strategic Energy Technology Plan (SETplan) aims to convert 50% of buildings in 25 cities into nearly zero-energy buildings (ZEB) by 2020, reducing Greenhouse Gas (GHG) emissions by 40% (Kylili & Fokaides, 2015). Additionally, innovative approaches, such as biomimicry, offer promising solutions to mitigate climate impacts from the urban construction industry (Austin et al., 2020).

Biomimicry involves drawing inspiration from nature's functional principles to design objects or systems, aligning closely with natural mechanisms (Pawlyn, 2019). Its core principle is emulating natural systems or processes to solve design challenges sustainably (Ahamed et al., 2022). While biomimetic solutions may influence a building's form, their primary goal is to derive functional, sustainable solutions from nature (Dicks et al., 2021). This approach is applied across various design fields, from fabric creation to complex building systems development (Nazir et al., 2023). The human impact on the natural and built environment underscores the need for a shift in city planning and construction, aiming for sustainable cities where biomimicry is a guiding concept (Ferwati et al., 2019).

This paper explores how integrating biomimicry into urban construction can address the dual challenges of urbanisation and climate change, leading to more sustainable, efficient, and resilient urban environments. It examines building designs that have achieved environmental benefits, such as energy efficiency and reduced carbon emissions, through biomimicry. The paper is structured as follows: a literature review, a methodology section, and an evaluation of biomimicry in building designs.

2. METHODOLOGY

The methodology of this study involves a two-part literature review process. The first part is a narrative literature review, where a comprehensive, critical, and objective analysis of current knowledge on biomimicry in urban design is conducted. This review involved searching academic databases such as PubMed, Google Scholar, and JSTOR using keywords including "biomimicry," "urban design," "sustainable architecture," and "climate change mitigation." The selection criteria included peer-reviewed articles, books, and reputable industry reports published within the last decade, ensuring a focus on recent advancements and relevant studies (Palmatier et al., 2018).

The second part is a brief literature survey evaluating the benefits of incorporating biomimicry concepts in building projects. This survey involved reviewing case studies and practical examples that demonstrate improved energy efficiency, enhanced resilience, and reduced environmental impacts. The sources were selected based on their relevance and evidence of successful implementation of biomimicry principles in real-world projects. This combined approach offers a thorough overview of biomimicry's potential to transform urban environments sustainably.

3. THE CONCEPT OF BIOMIMICRY

According to Benyus (1997), biomimicry involves the replication of natural processes to foster the development of innovative and sustainable design solutions. According to Zari and Hecht (2020), Biomimicry in Ecosystem Design Strategies revolves around “The emulation of strategies seen in the living world as a basis for design and innovation and has the potential to contribute to the creation of more sustainable architecture and urban environments”. Biomimicry encompasses two primary design approaches i.e. (i) the problem-based approach, often referred to as "design to biology," and (ii) the solution-based approach, entitled "biology to design," or the bottom-up approach (Aboulnaga & Helmy, 2022). The bottom-up approach relies on design solutions initially derived from scientific discoveries by biologists, such as the self-cleaning ability observed in lotus flowers, while the problem-based approach finds inspiration in biology by matching a problem to an organism that has already solved a similar challenge (Radwan & Osama, 2016). Furthermore, the solution-based approach is employed when the design process relies primarily on the scientific expertise of biologists and scientists rather than being driven by human design challenges from the outset (Martín-Gómez et al., 2019). One potential drawback of the problem-based approach is that it may not investigate how buildings relate to both each other and the ecosystem they are part of, thereby potentially neglecting to address the underlying causes of non-sustainable or even deteriorating built environments (Nkandu & Alibaba, 2018). Nonetheless, the problem-based approach can serve as a promising starting point for initiating the transformation of the built environment from inefficiency to a more sustainable state (Januszkiewicz & Alagoz, 2020). Moving on to the solution-based approach one drawback involves the necessity for conducting extensive biological research, followed by the critical assessment of gathered information to establish its relevance in a design context (Zari & Hecht, 2020). However, one of its benefits is that biological knowledge can influence the design in ways that step beyond addressing the initially defined design problem (Nkandu & Alibaba, 2018).

3.1 BENEFITS OF BIOMIMICRY

The escalating environmental deterioration and rapid climate change necessitate the imperative incorporation of biomimicry thinking into contemporary society for knowledge, adoption, integration, and application (Jamei & Vrcelj, 2021). Biomimicry has garnered widespread popularity and proven successful across diverse academic disciplines on a global scale (Oguntona & Aigbavboa, 2023). Table 1 illustrates the primary benefits of incorporating Biomimicry features in the urban built environment.

Table 1: Benefits of biomimicry in urban built environment

Benefits of Biomimicry	Authors											
	A	B	C	D	E	F	G	H	I	J	K	L
Resource (material and energy) efficient	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sustainability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Resilience and Adaptability	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Cost Efficiency (Maintenance and Operating)	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Waste Reduction	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓
Reduced CO2 Emissions	✓	✓	✓				✓	✓			✓	
Reduce Thermal Stress	✓	✓	✓		✓		✓	✓	✓	✓		✓
Improved Aesthetic Appearance	✓	✓	✓		✓			✓	✓		✓	
Protect Biodiversity	✓	✓	✓		✓			✓	✓		✓	
Reduce Climate Impact	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓
Enhance the Human Condition	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓
Material Recycling	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Innovative Design Solutions	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓

[A] (Oguntona & Aigbavboa, 2023) [B] (Bayhan & Karaca, 2019) [C] (AlAli et al., 2023) [D] (Zari & Hecht, 2020) [E] (Jamei & Vrcelj, 2021) [F] (Beermann & Chen Austin, 2021) [G] (Du Plessis et al., 2021) [H] (Verbrugghe et al., 2023) [I] (Chayaamor-Heil, 2023) [J] (Ahamed et al., 2022) [K] (Dixit & Stefańska, 2023) [L] (Othmani et al., 2022)

According to Table 1, the expanding realm of biomimicry as a concept in sustainability has garnered worldwide attention and demand to harness the multitude of advantages presented by the natural world (Oguntona & Aigbavboa, 2023). Subsequently, Biomimicry arises as a viable biological approach that plays a role in the creation of eco-friendly constructed spaces (Aboulnaga & Helmy, 2022). The consumption of embodied and operational energy within the Construction Industry has been recognised as a key factor contributing to the ongoing increase in the atmospheric Carbon footprint (Lawrence, 2015). Therefore, Chayaamor-Heil (2023) has illustrated that Biomimicry is one of the best solutions to reduce energy consumption especially, in urban buildings.

3.2 Challenges in Adopting Biomimicry Features

Even though Biomimicry has numerous benefits especially in terms of energy efficiency and climate change mitigation due to rapid urbanisation, there are several challenges in adopting these strategies in the building construction industry (Chen Austin et al., 2020).

The following table illustrates some major barriers to implementing Biomimicry in the urban built environment.

Table 2: Challenges in adopting biomimicry features in the urban built environment

Benefits of Biomimicry	Authors											
	A	B	C	D	E	F	G	H	I	J	K	L
Poor knowledge and awareness	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
High initial cost	✓		✓	✓		✓		✓		✓		✓
Poor policies and regulations	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓
Interdisciplinary Collaboration		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Research and Development	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Technological Limitations			✓		✓	✓			✓	✓	✓	✓
Time consumption	✓	✓	✓		✓	✓	✓	✓		✓		✓
Attitude of the people	✓	✓	✓	✓	✓		✓	✓	✓		✓	
Unavailability of material and technology	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓
Scalability	✓		✓	✓	✓	✓		✓	✓		✓	

[A] (Dixit & Stefańska, 2023) [B] (Jamei & Vrcelj, 2021) [C] (Nkandu & Alibaba, 2018) [D] (Pawlyn, 2019) [E] (Othmani et al., 2022) [F] (Sodiq et al., 2019) [G] (Ferwati et al., 2019) [H] (Aboulnaga & Helmy, 2022) [I] (AlAli et al., 2023) [K] (Viholainen et al., 2016) [L] (Chen Austin et al., 2020)

As per Table 2, higher initial costs and investments in advanced materials and technologies can be prohibitive, despite the long-term savings and efficiencies offered (Dicks et al., 2021). Additionally, a lack of awareness and understanding among stakeholders, including architects, engineers, and planners, hampers widespread implementation (Zari & Hecht, 2020). The complexity of integrating biomimetic features requires a multidisciplinary approach and extensive collaboration, which can be difficult to coordinate (MacKinnon et al., 2022). Furthermore, there are challenges in measuring the sustainability impact of biomimetic designs due to the lack of standardised metrics (MacKinnon et al., 2022). Overcoming these barriers necessitates increased education, training, and a shift in industry practices to fully realise the potential of biomimicry in sustainable urban design (Pawlyn, 2019).

4. BIOMIMICRY IN URBAN DESIGN

In urban and architectural design, biomimetic concepts can be applied to tackle global environmental issues (Zari, 2018). Architecture in modern cities requires a tremendous amount of energy for construction, maintenance, and operation, directly and indirectly causing global environmental issues, such as loss of biodiversity or climate change through greenhouse gas emissions (Grimm et al., 2008). It has been proposed that the biomimetic approach can address these challenges at multiple scales, from single mechanical units (materials) to buildings, up to entire urban areas (Aboulnaga & Helmy, 2022). Biomimicry offers an opportunity to operationalise sustainability and regenerative development on architectural and urban projects (Hes & Du Plessis, 2014; Zari, 2018). The practice of biomimetic architecture faced the first increase throughout the nineties, within the beginning of a global context of the energy transition, giving birth to iconic biomimetic projects such as the Eastgate building, (1996) (Chayaamor-Heil, 2023). According to Zari (2017, 2018) analysing the urban built environment from the perspective of how ecosystems function, and then designing changes to cities, buildings, and building components so that they begin to quantifiably emulate the functions of ecosystems could work towards the creation of cities where positive integration with, and restoration of local ecosystem services could be realised. Mimicking biological morphology is one of many conventional applications of biomimetics in the field of architecture, and the subjects of this mimicry are not exclusively single organisms or organisms per se, but also the products of their biological behaviour, such as nests (Fujii et al., 2016; Uchiyama et al., 2020). Currently, the focus is less on aesthetics and more on mimicking functional aspects of living systems. As a measure to reduce the environmental impacts of buildings, the biomimetic approach provides design elements that, for example, collaborate with the economics of materials and the optimisation of lighting and heating (Buck, 2017). Therefore, it is believed that using biomimicry in architectural design will result in more ecological buildings that will be easier to update in the future while using less energy and spending less money on maintenance (Pradhan & Choudhury, 2023; Suresh Kumar et al., 2020). Having discussed the concept of Biomimicry, the below section discusses a few examples of buildings that have used the Biomimicry concept and the benefits gained due to their incorporation.

4.1 BIOMIMICRY INCORPORATED BUILDING PROJECTS

Eden Project, Cornwall

The Eden Project, situated in a reclaimed kaolinite mine, stands as the largest greenhouse plant globally. As mining activities continued during the design phase, the project necessitated a structure adaptable to fluctuating ground levels (Nkandu & Alibaba, 2018). The outcome is an array of dome structures resembling bubbles of different sizes scattered across the landscape. Inspired by nature, engineers opted for geodesic shapes, employing hexagons and pentagons, to create spherical surfaces effectively (Beermann & Chen Austin, 2021).

Figure 1: Eden project

Sinosteel International Plaza

The objective of this building was to create a lightweight structure that minimises material usage while effectively managing heat and maximising natural light (Mohamed et al., 2019). The solution for the building's design involved incorporating the optimal hexagonal honeycomb structure into the window system (Holstov et al., 2022). By analysing the various airflows and solar orientations across the site, the honeycomb building design ensures energy efficiency. This approach has resulted in an impressive energy efficiency rate of 75% (Chen et al., 2015).

Figure 2: Sinosteel International Plaza

East Gate Center, Harare

The Eastgate Centre, predominantly constructed from concrete, features a ventilation system inspired by termite mounds (Garcia-Holguera et al., 2016). This innovative approach has resulted in a remarkable 100% reduction in energy consumption for HVAC systems. Additionally, the building design facilitates natural ventilation and lighting, further enhancing its energy efficiency (Attia et al., 2022).

Figure 3: East Gate Center, Harare

Council House, Melbourne

CH2 employs a ventilation strategy inspired by termite mounds, utilising natural convection, ventilation stacks, thermal mass, phase change materials, and water for cooling (Beermann & Chen Austin, 2021). The building's façade is designed with dermis and epidermis layers to create a microclimate (Bayhan & Karaca, 2019). Ventilation stacks are incorporated on both the north and south facades (Radwan & Osama, 2016). The ceilings feature a wavy shape to maximise surface area and enhance thermal mass capacity (Singh, 2020). Additionally, the west façade is equipped with timber louvres to optimise natural light penetration and views (Ahamed et al., 2022). The epidermis serves as the primary mechanism for sun and glare control while establishing a semi-closed microenvironment. Moreover, the presence of shower towers results in a temperature reduction of four to 13 degrees Celsius from the top of the tower to the bottom (AlAli et al., 2023).

Figure 4: Council House, Melbourne

Coral Reef Project Haiti

The self-sufficient energy village is designed to accommodate refugees from humanitarian disasters using standardised and prefabricated parts. This innovative project features two duplex passive residences interconnected by a transversal horizontal circulation, creating a cohesive living structure that can house over a thousand Haitian families (Achal et al., 2016). Each residence's roof serves as an organic suspended garden, promoting self-sufficiency by allowing families to cultivate their food and recycle waste. Additionally, the design fosters a thriving tropical ecosystem for local fauna and flora. The project is eco-designed, incorporating bioclimatic systems and renewable energy sources to ensure sustainability and resilience (Elshapasy et al., 2022).

Figure 5: Coral Reef Project Haiti

City Hall, London

Designed by Norman Foster, this building emulates a cut sphere to reduce the surface area exposed to direct sunlight, allowing for passive energy savings. The form minimises wind resistance, contributing to the building's energy efficiency (Nkandu & Alibaba, 2018).

Figure 6: City Hall, London

Biomimicry has been successfully employed in numerous projects, yielding significant benefits, particularly in energy efficiency. This paper underscores the importance of transferring ideas from nature to engineering by comprehending fundamental concepts such as composition, behaviour, and ecology. It emphasises the necessity of differentiating between levels of biomimicry in architectural design, which range from organism-level information to ecosystem-level behaviour. These examples consist of various building typologies, the influence of natural systems, the application of architectural design principles, and problem-solving through diverse design solutions. Accordingly, the paper compares case studies and their objectives to extract key considerations for designing biomimetic urban building projects.

5. CONCLUSIONS

Biomimetic approaches in urban building construction and climate change mitigation leverage nature-inspired solutions to address environmental challenges. Biomimicry can reduce the urban heat island effect, lower CO_2 emissions, and enhance building energy efficiency by mimicking natural processes and systems. This study highlights the potential of biomimicry for innovative and sustainable urban design, emphasising its role in climate regulation, ventilation, and energy management. Despite its promise, widespread adoption faces obstacles such as limited awareness among stakeholders. Promoting education, training, and interdisciplinary collaboration is essential for integrating biomimicry into sustainable practices. Future research should focus on conducting empirical studies and developing pilot projects to validate the efficacy of biomimetic approaches. These studies can provide concrete evidence of the benefits and feasibility of biomimicry, encouraging broader adoption in the construction industry. Additionally, establishing policies and regulations that support and incentivise the use of biomimetic solutions can drive industry-wide changes towards sustainability.

6. REFERENCES

Aboulnaga, M., & Helmy, S. E. (2022). Biomimicry in architecture for climate change mitigation and adaptation: An overview of Egypt, Italy, and Germany actions towards climate change. *In Biomimetic architecture and its role in developing sustainable, regenerative, and livable cities: Global Perspectives and Approaches in the Age of COVID-19* (pp. 333–410). Springer International Publishing. https://doi.org/10.1007/978-3-031-08292-4_5

Achal, V., Mukherjee, A., & Zhang, Q. (2016). Unearthing ecological wisdom from natural habitats and its ramifications on development of biocement and sustainable cities. *Landscape and Urban Planning, 155,* 61–68. https://doi.org/10.1016/j.landurbplan.2016.04.013

Ahamed, M. K., Wang, H., & Hazell, P. J. (2022). From biology to biomimicry: Using nature to build better structures – A review. *Construction and Building Materials, 320,* 126195. https://doi.org/10.1016/j.conbuildmat.2021.126195

AlAli, M., Mattar, Y., Alzaim, M. A., & Beheiry, S. (2023). Applications of biomimicry in architecture, construction and civil engineering. *Biomimetics, 8*(2), 202. https://doi.org/10.3390/biomimetics8020202

Attia, S., Kurnitski, J., Kosiński, P., Borodiņecs, A., Deme Belafi, Z., István, K., Krstić, H., Moldovan, M., Visa, I., Mihailov, N., Evstatiev, B., Banionis, K., Čekon, M., Vilčeková, S., Struhala, K., Brzoň, R., & Laurent, O. (2022). Overview and future challenges of nearly zero-energy building (nZEB) design in Eastern Europe. *Energy and Buildings, 2*67, 112165. https://doi.org/10.1016/j.enbuild.2022.112165

Bayhan, H. G., & Karaca, E. (2019). SWOT analysis of biomimicry for sustainable buildings – A literature review of the importance of kinetic architecture applications in sustainable construction projects. *IOP Conference Series: Materials Science and Engineering, 471*, 082047. https://doi.org/10.1088/1757-899X/471/8/082047

Beermann, K., & Chen Austin, M. (2021). An inspection of the life cycle of sustainable construction projects: Towards a biomimicry-based road map integrating circular economy. *Biomimetics*, *6*(4), 67. https://doi.org/10.3390/biomimetics6040067

Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature*. Morrow.

Buck, N. (2017). The art of imitating life: The potential contribution of biomimicry in shaping the future of our cities. *Environment and Planning B: Urban Analytics and City Science, 44*(1), 120–140. https://doi.org/10.1177/0265813515611417

Chayaamor-Heil, N. (2023). From bioinspiration to biomimicry in architecture: Opportunities and challenges. *Encyclopedia, 3*(1), 202–223. https://doi.org/10.3390/encyclopedia3010014

Chen Austin, M., Garzola, D., Delgado, N., Jiménez, J. U., & Mora, D. (2020). Inspection of biomimicry approaches as an alternative to address climate-related energy building challenges: A framework for application in Panama. *Biomimetics, 5*(3), 40. https://doi.org/10.3390/biomimetics5030040

Chen, D. A., Ross, B. E., & Klotz, L. E. (2015). Lessons from a coral reef: biomimicry for structural engineers. *Journal of Structural Engineering, 141*(4), 02514002. https://doi.org/10.1061/(asce)st.1943-541x.0001216

Dicks, H., Bertrand-Krajewski, JL., Ménézo, C., Rahbé, Y., Pierron, J.P., Harpet, C. (2021). Applying Biomimicry to Cities: The Forest as Model for Urban Planning and Design. In: Nagenborg, M., Stone, T., González Woge, M., Vermaas, P.E. (eds), *Technology and the City: Philosophy of Engineering and Technology*, (pp. 271-288). Springer, Cham. https://doi.org/10.1007/978-3-030-52313-8_14

Dixit, S., & Stefańska, A. (2023). Bio-logic, a review on the biomimetic application in architectural and structural design. *Ain Shams Engineering Journal, 14*(1), 101822. https://doi.org/10.1016/j.asej.2022.101822

Du Plessis, A., Babafemi, A. J., Paul, S. C., Panda, B., Tran, J. P., & Broeckhoven, C. (2021). Biomimicry for 3D concrete printing: A review and perspective. Additive *Manufacturing*, *38*, 101823. https://doi.org/10.1016/j.addma.2020.101823

Elshapasy, R. A. I., Ibrahim, M. A., & Elsayad, Z. (2022). Bio-tech retrofitting to create a smart-green university. *In Sustainable Development and Planning XII* (p. 127).

Emmanuel, R., & Krüger, E. (2012). Urban heat island and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK. *Building and Environment, 53*, 137–149. https://doi.org/10.1016/j.buildenv.2012.01.020

Fahed, J., Kinab, E., Ginestet, S., & Adolphe, L. (2020). Impact of urban heat island mitigation measures on microclimate and pedestrian comfort in a dense urban district of Lebanon. *Sustainable Cities and Society, 61*, 102375. https://doi.org/10.1016/j.scs.2020.102375

Ferwati, M. S., Alsuwaidi, M., Shafaghat, A., & Keyvanfar, A. (2019). Employing biomimicry in urban metamorphosis seeking for sustainability: Case studies. Architecture, *City and Environment, 14*(40), 133–162. https://doi.org/10.5821/ace.14.40.6460

Fujii, S., Sawada, S., Nakayama, S., Kappl, M., Ueno, K., Shitajima, K., Butt, H.-J., & Nakamura, Y. (2016). Pressure-sensitive adhesive powder. *Materials Horizons, 3*(1), 47–52. https://doi.org/10.1039/C5MH00203F

Garcia-Holguera, M., Clark, O. G., Sprecher, A., & Gaskin, S. (2016). Ecosystem biomimetics for resource use optimization in buildings. *Building Research and Information, 44*(3), 263–278. https://doi.org/10.1080/09613218.2015.1052315

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., & Briggs, J. M. (2008). Global change and the ecology of cities. *Science, 319*(586), 756–760. https://doi.org/doi:https://doi.org/10.1126/science.1150195

Hes, D., & Du Plessis, C. (2014). *Designing for hope: Pathways to regenerative sustainability*. Routledge.

Holstov, A., Bridgens, B., & Farmer, G. (2022). Material ecology 3—Smart materials: Essay two: Towards passively responsive biomimetic architecture. *In The Routledge Companion to Ecological Design Thinking* (1st Edition, pp. 285–292). Routledge.

Jamei, E., & Vrcelj, Z. (2021). Biomimicry and the built environment, learning from nature's solutions. *Applied Sciences, 11*(16), 7514. https://doi.org/10.3390/app11167514

Januszkiewicz, K., & Alagoz, M. (2020). Inspired by nature: The sun and shadow pavilion, social integration and energy saving in the built environment. *IOP Conference Series: Materials Science and Engineering, 960*, 042081. https://doi.org/10.1088/1757-899X/960/4/042081

Kylili, A., & Fokaides, P. A. (2015). European smart cities: The role of zero energy buildings. *Sustainable Cities and Society, 15*, 86–95. https://doi.org/10.1016/j.scs.2014.12.003

Lawrence, M. (2015). Reducing the environmental impact of construction by using renewable materials. *Journal of Renewable Materials, 3*(3), 163–174. https://doi.org/10.7569/JRM.2015.634105

MacKinnon, M., Pedersen Zari, M., Brown, D. K., Benavidez, R., & Jackson, B. (2022). Urban biomimicry for flood mitigation using an ecosystem service assessment tool in Central Wellington, New Zealand. *Biomimetics, 8*(1), 9. https://doi.org/10.3390/biomimetics8010009

Martín-Gómez, C., Zuazua-Ros, A., Bermejo-Busto, J., Baquero, E., Miranda, R., & Sanz, C. (2019). Potential strategies offered by animals to implement in buildings′ energy performance: Theory and practice. *Frontiers of Architectural Research, 8*(1), 17–31. https://doi.org/10.1016/j.foar.2018.12.002

Min, J., Yan, G., Abed, A. M., Elattar, S., Amine Khadimallah, M., Jan, A., & Elhosiny Ali, H. (2022). The effect of carbon dioxide emissions on building energy efficiency. *Fuel, 326*, 124842. https://doi.org/10.1016/j.fuel.2022.124842

Mohamed, N. A., Bakr, A. F., & Hasan, A. E. (2019, April). Energy efficient buildings in smart cities: Biomimicry approach. *In Proceedings of the 24th International Conference on Urban Planning, Regional Development and Information Society*, Karlsruhe, Germany (pp. 2-4).

Musah, M., Kong, Y., & Vo, X. V. (2021). Predictors of carbon emissions: an empirical evidence from NAFTA countries. *Environmental Science and Pollution Research, 28*(9), 11205–11223. https://doi.org/10.1007/s11356-020-11197-x/Published

Nazir, A., Gokcekaya, O., Md Masum Billah, K., Ertugrul, O., Jiang, J., Sun, J., & Hussain, S. (2023). Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D printing of materials and cellular metamaterials. *Materials & Design, 226*, 111661. https://doi.org/10.1016/j.matdes.2023.111661

Nkandu, M. I., & Alibaba, H. Z. (2018). Biomimicry as an alternative approach to sustainability. *Architecture Research, 8*(1), 1–11. https://doi.org/10.5923/j.arch.20180801.01

Oguntona, O. A., & Aigbavboa, C. O. (2023). Nature inspiration, imitation, and emulation: Biomimicry thinking path to sustainability in the construction industry. *Frontiers in Built Environment, 9*, 1085979. https://doi.org/10.3389/fbuil.2023.1085979

Othmani, N. I., Mohd Yunos, M. Y., Ramlee, N., Abdul Hamid, N. H., Mohamed, S. A., & Yeo, L. B. (2022). Biomimicry levels as design inspiration in design. International Journal of Academic *Research in Business and Social Sciences, 12*(8), 1094–1107. https://doi.org/10.6007/IJARBSS/v12-i8/14679

Palmatier, R. W., Houston, M. B., & Hulland, J. (2018). Review articles: purpose, process, and structure. *Journal of the Academy of Marketing Science*, *46*(1), 1–5. https://doi.org/10.1007/s11747-017-0563-4

Pawlyn, M. (2019). *Biomimicry in architecture* (2nd Edition). Riba Publishing.

Pradhan, J., & Choudhury, R.S. (2023). Finding a strategic approach for application of biomimicry in architecture. Encontrar un enfoque estratégico para la aplicación de la biomimética en la arquitectura. *Sustainability, Agri, Food and Environmental Research, 11*. https://doi.org/10.7770/safer.v11i1.2975

Radwan, Gehan. A. N., & Osama, N. (2016). Biomimicry, an approach, for energy efficient building skin design. *Procedia Environmental Sciences, 34*, 178–189. https://doi.org/10.1016/j.proenv.2016.04.017

Sijakovic, M., & Peric, A. (2021). Sustainable architectural design: towards climate change mitigation. *International Journal of Architectural Research, 15*(2), 385–400. https://doi.org/10.1108/ARCH-05-2020-0097

Singh, R. (2020). Biomimicry: Learning from nature. *Engineering Science, 11*(6), 533–547. www.jespublication.com

Sodiq, A., Baloch, A. A. B., Khan, S. A., Sezer, N., Mahmoud, S., Jama, M., & Abdelaal, A. (2019). Towards modern sustainable cities: Review of sustainability principles and trends. *Journal of Cleaner Production, 227*, 972–1001. https://doi.org/10.1016/j.jclepro.2019.04.106

Stadler, F., & Houghton, L. (2020). Breathing life into climate change adaptation. *Journal of Industrial Ecology, 24*(2), 400–409. https://doi.org/10.1111/jiec.12922

Suresh Kumar, N., Padma Suvarna, R., Chandra Babu Naidu, K., Banerjee, P., Ratnamala, A., & Manjunatha, H. (2020). A review on biological and biomimetic materials and their applications. *Applied Physics A, 126*(6), 445. https://doi.org/10.1007/s00339-020-03633-z

Uchiyama, Y., Blanco, E., & Kohsaka, R. (2020). Application of biomimetics to architectural and urban design: A review across scales. *Sustainability, 12*(23), 9813. https://doi.org/10.3390/su12239813

United Nations Department of Economic and Social Affairs Population Division. (2018, May 16). *World Urbanization Prospects the 2018 Revision*. https://www.un.org/en/desa/2018-revision-world-urbanization-prospects

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

Viholainen, J., Luoranen, M., Väisänen, S., Niskanen, A., Horttanainen, M., & Soukka, R. (2016). Regional level approach for increasing energy efficiency. *Applied Energy, 163*, 295–303. https://doi.org/10.1016/j.apenergy.2015.10.101

Zari, M. P. (2017). Utilizing relationships between ecosystem services, built environments, and building materials. *In Materials for a Healthy, Ecological and Sustainable Built Environment: Principles for Evaluation*, 3-7. https://doi.org/10.1016/B978-0-08-100707-5.00001-0

Zari, M. P., & Hecht, K. (2020). Biomimicry for regenerative built environments: Mapping design strategies for producing ecosystem services. *Biomimetics, 5*(2), 18. https://doi.org/10.3390/BIOMIMETICS5020018

Zari, P. (2018). *Regenerative Urban Design and Ecosystem Biomimicry* (1st Edition). Routledge.

Zu Ermgassen, S. O. S. E., Utamiputri, P., Bennun, L., Edwards, S., & Bull, J. W. (2019). The role of “no net loss” policies in conserving biodiversity threatened by the global infrastructure boom. *One Earth, 1*(3), 305–315. https://doi.org/10.1016/j.oneear.2019.10.019

Aderibigbe, A., Umeokafor, N., Umar, T. and Upadhyay, Y., 2024. Impact of corruption on achieving sustainable development goals within Africa's construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 544-554. DOI: https://doi.org/10.31705/WCS.2024.43. Available from: https://ciobwcs.com/papers/

IMPACT OF CORRUPTION ON ACHIEVING SUSTAINABLE DEVELOPMENT GOALS WITHIN AFRICA'S CONSTRUCTION INDUSTRY

Abiola Aderibigbe[1], Nnedinma Umeokafor[2], Tariq Umar[3], and Yog Upadhyay[4]

ABSTRACT

Corruption is prevalent across the construction industry in developing countries. This is due to converging factors such as (a) the sector's requirement for substantial capital investment, (b) government involvement, (c) time pressures to deliver new projects in response to the climate crisis and (d) unharmonised and complex regulatory environments. These factors together with access to lucrative contracts, and the presence of rent-seeking 'gatekeepers' establish that corruption represents a significant challenge in developing countries. This research undertook a critical and analytical review of the literature and found that thus far, corruption remains a threat to the construction of renewable energy assets in Africa. It also found that despite solutions (anti-corruption strategies) proffered by academics, experts, and institutions including the United Nations, Transparency International and the World Bank, these have had minimal impact. Hence, in Africa, challenges to implement sustainable urbanisation via the construction of renewable energy infrastructure persist. Furthermore, it explored if the creation of a binding duty of good faith via legislation harmonised across Africa could have an impact on corruption. This led to the creation of an assessment framework, and recommendations of empirical investigations including whether harmonised legislation across Africa can reduce corruption within its construction industry. To empower the industry to achieve sustainable development goals, this research was produced to advance the understanding of corruption within Africa's construction industry on renewable energy infrastructure. This research also addresses the gap in knowledge regarding the possible and plausible impact of the binding duty of good faith on overcoming corruption within Africa's construction industry.

Keywords: *Africa; Construction Industry; Corruption; Good Faith; Renewable Energy.*

[1] Abiola Aderibigbe, Faculty of Engineering and Technology, Liverpool John Moores University, UK, abioladeola@live.co.uk
[2] Dr Nnedinma Umeokafor, Senior Lecture, Faculty of Engineering and Science, University of Greenwich, UK, ned@nnedinmaumeokafor.com
[3] Dr Tariq Umar, Senior Lecturer, Architecture and Built Environment, University of West England, UK, tariqumar1984@gmail.com
[4] Dr Yog Upadhyay, Senior Lecturer in Construction Law, Faculty of Engineering and Technology, Liverpool John Moores University, UK, Y.P.Upadhyay@ljmu.ac.uk

1. INTRODUCTION

The 17 Sustainable Development Goals (SDGs) introduced by the United Nations (UN) in 2015 have been adopted by all its Member States (United Nations [UN], 2015). The SDGs are an urgent call for action for all nations, with Goals 7 (Affordable and Clean Energy) and 9 (Industry, Innovation, and Infrastructure) being directly relevant to the construction industry (Ibid). Yet, despite its adoption, constructing renewable energy assets in developing countries continues to be challenging due to corruption (Rahman, 2020). Converging factors such as (i) government involvement, (ii) pressures to deliver new projects in response to the climate crisis, (iii) unharmonised/complex regulatory environments, (iv) access to lucrative contracts, and (v) the presence of rent-seeking 'gatekeepers' precipitate corruption within developing nations (Rahman, 2020; James, 2022; Sabouri et al., 2023). Moreover, circumstances which produce these factors develop during the inception, construction, and lifecycle of renewable energy assets. These circumstances include (a) challenges in obtaining planning permission/concessions, (b) generation of applicable licenses, (c) government joint venture partnerships, and (d) importing vital/needed equipment and materials into the developing country the project is situated (Sabouri et al., 2023).

Typically, the requirement to obtain permits/licenses creates opportunities for soliciting bribes (James, 2022). Public officials/leaders/politicians act as gatekeepers of permissions, permits, certificates and customs handling; demonstrating 'rent-seeking' behaviour (James, 2022; Moliterni, 2017; Rahman, 2020; Sabouri et al., 2023). For example, tendering bribes to regional leaders to obtain exploration and exploitation licences for natural resources is typical in Indonesia (Adjie, 2020; Rahman, 2020). The same is typical in Africa where public officials are bribed to grant permits/rights. To illustrate, an agent representing CEFC China Energy Company was convicted for presenting bribes to officials from Chad and Uganda to secure oil/energy rights (Transparency International, 2020). In addition, the necessity of navigating political fronts creates further avenues for corruption (Sabouri et al., 2023). An example is when politicians jostle for payment for their political party/group in return for favours; promising that the owner/developer/contractor will not face issues regarding its assets (James, 2022). Public officials, leaders, and politicians also solicit bribes by requesting 'facilitation' payments (i.e., payments made to speed up processes) (ibid). Corruption is a significant barrier to the construction, development, and operation of renewable energy infrastructure. Thus, it remains a threat to the green transition required to attain sustainable urbanisation within Africa. Therefore, this research aims to critically review and analyse corruption globally, as well as in Africa, and its impact on renewable energy infrastructure within Africa's construction industry. It aims to explore the proposition that establishing a binding duty of good faith through harmonised legislation across Africa could positively impact and reduce corruption. This research contributes to advancing the understanding of corruption within Africa's construction industry (on renewable energy infrastructure) and bridges the gap in knowledge regarding the possible and plausible impact of a binding duty of good faith in overcoming corruption within Africa.

2. METHODOLOGY

The literature research methodology (Lin, 2009) was used to produce this research. This involved perusing, reviewing, analysing, sorting, and selecting relevant literature to identify the necessary facts for the research. In the first instance, a bibliometric table was produced using two of the keywords mentioned above i.e., (i) Corruption, and (ii) Renewable Energy, as search parameters within the 'Web of Science' platform. This produced 228 sources from the year 2007-2023 made up of articles, journals and books that were relevant to the topic. Then, a qualitative approach was used with the addition of a third keyword "Africa" to extract relevant, and applicable literature from the bibliometric table to attain an accurate and precise outlook of the state and impact of corruption within Africa's construction industry (on renewable energy).

In addition to using the bibliometric table, a wide body of sources were consulted and examined. These included reports, writs and sources issued by governments and institutions such as the World Bank, Transparency International, UN, United Nations Development Programme (UNDP), United Nations Office on Drugs and Crime (UNDOC), Extractive Industries Transparency Initiative (EITI), Peace Research Institute Oslo (PRIO), the Economist, as well as various academic sources cited in the literature review and outlined in the references.

3. LITERATURE REVIEW

3.1 CORRUPTION GLOBALLY

In many developing countries, corruption is a major obstacle to social development, economic expansion, and effective governance (Defreitas, 2023). This appears in several ways including bribery, embezzlement, nepotism, and fraud (ibid). The UN (2018) estimates the global cost of corruption to be more than US$2.6 trillion annually, while 25% of the US$13 trillion that governments globally expend on public spending is lost to corruption (United Nations Development Programme [UNDP], 2022). In addition, the UNDP considers US$483 billion to be the tax figure abused by wealthy/high-net-worth individuals and multinational corporations (Ibid). International bribery remains prevalent and thriving because more than half of all international bribery cases are related to public spending (Defreitas, 2023; UNDP, 2022).

According to the 2023 iteration of the Corruption Perceptions Index (CPI) produced by Transparency International, the global levels of corruption have remained unchanged for over a decade (Defreitas 2023; Transparency International, 2023). The CPI which ranks 180 countries and territories around the world for their perceived levels of public sector corruption, revealed that over two-thirds of countries assessed scored below 50 out of 100, strongly indicating that they have serious corruption problems (Transparency International, 2023). The CPI further confirmed that the global average is at 43 whilst most countries have made no progress or declined in the last decade (ibid). Even some countries with high scores on the CPI assessment are considered corruption threats because they have welcomed dirty/illicit/illegal money for decades allowing kleptocrats to increase their wealth, power, and destructive geopolitical ambitions (Transparency International, 2022).

3.2 CORRUPTION IN AFRICA

Africa holds a perception/reputation of high levels of corruption (Amoah et al., 2022; UNDP, 2022). This is also evidenced on the CPI because a lot of African countries on the index were ranked poorly. The African nation of Somalia was ranked the worst on the index (Transparency International, 2023). This was the same in 2021 and 2022 where the average score of sub-Saharan Africa on the CPI was (and remains) 33 out of 100; the lowest of any region assessed on the index (The Economist, 2022; Transparency International, 2022; Transparency International 2023). Between 2000 and 2015, US$836 Billion of illegal/corrupt money left Africa i.e., about 3.7%rof its GDP (UNDP, 2022). Moreover, it is well documented that governments in Africa are spending 58% less on education and 25% less on health due to corruption (ibid). The cost of corruption is not only financial, paid for by (a) the destruction of human potential, (b) poverty, and (c) inequality (UNDP, 2022; United Nations Office on Drugs and Crime [UNODC], n.d.). To illustrate, in Nigeria an (in) famous bribery matter, involving Shell (an international oil company) deprived Nigerians of over $1.1 billion (Global Witness, 2017). The money paid out went to corrupt officials instead of the national budget (ibid). prompting the World Bank (2019) to declare that despite the nation's wealth, 50% of Nigerians continue to live in extreme poverty. The Nigeria example demonstrates that political and economic systems are typically utilised by corrupt actors causing the nation's wealth to be redistributed to the least needy (UNDOC, n.d.). Undoubtedly, corruption remains a scourge of modern life in Africa (UNDP, 2022).

3.3 CORRUPTION IN AFRICA'S CONSTRUCTION INDUSTRY/ENERGY SECTOR

In the construction industry, the term 'energy' is typically utilised in the context of generating heat, powering equipment, creating products and materials, transportation etc. (Designing Buildings, 2022). Thus, a reference to the 'energy sector' in the construction industry covers both renewable and non-renewable energy. Renewable energy in this context would include solar thermal energy, geothermal energy, wind energy, biomass, hydropower, etc., while non-renewable energy would include petroleum products, Hydrocarbon gas, natural gas, coal, nuclear energy etc. (Ibid). Corruption is prevalent within the 'energy sector' (of the construction industry) in Africa (Amoah et al., 2022). According to Rimšaitė (2019), corruption in the energy sector is mostly reliant on the location of the resources and the monopoly of political appointees. Acemoglu and Verdier (2000) contend that corruption in public spaces thrives when government agents and officials have self-interest, superior information, and cannot be adequately monitored. Unfortunately, the gatekeeping and rent-seeking behaviour exhibited by African leaders/politicians prove that the description/definition proffered by Rimšaitė, Acemoglu and Verdier, accurately depict African governments and political institutions. Therefore, it can be deduced that achieving sustainable urbanisation via the adoption of renewable energy opportunities is hindered by corruption in Africa (Amoah et al., 2022).

3.4 RENEWABLE ENERGY IN AFRICA AND THE "GREEN CURSE"

Notwithstanding the points made above, it should be noted that Africa has nonetheless witnessed remarkable growth in using renewable energy in recent years (Rahman, 2020). According to Amuakwa-Mensah and Näsström (2022), the wide growth of solar power in Africa has contributed to the overall increasing adoption of renewable energy consumption and investments in developing countries. The authors establish that from 61% in the 1990s, the share of renewable energy consumption in developing countries increased to 71% in the 2000s (Amoah et al., 2022). By 2015 this had increased again to 79% (ibid), which was largely due to the adoption of renewable energy across Africa.

Moreover, the creation and implementation of energy transition policies/legislative frameworks by countries in Africa demonstrate further that renewable energy is embraced (du Preez, 2022). These policies/frameworks tackle, the need for a renewable, decarbonised, decentralised energy supply which addresses climate change, and the commitments made under the Paris Climate Accords (Accord de Paris). These African countries include Nigeria, Ghana, Egypt, Kenya, Morocco, Tanzania, South Africa, and Uganda (ibid). Unfortunately, analysts and experts have established that the continued growth of the renewable energy sector in Africa has caused a significant increase in corruption, resulting in a 'green curse' (Peace Research Institute Oslo, 2019; Rahman, 2020). Gennaioli and Tavioni (2011) established the “green” or “resource” curse in their study when they found that malfeasance within the renewable energy market is a significant risk for countries characterised by abundant renewable/natural resources and weak (governmental) institutions. The authors demonstrated that public support for renewable energy schemes within the construction industry can be highly vulnerable to corruption and attract rent-seeking, especially in settings with high levels of organised crime (Rahman, 2020). The green curse underscores the fact that corruption continues to manifest itself within Africa’s construction industry (on renewable energy).

4. DISCUSSION: SOLUTIONS PROPOSED TO ADDRESS CORRUPTION (ANTI-CORRUPTION STRATEGIES)

4.1 CLARITY ON ELIGIBILITY REQUIREMENTS

Boamah and Wiliams (2019) advocate that the first/necessary step to successfully tackling corruption is understanding how corrupt practices benefit stakeholders. In their Kenyan study, they discovered that the Kenyan energy sector was driven by poor planning and an inability to rapidly expand access to the electricity market. Consequently, corruption was used as the ‘problem-solver,’ a means to secure connections to the power grid (Rahman, 2020). This was the issue with a hydropower/hydroelectric project in Tanzania, where the Rufiji Dam project faced controversy due to being constructed on a wildlife reserve (Dalton, 2019). Poor/inadequate planning is a typical/ recurring issue in Africa (Frankfurt School-UNEP Centre, 2020). Thus, in the context of their study Boamah and Williams considered an apt solution to corruption to be about providing clear fee structures, clarity on eligibility requirements for applicable initiatives and designing the rollout system in line with the capacity of engineers (Rahman, 2020). In essence, the authors argued for addressing the ‘root causes’ of corruption rather than focusing exclusively on corrupt symptoms of a deeper malaise (ibid). Although this argument is commendable, there are some significant issues to overcome. Their approach to tackling corruption is limited in scope. It does not consider the external influence of the ‘non-corrupt’ developed nations who according to the CPI continue to accept illicit monies gained from corruption and kleptocrats (Transparency International, 2020). It is likely that to effectively tackle corruption within Africa’s construction industry a harmonised international effort is required. Moreover, corruption also speaks to the behaviour of parties i.e., parties engaging in gatekeeping and rent-seeking behaviour. Therefore, an adequate solution may be needed to consider measures to modify behaviour and practices as opposed to merely clarifying procedures and processes.

4.2 CORRUPTION RISK ASSESSMENT/MAPPING

Corruption risk assessments/mapping has been advanced as an effective strategy to tackle corruption (James, 2022; Rahman, 2020). This strategy involves educating a potential investor/developer/operator on how corrupt practices work in each sector (ibid). The point behind doing this is to ensure individuals are equipped with the knowledge of such corrupt practices to enable them to adequately conduct business in corrupt nations. The Oxford Institute for Energy Studies conducted this type of exercise by analysing the renewable energy sector in Ethiopia and Kenya (Gordon, n.d.; Rahman, 2020). It discovered that the investment risk profile in each country essentially dictated the type of renewable energy projects being undertaken. To further elaborate, the Oxford assessment found that in Ethiopia, risk primarily occurred at the political and regulatory stage, with hidden barriers to market entry; while gaps in the legislation prevented rapid construction/expansion of private off-grid investments, and the government tended to prefer large utility-scale/on-grid projects (ibid). The Kenya assessment on the other hand revealed that risks to on-grid/physical assets were significantly higher and regulatory gaps fewer. It also revealed that challenges in land access and a high risk of protests also lead to substantial delays to larger on-grid projects, meaning sizeable/physical projects could likely suffer, but off-grid options did not encounter much opposition. Although the identification of project-specific risks is beneficial, this strategy still does not appropriately tackle the fundamental corruption issue, meaning that from the analysis provided, should the need arise to conduct an off-grid project in Ethiopia or an on-grid project in Kenya, corruption would still be a persistent hindrance.

4.3 TRANSPARENCY OF CONDITIONS

Other experts have determined that the transparency of conditions at project design could also be an effective way to tackle corruption in Africa. Sobják (2018) contends that misconduct and mismanagement at the initial phase of a renewable energy project allow for corruption at later project stages. Thus, transparency is key. The importance of transparency is already well documented in the energy sector (Grasso 2017; Grasso, 2020; Lu et al., 2019; Rahman, 2020). Institutions such as the Africa Progress Panel (2015), and the EITI (2018) have echoed similar sentiments regarding the importance of transparency. Yet, African corruption persists.

Ikejemba et al. (2017) conducted a study into failed renewable energy projects in Sub-Saharan Africa and found that corruption during project tender/award was typically decisive in a project's failure. This was because it is hard to enforce rules or sanctions of projects awarded/approved on corrupt or nepotistic grounds. The focus on transparency, community ownership, and shared responsibility by the studies/authors highlight a suggestion that tackling the corruption would suitably be from a culture/practice and behavioural aspect.

4.4 HARMONISED LEGISLATIVE FRAMEWORK BASED ON GOOD FAITH

The introduction of laws/directives/regulations is already established as an effective way to change practices, attitudes, and behaviours (Aderibigbe et al., 2023; Bilz & Nadler 2014). For example, a change in law i.e., the Smoking Ban in developed nations was paramount to stopping people smoking indoors. As a result, in some developed nations, smoking outdoors has become the cultural norm/typical practice. This effect is also demonstrable in the UK construction industry/construction industry. For example, in the UK the introduction of the Environmental Permitting (England & Wales) Regulations 2007, (S.I. 3538 of 2007), and 2010 (S.I 1154 of 2016)) (collectively "the Environmental Regulations") compelled stakeholders within the construction industry to change their attitudes toward environmental awareness (Constructing Excellence, 2007; Wilmott Dixon, 2010). Compliance with the Environmental Regulations in the UK brought about impactful initiatives. Thus, it stands to reason that the use of a binding legislative framework may be applied to tackle corruption within Africa. Therefore, it is proposed that the introduction of a harmonised legislative framework underpinned by the duty of good faith and binding on African nations regarding the construction, development, and operation of renewable energy assets, could potentially mitigate corruption experienced within the sector. The theoretical framework is summarised in Figure 1.

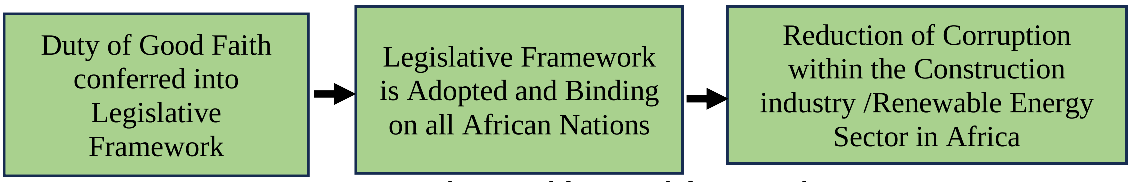


Figure 1: Theoretical framework for research.

Good faith at its core is about transparency, mutual trust, honesty, and fair dealing between stakeholders (Mante, 2018). It closely embraces the precepts and principles derived from the Ikejemba et al. (2017) and Sobjak (2018) studies. Considering that the duty of good faith possesses corresponding principles to the principles highlighted from the studies, it could be argued that the creation of a harmonised duty of good faith adopted by African nations may achieve the same outcome as proposed by these authors/academics, thus fostering an atmosphere of reduced corruption across Africa's construction industry/renewable energy sector.

5. RECOMMENDATIONS

Drawing on the points covered in this research, the following propositions and hypotheses need empirical investigation: (a) Good faith has an impact on corruption; (b) The realities of creating a harmonised legislative framework underpinned by good faith; (c) Goal-based rules underpinned by good faith within the context of an international legislative framework can contribute towards reducing corruption within the renewable energy sector; (d) The conduct of transparency regarding the process and procedures for the delivery of renewable energy infrastructure projects will improve if a good faith legislative framework is adopted across the continent. The next phase is an empirical study investigating the propositions and hypotheses.

It is recommended that a qualitative approach based on an ontological philosophical belief system is utilised. This would include a further/extensive literature review, document analysis and the use of interviews with renewable energy professionals (at least twelve participants) experienced within Africa's construction industry. The number of interviews was determined by saturation (Guest et al., 2006; O'Reilly & Parker, 2013). Further, it is recommended that the interviews explore the professional's: (a) experience with corruption in Africa, (b) experience with the impact of corruption on renewable energy construction/infrastructure projects, (c) understanding of the duty of good faith, as well as their views on the creation of a legal duty harmonised across African nations. Upon completion of the interviews, the following produced framework is recommended which may assist in assessing and interpreting interview responses:

Negative Impact on Corruption: An answer which demonstrates an apathy or outright rejection of a potential impact of a harmonised duty of good faith and/or a reluctance to acknowledge or consider any potential potency upon renewable energy construction projects in Africa. In addition, the answer would consider the application of such harmonised legislation to mean more 'red' tape, and 'unnecessary' or complex processes and/or procedures.

No Impact on Corruption: An answer which demonstrates that the participant expects that even if such legislation was introduced, actions within Africa's construction industry would continue as 'status quo'.

Marginally Positive Impact: An answer where a participant expects not much of a difference in status quo but concurrently admits that such harmonised legislation would make a 'slight' difference.

Positive Impact: An answer which demonstrates a total acceptance of the potential impact of a harmonised legislation underpinned by good faith with consideration of substantial potential potency on renewable energy construction projects in Africa.

6. LIMITATIONS

Legislation and legislative frameworks have limitations, including difficulties in interpretation if goal-based (Xanthaki, 2005), and may incur general user aversion (Office of the Parliamentary Counsel, 2013). Furthermore, it does not guarantee regulatory success, as it depends on the user's intent and interpretation for compliance (Xanthaki, 2005). Considering the difference in African Nations, proposed binding legislative framework may be difficult to transcribe/adopt into domestic/national laws. Using guidelines/prescriptive legislation has proved to help address this however this could limit innovation (Umeokafor et al., 2020). Nevertheless, the positives of using legislation necessitate the exploration of a new harmonised legislative framework underpinned by good faith binding on African nations. It is poorly understood if and how this will occur. Additionally, good faith can be challenging. Although, legal scholars/practitioners in jurisdictions worldwide generally understand the meaning of good faith (Legatt, 2016), its broad/nebulous nature causes difficulties in defining it. Thus, its application is sometimes subjective (Saintier, 2017). This potential subjectivity may be an issue, as enforcement of such legislative framework may differ from one African nation to the other. Therefore, specific questions such as how and if to objectively define good faith need to be addressed for harmonisation.

7. CONCLUSIONS

This research highlights the need for an empirical study to determine whether a binding duty of good faith established through a harmonised legislative framework will help reduce corruption within Africa's construction industry. Despite associated challenges (such as the achievement of true harmonisation, the implementation of the legislative framework into domestic laws across the continent and the broad and nebulous nature of good faith), this research has highlighted the potential such harmonised legislative framework could have. The findings of the recommended empirical study will further bridge the gap in knowledge regarding the impact of good faith on corruption within Africa's construction industry in renewable energy infrastructure.

8. REFERENCES

Acemoglu, D., & Verdier, T. (2000). The choice between market failures and corruption. *American Economic Review, 90*(1), 194-211. https://www.aeaweb.org/articles?id=10.1257/aer.90.1.194

Aderibigbe, A., Umeokafor, N., & Umar, T. (2023). Constructing for the future: Can the duty of good faith improve payment in the UK construction industry?. In A. Tutesigensi, & C.J. Neilson, (Eds.) *Proceedings of the 39th Annual ARCOM Conference* (pp. 14-23*).* Association of Researchers in Construction Management. https://secure.arcom.ac.uk/submissions/40/published/5c951cf7298bd1f0dc839d996f1d8ef3.pdf

Adjie, M. (2020, July 17). *Corruption in resources sector in Indonesia may worsen climate crisis*. The Jakarta Post. https://www.thejakartapost.com/news/2020/07/15/corruption-in-resources-sector-could-worsen-climate-crisis-says-activist.html

Africa Progress Panel. (2015). *Power people planet: Seizing Africa's energy and climate opportunities*. Africa progress report. https://reliefweb.int/sites/reliefweb.int/files/resources/APP_REPORT_2015_FINAL_low1.pdf

Amoah, A., Asiama R.K., Korle, K., & Kwablah, E. (2022). Corruption: Is it a bane to renewable energy consumption in Africa? *Energy Policy*, *16*, 112854.. https://doi.org/10.1016/j.enpol.2022.112854

Amuakwa-Mensah, F., & Näsström, E. (2022). Role of banking sector performance in renewable energy consumption. *Applied Energy*, *306*(part B), 118023. Retrieved from https://doi.org/10.1016/j.apenergy.2021.118023

Bilz, K., & Nadler, J. (2014) Law, moral attitudes, and behavioural change. In E. Zamir & D. Teichman (Eds.), The Oxford handbook of behavioural economics and the law (pp. 241–267). https://wwws.law.northwestern.edu/faculty/fulltime/nadler/bilz-nadler-lawmoralattitudespageproofs.pdf

Boamah, F., & Williams, A. (2019) 'Kenyapowerless': *Corruption in electricity as 'problem-solving' in Kenya's periphery*. CHR Michelsen Institute. https://www.u4.no/publications/kenyapowerless-corruption-in-electricity-as-problem-solving-in-kenyas-periphery.pdf

Constructing Excellence. (2007). *Industry performance report 2007: Based on the UK construction industry key performance indicators*. https://constructingexcellence.org.uk/wp-content/uploads/2014/10/industry_performance-report_kpi2007.pdf

Dalton, J. (2019, July 27). *Tanzania inaugurates dam that will 'boost power supply but threaten rhino and elephants'*. The Independent. https://www.independent.co.uk/climate-change/news/tanzania-dam-project-elephant-rhino-selous-game-reserve-a9022966.html

Defreitas, L. (2023, April 4). *How corruption in developing countries impacts poverty*. The Borgen Project. https://borgenproject.org/corruption-in-developing-countries/

Designing Buildings. (2022, September 5). *Energy in the construction industry*. https://www.designingbuildings.co.uk/wiki/Energy_in_the_built_environment#:~:text=In%20the%20built%20environment%2C%20the,either%20renewable%20or%20non%2Drenewable.

du Preez, L.W. (2022, October 24). *Africa: Energy transition policies and regulatory developments light up across the continent*. Baker McKenzie. https://www.bakermckenzie.com/en/newsroom/2022/10/energy-transition-policies#:~:text=Under%20the%20Renewable%20Energy%20Master,or%20assembling%20renewable%20energy%20resources

Extractive Industries Transparency Initiative. (2018, December 19). *What the extractives sector can teach renewables on curbing corruption*. https://eiti.org/blog-post/what-extractives-sector-can-teach-renewables-curbing-corruption

Frankfurt School-UNEP Centre. (2020, June 10). *Global trends in renewable energy investment*. https://www.fs-unep-centre.org/global-trends-in-renewable-energy-investment-2020/

Gennaioli, C. & Tavoni, M. (2011, June 29). *Clean or "dirty" energy: Evidence on a renewable energy resource curse.* Fondazione Eni Enrico Mattei. https://www.feem.it/en/publications/clean-or-dirty-energy-evidence-on-a-renewable-energy-resource-curse/

Gordon, E. (n.d.). *The politics of renewable energy in East Africa*. Oxford Institute for Energy Studies (OIES). Retrieved June 30, 2024 from https://www.oxfordenergy.org/publications/politics-renewable-energy-east-africa/

Global Witness. (2017, April 10). Shell Knew. https://www.globalwitness.org/en/campaigns/oil-gas-and-mining/shell-knew/

Grasso, C. (2017, December 15). *The dark side of power: Corruption and bribery within the energy sector*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3343314

Grasso, C. (2020). The troubled path toward greater transparency as a means to foster good corporate governance and fight against corruption in the energy sector. In S. Goutte & D.K. Nguyen (Eds.), *Handbook of energy finance: Theories, practices and simulations* (pp. 363-393). World Scientific. https://doi.org/10.1142/9789813278387_0016

Guest, G., Bunce, A. & Johnson, L., (2006). How many interviews are enough? An experiment with data saturation and variability. *Field Methods*, *18*(1), 59-82. https://journals.sagepub.com/doi/abs/10.1177/1525822X05279903?journalCode=fmxd

Ikejemba, E.C.X., Schuur, P.C., Hillegersberg. J.V., & Mpuan, P.B. (2017). Failures and generic recommendations towards the sustainable management of renewable energy projects in sub-saharan Africa. *Renewable Energy, 113,* 639-647. https://doi.org/10.1016/j.renene.2017.06.002

James, E. (2022, December 8). *How to manage corruption risk in renewable energy projects*. Pinsent Masons. https://www.pinsentmasons.com/out-law/guides/how-to-manage-corruption-risk-in-renewable-energy-projects

Legatt, J. (2016, October 18). *Contractual duties of good faith*. Commercial Bar Association. https://www.judiciary.uk/wp-content/uploads/2016/10/mr-justice-leggatt-lecture-contractual-duties-of-faith.pdf

Lin, G. (2009). Higher education research methodology-literature method. *International Education Studies*, *2*(4), 179-181. https://files.eric.ed.gov/fulltext/EJ1065734.pdf

Lu, J., Ren, L., Qiao, J., Yao, S., Strielkowski, W., & Streimikis, J. (2019). Corporate social responsibility and corruption: Implications for the sustainable energy sector. *Sustainability*, *11*(15), 4128. https://doi.org/10.3390/su11154128

Mante, J. (2018) Mutual trust and co-operation under NEC 3&4: A fresh perspective. *Construction Law Journal*, *34*(4), 231-252. http://westlaw.co.uk

Moliterni, F. (2017, June 16). *Analysis of public subsidiaries to the solar energy sector: Corruption and the role of institutions*. Fondazione Eni Enrico Mattei. https://www.feem.it/en/publications/analysis-of-public-subsidies-to-the-solar-energy-sector-corruption-and-the-role-of-institutions/

Office of the Parliamentary Counsel. (2013, April 16). *When laws become too complex*. https://www.gov.uk/government/publications/when-laws-become-too-complex/when-laws-become-too-complex

O'Reilly, M. & Parker, N., (2013). 'Unsatisfactory saturation': A critical exploration of the notion of saturated sample sizes in qualitative research. *Qualitative Research*, *13*(2), 190-197. https://doi.org/10.1177/1468794112446106

Peace Research Institute Oslo. (2023, December). *Green curses and violent conflicts: The security implications of renewable energy sector development in Africa*. https://www.prio.org/projects/1878

Rahman, K. (2020, October 13). *Anti-corruption in the renewable energy sector*. UP Helpdesk Answer. Transparency International. https://www.u4.no/publications/anti-corruption-in-the-renewable-energy-sector

Rimšaitė, L. (2019). Corruption risk mitigation in energy sector: Issues and challenges. *Energy Policy*, *125*, 260-266. https://doi.org/10.1016/j.enpol.2018.10.066

Sabouri, B., Demetriades, L., & Mallela, S.K. (2023, June 7). *The dirty side of going green: Corruption and human rights risks within the clean energy supply chain*. ankura. https://angle.ankura.com/post/102igdn/the-dirty-side-of-going-green-corruption-and-human-rights-risks-within-the-clean

Saintier, S.D.A. (2017). The elusive notion of good faith in the performance of a contract, why still a bête noire for the civil and the common law?. *Journal of Business Law*, *6*, 441-460. https://www.semanticscholar.org/paper/The-elusive-notion-of-good-faith-in-the-performance-Saintier/5f64727443eed32b478c1e1fdf1e5909cc7cce9b

Sobják, A. (2018). Corruption risks in infrastructure investments in sub-saharan Africa. *OECD Global Anti-Corruption & Integrity Forum, Paris*, 27-28 March 2018.

The Economist. (2022, January 25). *Corruption is getting worse in many poor countries: But rich countries have problems too*. https://www.economist.com/graphic-detail/2022/01/25/corruption-is-getting-worse-in-many-poor-countries

Transparency International. (2020). *Exporting corruption. progress report 2020*. https://www.transparency.org/en/publications/exporting-corruption-2020

Transparency International. (2022). *Corruption perceptions index*. https://www.transparency.org/en/cpi/2022

Transparency International. (2023). *Corruption perceptions index*. https://www.transparency.org/en/cpi/2023

Umeokafor, N. (2020). Why copied or transposed safety, health and well-being legislation and standards are impracticable and irrelevant in developing economies. *Policy and Practice in Health and Safety*, *18*(1), 41–54. https://doi.org/10.1080/14773996.2019.1667095

United Nations [UN]. (2018, September 10). *Pervasive corruption costs $2.6 trillion; disproportionately affects 'poor and vulnerable' says UN chief*. United Nations. https://news.un.org/en/story/2018/09/1018892

United Nations Development Programme [UNDP]. (2022, December 6). *The cost of corruption*. Medium. https://undp.medium.com/the-cost-of-corruption-a827306696fb

United Nations Office on Drugs and Crime [UNDOC]. (n.d.). *Effects of corruption*. Retrieved June 30, 2024 from https://www.unodc.org/e4j/zh/anti-corruption/module-1/key-issues/effects-of-corruption.html

Willmott Dixon. (2010). *The impacts of construction and the built environment* (FM-RE-07. #). https://www.willmottdixon.co.uk/asset/9462/download

World Bank. (2019). *Poverty & equity brief – Nigeria*. https://databankfiles.worldbank.org/public/ddpext_download/poverty/33EF03BB-9722-4AE2-ABC7-AA2972D68AFE/Global_POVEQ_NGA.pdf

Xanthaki, H. (2005). *The limits of legislation as a product*. [Thesis, University College London]. https://discovery.ucl.ac.uk/id/eprint/1575216/1/Xanthaki_The%20limits%20of%20legislation%20as%20a%20product.pdf

Wickrama, W.D.R.P., Waidyasekara, K.G.A.S. and Victar, H.C., 2024. Implementation of biophilic design concept in leisure industry: Benefits and challenges. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 555-567. DOI: https://doi.org/10.31705/WCS.2024.44. Available from: https://ciobwcs.com/papers/

IMPLEMENTATION OF BIOPHILIC DESIGN CONCEPT IN LEISURE INDUSTRY: BENEFITS AND CHALLENGES

W.D.R.P. Wickrama[1], K.G.A.S. Waidyasekara[2], and H.C. Victar[3]

ABSTRACT

This study investigates the incorporation of Biophilic Design (BD) into the Leisure Industry (LI), with a focus on its ability to improve human well-being and economic productivity. Biophilia, a fundamental human tendency to form a bond with the natural world, has significant ramifications for architecture and recreation, especially in improving physical, psychological, and cognitive well-being. The study centres on the implementation of BD in LI facilities and assesses its importance, benefits, and challenges. The data was collected through semi-structured interviews to offer an avenue to explore the comprehensive views of 15 BD experts on its implementation in LI through this study. The results indicate that although BD has had positive effects in promoting health and environmental sustainability, there are still obstacles to its widespread adoption due to differing client expectations and a lack of awareness. The study emphasises the importance of increased education and advocacy to successfully incorporate BD principles into the LI, in order to promote a sustainable and health-focused approach to building design and leisure activities.

Keywords: *Biophilia; Biophilic Design; Leisure Industry.*

1. INTRODUCTION

The natural environment is a crucial aspect of human existence, influencing physical and mental well-being (Kellert & Calabrese, 2015). However, the connection to nature has weakened since the 1800s, leading to a decline in personal identity, purpose in life, and the inherent link between humans and the natural world (Softas-Nall & Woody, 2017). The modern indoor lifestyle, characterised by sedentary lifestyles and the internet, has led to an increase in anxiety and depression (Softas-Nall & Woody, 2017), highlighting the importance of a positive connection with nature (Qadir et al., 2023).

Kellert and Calabrese (2015) maintained that the concept of biophilia stems from a recognition of human evolution, wherein over 99% of species' history, the biological development was shaped by adaptive reactions to natural rather than artificial or human-made influences. Biophilia, the natural bond humans have with nature, is reflected in BD, which creates built environments that capture its essence (Browning et al., 2014).

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, wickramawdrp.19@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, hasithc@uom.lk

Biophilic architecture aims to strengthen connections between inhabitants and the natural world (Ariyawansa & Perera, 2022), enhancing indoor air quality and health benefits (Qadir et al., 2023). BD challenges current approaches by providing a fresh framework for incorporating nature more fully in constructed spaces (Browning et al., 2014; Kellert, 2005; Kellert et al., 2008). When considering LI, as Mikalauskas and Kaspariene (2016) highlighted, tourism encompassing heritage and visitor attractions is one of the primary constituents of the leisure sector. The World Travel and Tourism Council's 2022 Economic Impact Research shows that the travel and tourism sector has contributed 7.6% to global GDP, a 22% increase from 2021, highlighting the significant impact of LI growth on a country's economic development (World Travel and Tourism Council [WTTC], 2022). The leisure sector encompasses various fields such as sports, recreation, health, fitness, play supervision, outdoor activities, caravanning, and gaming (Mikalauskas & Kaspariene, 2016). The recreation sector is a significant contributor to human fitness and quality of life, as it involves contact with nature (Browning et al., 2014; Kellert, 2012). Leisure is used for relaxation and enjoyment, shaping human identity, growth, health, motivations, emotions, and behaviours (Watkins & Bond, 2007). The main focus of LI is to enhance guest experience and promote well-being (Mikalauskas & Kaspariene, 2016). The physical and mental health of individuals depend on interactions with the natural world, which is a vital requirement for achieving well-being and contentment (Searles, 1960). Natural resources including fields, woods, rivers, beaches, and sunshine are essential for leisure and fun (Torkildsen, 2005). Incorporating nature into the architecture of leisure establishments is crucial, as it contributes significantly to global economic development.

Research on integrating BD in buildings has been extensive, focusing on health and well-being. However, there is a lack of research on BD in LI and construction. The lack of empirical evidence in Sri Lanka highlights the need for a holistic approach to BD, aiming to create environments that resemble nature and foster a deeper connection with the natural world. This study aims to bridge the research and industry gaps in BD implementation by assessing its importance, benefits and challenges.

2. LITRATURE REVIEW

2.1 BIOPHILIC DESIGN CONCEPT

Biophilia is the natural and instinctive bond that humans have with the natural world (Browning et al., 2014). BD plays a major role in crafting constructed environments that embody the essence of nature (Radha, 2022).

The term biophilia originates from the Greek words, ‘philia’, which conveys a sense of ‘love of’, and ‘bio’, which signifies ‘life’ (Ariyawansa & Perera, 2022). Essentially, it represents a deep affection or love for life and living organisms. Furthermore, biophilia is not limited to a single characteristic but encompasses an individual’s complete physical and emotional disposition, impacting their receptivity to what is most vital and innovative in others (Maccoby & Feldman, 1972). Furthermore, numerous authors have emphasised for a significant period that biophilia represents the intrinsic human tendency to connect with the natural world, which remains crucial for the physical and mental health and overall well-being of individuals, even in the contemporary era (Wilson, 1984; Kellert & Wilson, 1993; Kellert, 1986, 2012). Biophilia, an inherent human quality, is linked to psychological health and the connection humans share with the natural world (Chen et al., 2013). It is an instinctive and inherent human quality, that promotes a natural inclination to engage with life and the environment (Browning et al., 2014). Integrating biophilia into design, it evolves into BD, an applied scientific approach that considers the connection between humans and nature to create environments that align with human inclinations towards biophilia (Bolten & Barbiero, 2020).

2.2 BIOPHILIC DESIGN CONCEPT IN THE LEISURE INDUSTRY

The LI's attributes and potential outcomes from BD implementation make the BD concept a rational choice for LI facilities, yet their impact assessment is crucial for evaluating their contributions.

The leisure sector has emerged as a major global industry, consisting of various subdivisions operating within diverse business domains (Sevil et al., 2018). Tourism represents a highly valued form of leisure, offering similar advantages such as relaxation, and both tourist and leisure experiences share comparable benefits (Lubowiecki-Vikuk et al., 2021). On the other hand, in the modern world, leisure is increasingly recognised as an integral aspect of life (Mikalauskas & Kaspariene, 2016). Furthermore, these authors stressed that leisure plays a role in shaping individuals' identities as human beings, manifesting themselves across their lifespans and becoming evident in their development, health, motivations, emotions, and behaviours (Mikalauskas & Kaspariene, 2016). Researchers are keenly interested in the types and variety of leisure activities individuals participate in while on vacation (Singharat et al., 2023). According to Mikalauskas and Kasparienė (2016), LI encompasses diverse sectors, offering employment opportunities in fields such as sports, fitness, recreation, outdoor activities, play, camping, and gaming. It is essential to consider not only people's health but their engagement, fulfilment, and utilisation of nature for meaningful leisure activities (Lubowiecki-Vikuk et al., 2021). Hence outlining prominent trends in the leisure sector, and highlighting the integration of sustainable development principles is significant and one method involves incorporating biophilia in LI.

The Biophilia hypothesis suggests that humans have a natural desire for interactions with nature, encompassing aesthetic, intellectual, cognitive, and spiritual connections (Ariyawansa & Perera, 2022). This desire can lead to benefits for human well-being and environmental conservation (Simaika & Samways, 2010). Wilson (1984) explains that this inclination is expressed in admiration for living entities, which is reflected in the positive feelings towards certain habitats, activities, and objects. Biophilic design aims to create good habitats for individuals, promoting their physical well-being, health, and overall quality of life (Kellert & Calabrese, 2015).

Contemporary living, including urban expansion, work commutes, traffic congestion, media, and the internet, has led to a disconnection from nature, negatively impacting human well-being and the ecological environment (Chen et al., 2013). This disconnect not only threatens human health and quality of life but threatens the ecological balance (Simaika & Samways, 2010). It is crucial for individuals to allocate time and resources to reconnect with nature and living organisms (Ulrich et al., 1991). Leisure activities, which involve exposure to natural elements, have a positive impact on health and well-being, yet they must also be sustainable (Chen et al., 2013). Some scholars argue that leisure contributes to both human and natural well-being, a manifestation of biophilia (Rolston III & Coufal, 1991). However, there is limited evidence on whether individuals perceive the environmental benefits of their leisure activities (Chen et al., 2013).

2.3 BENEFITS OF IMPLEMENTING BIOPHILIC DESIGN IN THE LEISURE INDUSTRY

Modern environmental researchers and psychologists have highlighted the advantages of incorporating nature into constructed environments (Newman et al., 2012). Meanwhile, sustaining good health relies on maintaining a balanced ecological relationship consistently (Dustin et al., 2018). Hence, the connection between humans and greenery within urban settings, known as BD, is associated with refreshing human well-being across psychology, physiology, and cognition (Kellert et al., 2008).

2.3.1 Health Benefits for Building Occupants

BD applications are known for reducing stress, enhancing creativity, and boosting physical and psychological health (Bolten & Barbiero, 2020). BD applications promote positive mood, relaxation, and enjoyment (Chen et al., 2013). As global urbanisation continues, these benefits will be increasingly important in shaping urban spaces, architectural designs, and interiors (Bolten & Barbiero, 2020). Designers aim to create stress-free environments by incorporating natural elements, promoting healthier lives (Kua, 2022). Studies show a strong correlation between human interaction with nature and enhanced well-being. Leisure activities also positively impact psychological, physical, and social welfare. Implementing biophilic principles has therapeutic effects, particularly in reducing stress levels among individuals (Mikalauskas & Kaspariene, 2016). In addition, according to Browning et al. (2014), BD implementation offers significant benefits in reducing stress, enhancing cognitive performance, and improving emotional well-being.

2.3.2 Economic Benefits

Incorporating BD aspects into built environments can have economic benefits in addition to the health benefits as summarised in Table 1 (Browning et al., 2014).

Table 1: Economic benefits of BD

Benefit	Description	Source
Increase Productivity	Spaces designed with biophilic principles enhance productivity, contentment, and relaxation. Exposure to nature boosts workplace performance, efficiency, and profitability.	Kua, 2022; Barbiero & Berto, 2021
Improve Property Values	Biophilic design elements increase appeal to buyers and tenants, potentially raising property values and rental rates, especially in leisure facilities.	Barbiero & Berto, 2021
Reduce Energy Costs	Integration of biophilic design reduces energy costs through natural ventilation, lighting, and energy-efficient materials.	Barbiero & Berto, 2021
Increase Customer Satisfaction	Biophilic elements create inviting and comfortable spaces, enhancing customer satisfaction in businesses.	Barbiero & Berto, 2021
Improve Employee Retention	Making workplaces more appealing helps retain employees, reducing costs associated with turnover and training.	Barbiero & Berto, 2021

2.4 CHALLENGES IN INTERVENING BIOPHILIC DESIGN CONCEPT

Even though there are many advantages to implementing the BD concept, there are several challenges that can restrict its widespread implementation such as financial restrictions, psychological barriers, durability concerns, design restrictions and functional difficulties. The project cost can increase due to BD applications, as the expenses for environmentally sustainable designs are higher compared to conventional design approaches (Xue et al., 2019). Further, with the rigorous maintenance requirements, operational cost increases due to maintenance costs (Riley et al., 2019). In addition, persistent psychological conditions such as biophobia can threaten the long-term utilisation of a building (Estok, 2017). Cultural perceptions regarding human-nature connectedness impact the implementation of this concept in different types of buildings. Moreover, lack of evaluation tools and guidance, lack of agreed methods and lack of knowledge are the main challenges that affect the design restrictions for implementing the BD concept (Parsaee et al., 2019). Considering the durability of a building, it was mentioned that incorporating natural elements into building designs results in a reduced lifespan of building components (Riley et al., 2019). Further, land restrictions and reduction of land availability for other uses when applying the BD concept are other challenges with respect to functional difficulties (Church, 2018). The presence of animals and related complexities due to greenery applications in built environments is another challenge to overcome (Taylor, 2019) whilst legal barriers need to be considered with respect to implementing this concept in LI as a holistic approach (Littke et al., 2016). Even though these are general challenges, all these challenges affect the effective implementation of the BD concept in LI.

3. METHODOLOGY

A comprehensive literature review was conducted focusing on the BD concept in LI. The concept of biophilia and the importance and benefits of incorporating the BD concept in LI were identified. Accordingly, this research adopted the strategy of qualitative interview surveys to review in-depth opinions and views of experts on the implementation of the BD concept in LI. Hence, the contribution and involvement of industry professionals are essential to enhance the implementation of the BD concept in LI facilities. Especially, since LI facilities highly contribute to the economic development of a country, it is significant to explore the views, opinions, and experiences of the construction industry professionals for the enhancement of the implementation of the BD concept in LI. Hence, this study was conducted with a qualitative approach and 15 experts were interviewed to collect data through a semi-structured interview and the collected data was analysed through manual content analysis. The profile of experts is presented in Table 2.

Table 2: Respondents' profile details

Respondent	Profession	Experience (years)	
		Construction Industry	Leisure Industry
R1	Principal Architect	16-20	16-20
R2	Chartered Architect	5-10	less than 5
R3	Architect	over 20	over 20
R4	Chartered Architect	over 20	over 20

Respondent	Profession	Experience (years)	
		Construction Industry	Leisure Industry
R5	Chartered Architect	11-15	5-10
R6	Chartered Architect	over 20	5-10
R7	Principal Architect	11-15	5-10
R8	Architect	over 20	over 20
R9	Principal Architect	over 20	over 20
R10	Interior Designer	16-20	less than 5
R11	Interior Designer	over 20	over 20
R12	Principal Architect	over 20	over 20
R13	Biophilic Design Consultant	16-20	less than 5
R14	Architect	16-20	5-10
R15	Interior Architect	5-10	less than 5

All the professionals presented in Table 2 are BD experts and with their experience and expertise in this concept, their contributions have highly affected the findings of this study. These experts have been involved in many projects and conducted research to incorporate the BD concept while seeing this concept as an investment in health and economics. Further, some of the experts have implemented and consulted international projects as well.

4. ANALYSIS AND FINDINGS

4.1 LEISURE INDUSTRY AND ITS FACILITIES

The first question of the interview was designed to evaluate the interpretation of LI as per the different views of the experts in the construction industry. Accordingly, all the respondents agreed that the LI is crucial for fostering the economic growth of a country as it serves as a significant contributor to the tourism sector, providing essential sustenance and support for its growth and vitality. Even though this study focuses on enhancing this concept in overall countries, especially, R2's analysis centres on the role of the LI in the larger context of Sri Lankan tourism, mentioning that *"LI could be mostly the tourism industry in Sri Lankan standards"*. Supportively, R3 affirmed that with the reasons for the attraction of tourists to Sri Lanka (SL), stating *"LI which attracts tourists to SL is one of the biggest facilities that is available because of our environment and then occupation, a lot of people come, right?"*. This approach highlights the significance of SL's environmental and cultural heritage, emphasising why LI is more suited for the development of a country such as SL due to the inherent link between LI and its natural resources.

In addition, an expert from the USA, R9 simply identified LI as *"Places people go away from home to rest, restore, experience, enjoy with family plus friends to explore beyond their everyday life"* and supportively, R4 generally defined LI as *"An industry which provides facilities for "switch off", "action" and "togetherness"*. Further, R12 mentioned, "They *are the places for human leisure comforts, the comforts need for relaxation"*. Strengthening the statements of R4, R9 and R12 together, an expert from Italy, R13 further affirmed by stating that LI includes services that provide *"entertainment, relaxation and enjoyment for individuals, families or other groups"*. The same opinion has been repeatedly maintained by many respondents. Furthermore, this collective pool of views was enriched, adding more valuable insights by R8, commenting, *"Leisure facilities predominantly focus on providing relaxation, recreation, resting, entertainment, psychological healing, leisure sports facilities etc. under the main sector of tourism, hospitality or entertainment facilities"* while identifying those facilities as *"business facilities"*. From the term *"business facilities"*, it elaborates that these facilities highly contribute to the economic growth of a country.

In addition to that, some other respondents provide additional insights into the definition and extent of the LI, indicating that it includes diverse activities and facilities. R13 mentioned that LI encompasses a broad range of activities and facilities that *"cater to people's recreational and free-time pursuits"*. Supportively, R14 identified LI as quite a broad concept which includes many activities, commenting, *"When I say leisure, it's not just accommodation. So, it will mainly be thing that whatever the activities we do for leisure, right? So, for me, leisure is quite a broad of different kinds of activities we used for not like usual work. So, it's generally the opposite of work"*. The diverse perspectives of the respondents from different nations regarding the interpretation of LI demonstrate an intricate combination of opinions, expectations, and suggested approaches, highlighting the significance of LI for human beings in different aspects as discussed.

In addition, LI facilities can be categorised into different segments considering the experience that humans can gain by engaging in those activities provided by various facilities. In brief, based on the views of all the experts, Figure 1 summarises the leisure facilities.

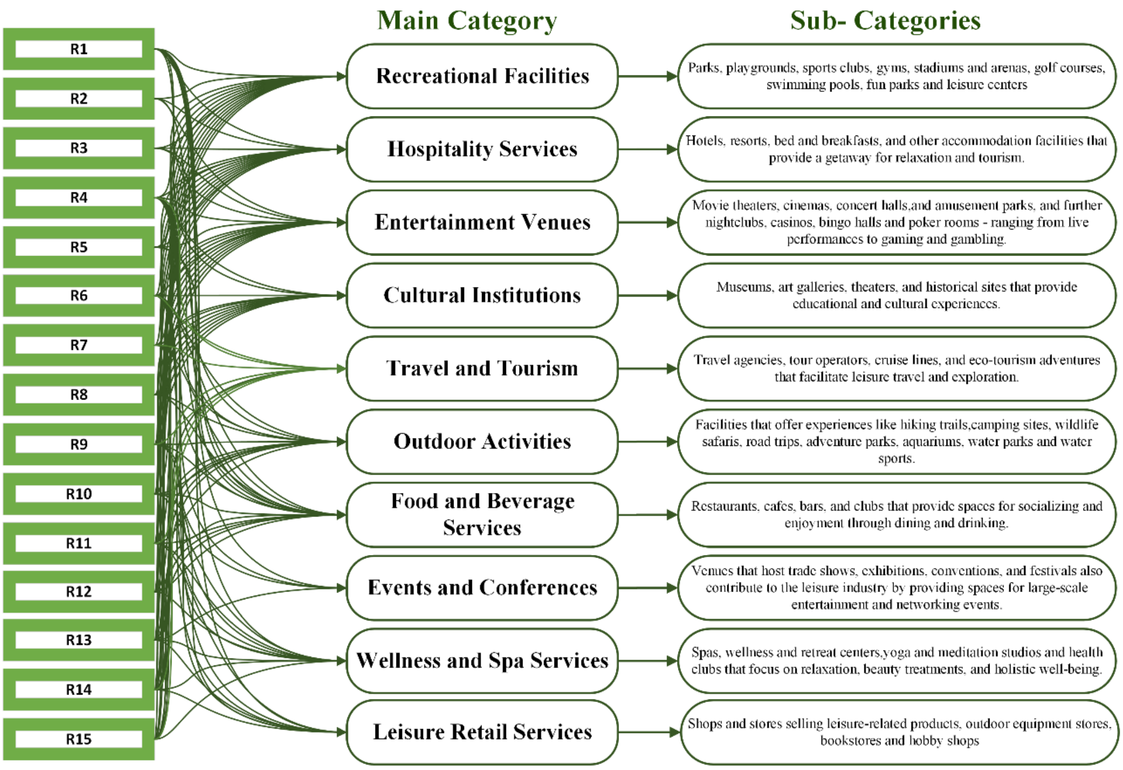


Figure 1: LI facilities

4.2 IMPLEMENTATION OF BIOPHILIC DESIGN IN THE LEISURE INDUSTRY

According to R4 and R7, implementing the BD concept in SL is not a novel phenomenon and it is something which has being done in past decades. As per the architectural view of R7, *"From 500 years ago or even 1000 years ago, the way we have done buildings, the way we have adapted nature to our benefits has always been in line with BDs"*. R7 and R4 pointed out a mud house as an example, *"It is absolutely biophilic, like there is nothing that goes against nature in that particular setup. That's just general living"*.

4.2.1 Importance of Biophilic Design in Leisure Industry

R7 affirmatively stated, *"BD concept in LI is prominent and it is a very active element in this particular sector since it gives a value for sure to the experience of the occupants who are living in LI facilities"*. In addition, R12 identified BD as an essential component for LI. Supporting the views of R7 and R12, R8 asserted that this implementation contributes to the enhancement of the positive impact on users' efficiency, health and well-being. Further, R8 pointed out that this is a must to implement in the modern world, highlighting the importance of *"enhancing our intrinsic human connection to the natural environment which has been forgotten or kept in isolation in the modern busy lifestyles"*.

Indeed, R2 asserted *"I personally think if somebody is going to build something there, we are destroying the atmosphere. So, if we want to minimise the impact that we do to architecture, we can implement those biophilic strategies. So, we can harm the environment in a minimal manner by using BD"*, convincing the importance of implementing this concept in the built environment to mitigate the damages to the natural world. According to R15, *"Nature-inspired designs, such as incorporating natural light, plant life, and organic materials, can create a more inviting and rejuvenating atmosphere"* instead of destroying it. More to the point, R5 identified this as a very good approach and highlighted the prevention of nature for the future stating, *"If we could be able to run a BD concept into a leisure field, then we can say accommodate less running cost in all of this as well as more nature, preventing the more nature for the future"*.

In addition, R3 indicated *"BD in the LI is going to play a big role in the future because again the world is moving towards sustainable practices"*, showing the connection between the BD concept and sustainability. Similarly, R4 conceded and strengthened the opinion of R3, mentioning, *"Now the trend is about nature, the worldwide... No more buildings and concrete. If you go for the biophilic concepts and the zero energy concepts and the sustainable concepts, we can sell ourselves. In the world-wide, now the setting point is sustainability. Biophilic directly addresses sustainable architecture"*.

Additionally, R6 revealed the importance of connecting with nature in LI, stating, *"People come for relaxation and enjoyment. Especially enjoyment of the place involves the nature and the context around it, right? The views, sky, landscape, sea, everything. So, it's very important to integrate the internal building spaces through views and in different ways"*. With that, it is very clear that the implementation of BD in LI is significant as per the views of all the respondents.

4.2.2 Benefits of Implementing Biophilic Design in Leisure Industry

R15 believes *"The implementation of BD in LI facilities is highly beneficial since it does not only improve aesthetic appeal but also promotes well-being and relaxation, which are key components in leisure spaces"*. Further, R6 emphasised the benefits for the occupants in leisure facilities with the embodied essence of nature mentioning, *"Nature can do wonders and even it stimulates brain and then it's good for health as well"*. Repeatedly all the respondents were stated that BD is intended to connect people to the natural environment and to each other to promote a *"healthier world"*. These opinions further validate the health benefits highlighted in the literature findings. As a summary, the benefits of implementing BD in LI mentioned by all the respondents are presented in Figure 2.

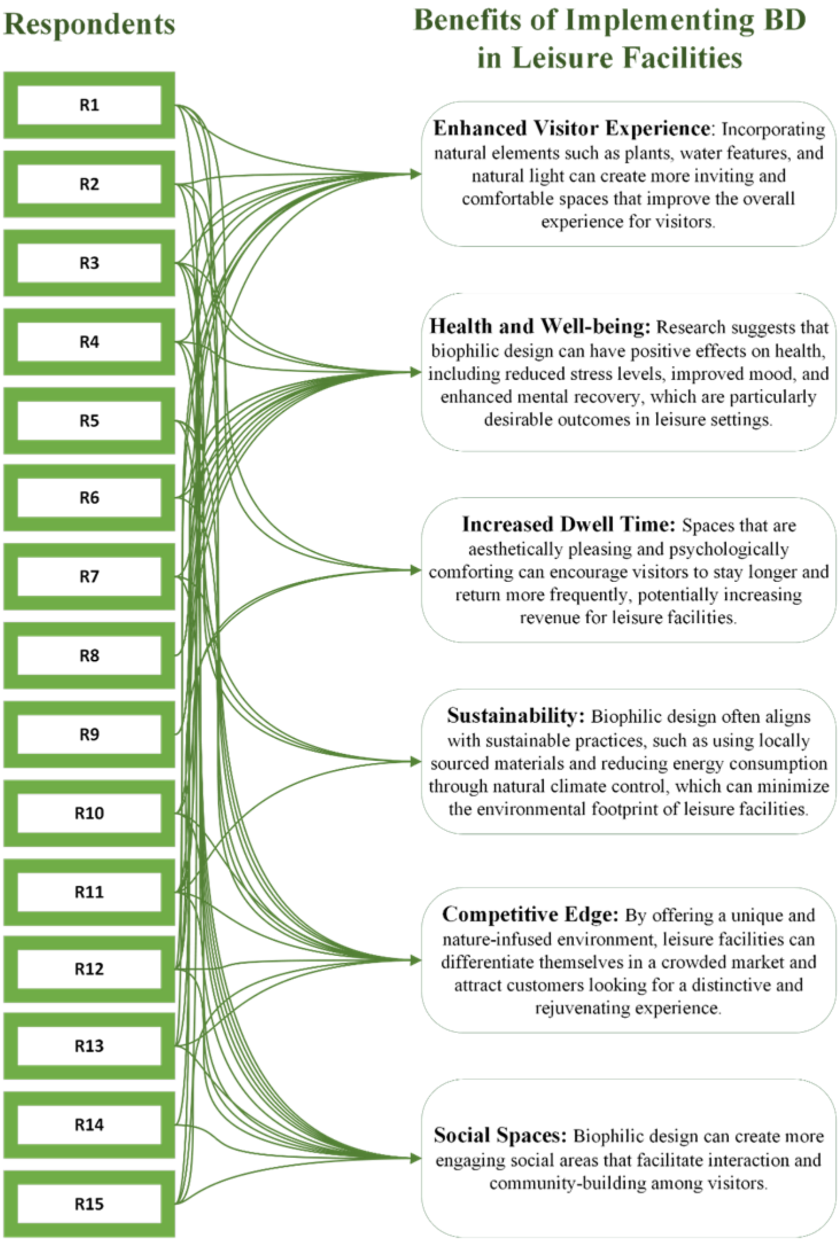


Figure 2: Benefits of implementing BD in LI

Especially, all these benefits were highlighted by R11, while other experts highlighted some of these benefits. As per the respondents' views, mainly six benefits have been identified and among them, enhanced visitor experience, increased dwell time, competitive edge, and social spaces, indirectly contribute to the economic benefits of the BD-implemented LI facilities. Therefore, the literature findings are further validated through the data collected through the interviews.

4.2.3 Challenges in Implementing Biophilic Design in Leisure Industry

Nevertheless, the discussion directed to practical obstacles that the architects are facing in designing these facilities. There is a requirement for greater knowledge and instruction regarding the advantages of implementing the BD concept. Because, as per the opinion of R2, there is a need for a change in client expectations towards more environmentally friendly luxury. R2 as a Sri Lankan expert faced for the interview mentioned this issue, especially directing to the Sri Lankan clients indicating that,

> *"So, the problem is satisfying the client. As architects we face, they don't get it. That's the awareness and their thinking pattern is more or less focused towards the luxury finishes. They are focusing on giving their customers high luxury and comfortable experience. Because they usually see those kinds of projects in other countries. They don't know about our strengths and all. That's the main reason for us to be here. How to make the maximum use of nature, they don't think about that. They just want to have luxury things. Actually, Maldives and Bali, they do design for their strengths. So that's why they are a success in the industry. However, because of the strength we have. We can go into the depth of this concept in SL."*.

In addition to that, R12 highlighted the lack of awareness of the BD concept, mentioning,

> *"When we say BD, most of the people, even some architects, believe that it is all about planting trees, adding water features, etc. but exactly BD is not that. From the term biophilic, it says the love for living beings, but when we say BD, it is embodying the essence of nature. It can be done naturally or artificially. For example, artificially we can incorporate the shapes of the natural elements to the building elements or else we can make an environment artificially where people can feel like they are in a jungle, under the sea, etc. For that we have to make that environment artificially. It is not only planning trees and all…So, this is a critical challenge that needs to be looked in to"*.

More to the point, according to R12, *"BD is a way of implanting natural organ in an artificial organ. For instance, giving intensities of natural lighting even for the places where we do not have access to get natural sunlight"*.

Moreover, R4 indicated "*The implementation of BD concept in LI will depend on the 'feeling', needed to be generated in that environment in different leisure facilities"*. Furthermore, R6 supported this idea stating, *"Through any architecture, we have to address the mindset of people who are living there"*. In addition, R6 introduced a new term to the discussion which is 'phenomenological experience' explaining it as,

> *"Phenomenological experience is, when you go to a place, you feel something, you know, it's, there is ambience in that place, even in nature. So how do you integrate, or how do you take the essence of that ambience into your piece of architecture, piece of building? How do you integrate the ambience of, of nature*

> *around a building into the building? Yeah… And then how do you connect inside and outside, poetically and with the pattern?".*

Further, the significance of conducting interviews with architects emerges as the optimal method for data collection in this study, as emphasised by R8. According to R8, *"As designers of the built environment, 'architects' have to have a thorough understanding of this concept and understanding of how to incorporate them carefully to enhance the quality of life of the users by taking natures inspirations"*.

To address the mindset of the people through BD, first the issues mentioned by R2 should be addressed which is to increase the awareness of the architects regarding this concept, since they are the designers to be addressed the mindsets of people. Among the challenges identified in the literature findings, lack of awareness of the BD concept was identified as the main challenge to implementing this concept as highlighted by the views of all the respondents.

To sum up this section, the responses together create a vision for a LI that is closely connected to the principles of BD. As R15 specifically stated, *"This approach aligns perfectly with the LI's goal to provide escapes and relaxation opportunities for its clients"*. The respondents, with their varied perspectives, describe BD as a perfect approach that has the potential to redefine the LI.

5. CONCLUSIONS

The research aim was met by conducting a comprehensive literature review and an expert survey with construction industry professionals. Human connection to nature is an essential value that has progressively weakened since the 1800s. As a result, the requirement for a positive connection with nature remains crucial for human health and well-being. Biophilia is the natural and instinctive bond that humans have with the natural world. BD has played a role in crafting built environments that capture the essence of nature. Incorporating natural elements indoors not only enhances the indoor environment and air quality but also leads to numerous health, well-being, psychological, cognitive, and behavioural advantages. BD can be implemented in different industries and LI is one of the most significant industries, which plays a role in shaping the identity as humans, evident in human growth, health, motivations, emotions, and behaviours across the lifespan which enhance physical and mental well-being. The findings of the study evident that BD is a great concept to implement in LI. Most of the respondents have the opinion that BD is a natural creation inside the buildings, while only a few respondents interpret it in the most correct way that BD is a concept to capture the essence of natural elements inside the buildings naturally or artificially. BD implementation in LI promotes a healthier world with fun for human beings while it considerably contributes to global economic development. However, as raised by the respondents, the major challenge for BD implementation is the lack of awareness of the BD concept among the construction industry professionals, clients and the building occupants.

6. REFERENCES

Ariyawansa, D. N., & Perera, N. G. R. (2022). The Role of biophilic design in hotel architecture: A case study of Heritance Kandalama, Sri Lanka. *15th International Research Conference - FARU 2022*, 214–223. https://doi.org/10.31705/FARU.2022.24

Barbiero, G., & Berto, R. (2021). Biophilia as evolutionary adaptation: An onto-and phylogenetic framework for biophilic design. *Frontiers in Psychology, 12*, http://dx.doi.org/10.3389/fpsyg.2021.700709

Bolten, B., & Barbiero, G. (2020). Biophilic design: How to enhance physical and psychological health and well-being in our built environments. *Visions for Sustainability, 13,* 11–16. http://dx.doi.org/10.13135/2384-8677/3829

Browning, W., Ryan, C., & Clancy, J. (2014). 14 Patterns of biophilic design: Improving health & well-being in the built environment. *Terrapin Bright Green*. https://www.terrapinbrightgreen.com/wp-content/uploads/2014/09/14-Patterns-of-Biophilic-Design-Terrapin-2014p.pdf

Chen, H. M., Tu, H. M., & Ho, C. I. (2013). Understanding biophilia leisure as facilitating well-being and the environment: An examination of participants' attitudes toward horticultural activity. *Leisure Sciences*, *35*(4), 301–319. http://dx.doi.org/10.1080/01490400.2013.797323

Church, S. P. (2018). From street trees to natural areas: Retrofitting cities for human connectedness to nature. *Journal of Environmental Planning and Management*, *61*(5-6), 878-903. https://doi.org/10.1080/09640568.2018.1428182.

Dustin, D., Zajchowski, C., Gatti, E., Bricker, K., Brownlee, M. T., & Schwab, K. (2018). Greening health: The role of parks, recreation, and tourism in health promotion. *Journal of Park & Recreation Administration*, *36*(1). http://dx.doi.org/10.18666/JPRA-2018-V36-I1-8172

Estok, S. C. (2017). Material ecocriticism, genes, and the phobia/philia spectrum. *Neohelicon*. *44*(2), 297-313 https://doi.org/10.1007/s11059-017-0395-8.

Kellert, S. (2005). Building for life: Designing and understanding the human-nature connection. *Bibliovault OAI Repository, the University of Chicago Press*, *24*(2). https://www.researchgate.net/publication/40777405_Building_for_Life_Designing_and_Understanding_the_Human-Nature_Connection

Kellert, S. (2012). *Birthright: People and nature in the modern world*. Yale University Press. http://dx.doi.org/10.12987/9780300188943

Kellert, S. R. (1986). Social and perceptual factors in the preservation of animal species. *The preservation of Species.* Princeton: Princeton University Press, 50-73. https://doi.org/10.1515/9781400857869.50

Kellert, S., & Calabrese, E. F. (2015). *The practice of biophilic design*. www.biophilic-design.com

Kellert, S., Heerwagen, J. H., & Mador, M. L. (2008). *Biophilic design: The theory, science, and practice of bringing buildings to life.* John Willey & Sons, Inc.

Kellert, S., & Wilson, E. O. (1993). *The biophilia hypothesis*. Washington Island Press.

Kua, M. (2022). *Biophilic Escapism: Designing the Hotel Mojave*. https://digitalscholarship.unlv.edu/cgi/viewcontent.cgi?article=1043&context=arch_grad_capstones

Littke, H., Yang, J., & Desha, C. (2016). Becoming biophilic: Challenges and opportunities for biophilic urbanism in urban planning policy. *Smart and Sustainable Built Environment*, *5*(1), 15-24. https://doi.org/10.1108/SASBE-10-2015-0036.

Lubowiecki-Vikuk, A., Dąbrowska, A., & Machnik, A. (2021). Responsible consumer and lifestyle: Sustainability insights. *Sustainable Production and Consumption, 25*, 91-101. https://doi.org/10.1016/j.spc.2020.08.007

Maccoby, E. E., & Feldman, S. S. (1972). Mother-attachment and stranger-reactions in the third year of life. *Monographs of the Society for Research in Child Development*, *37*(1), 1-86.

Mikalauskas, R., & Kasparienė, J. (2016). Holistic approach about leisure industry. *Transformations in Business & Economics, 15*(2), 723–740. https://www.researchgate.net/publication/311670264_Holistic_approach_about_leisure_industry

Newman, P., Hargroves, K. C., Desha, C., Reeve, A., Moham, A. A. M. M. O., Bucknum, M., & Beatley, T. (2012). *Can biophilic urbanism deliver strong economic and social benefits in cities? An economic and policy investigations into the increased use of natural elements in urban design.* http://dx.doi.org/10.13140/RG.2.1.2137.2886

Parsaee, M., Demers, C. M., Hebert, M., Lalonde, J. F., & Potvin, A. (2019). A photobiological approach to biophilic design in extreme climates. *Building and Environment*, *154*, 211-226. https://doi.org/10.1016/j.buildenv.2019.03.027.

Qadir, G., Wijesooriya, N., Brambilla, A., & Alonso-Marroquin, F. (2023). Improving the indoor environment through an indoor green curtain system. *Buildings, 13*(5). https://doi.org/10.3390/buildings13051307.

Radha, C. H. (2022). Biophilic design approach for improving human health in the built environment. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies*, *13*(9), 1–12. https://doi.org/10.14456/ITJEMAST.2022.188.

Riley, B., De Larrard, F., Malécot, V., Dubois-Brugger, I., Lequay, H., & Lecomte, G. (2019). Living concrete: Democratiizing living wall, *Science of The Total Environment, 673, 281-295. https://doi.org/10.1016/j.scitotenv.2019.04.065*

Rolston III, H., & Coufal, J. (1991). A Forest ethic and multivalue forest manageunent. *Journal of Forestry, 89*(1), 35-40. https://api.mountainscholar.org/server/api/core/bitstreams/c046d81a-78f4-4f3e-bec1-8b90fb796796/content

Searles, H. (1960). *The nonhuman environment in normal development and in schizophrenia*. International Universities Press.

Sevil, J., García-González, L., Abos, A., Lanaspa, E. G., & Solana, A. A. (2018). Which school community agents influence adolescents' motivational outcomes and physical activity? Are more autonomy-supportive relationships necessarily better? *International Journal of Environmental Research and Public Health, 15*(9), 1875. https://doi.org/10.3390/ijerph15091875

Simaika, J. P., & Samways, M. J. (2010). Biophilia as a universal ethic for conserving biodiversity. *Conservation Biology, 24*(3), 903-906. https://doi.org/10.1111/j.1523-1739.2010.01485.x

Singharat, W., Kraiwanit, T., Sonsuphap, R., & Shaengchart, Y. (2023). The sharing economy in a developing economy: The perspective of the leisure business. *Corporate Law & Governance Review, 5*(2), 27-34. http://dx.doi.org/10.22495/clgrv5i2p3

Softas-Nall, S., & Woody, W. D. (2017). The loss of human connection to nature: Revitalizing selfhood and meaning in life through the ideas of Rollo May. *Ecopsychology, 9*(4), 241–252. https://doi.org/10.1089/eco.2017.0020.

Taylor, D. E. (2019). College students and nature: Differing thoughts of fear, danger, disconnection, and loathing. *Environmental Management, 64*(1), 79-96. https://doi.org/10.1007/s00267-019-01172-9.

Torkildsen, G. (2005). *Leisure and recreation management* (5th edition). http://ndl.ethernet.edu.et/bitstream/123456789/49085/1/24..pdf

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*(3), 201-230. https://doi.org/10.1016/S0272-4944(05)80184-7

Watkins, M., & Bond, C. (2007). Ways of experiencing leisure. *Leisure Sciences, 29*(3), 287–307. http://dx.doi.org/10.1080/01490400701259985

Wilson, E. O., (1984). *Biophilia.* Harvard University Press.

World Travel and Tourism Council. (2022). *Global tourism economic impact report.*

Xue, F., Gou, Z., Lau, S. S. Y., Lau, S. K., Chung, K. H., & Zhang, J. (2019). From biophilic design to biophilic urbanism: Stakeholders' perspectives. *Journal of Cleaner Production, 211*, 1444–1452. https://doi.org/10.1016/j.jclepro.2018.11.277.

Abeywickrama, A.P.T.M., Abeynayake, M.D.T.E., Eranga, B.A.I. and Illeperuma, I.E., 2024. Incorporating digital technologies for alternative dispute resolution in the Sri Lankan construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 568-580. DOI: https://doi.org/10.31705/WCS.2024.45. Available from: https://ciobwcs.com/papers/

INCORPORATING DIGITAL TECHNOLOGIES FOR ALTERNATIVE DISPUTE RESOLUTION IN THE SRI LANKAN CONSTRUCTION INDUSTRY

A.P.T.M. Abeywickrama[1], M.D.T.E. Abeynayake[2], B.A.I. Eranga[3] and I.E. Illeperuma[4]

ABSTRACT

The Construction Industry (CI) faces disputes that cause several negative impacts such as project delays and cost overruns. Alternative Dispute Resolution (ADR) methods are often recommended in resolving disputes due to their time and cost efficiency. However, with the technological advancements of the CI, it is necessary to incorporate Digital Technologies (DT) for effective dispute resolution. Thus, the study aims to explore the applications of DT in ADR in the CI to address the challenges in the Sri Lankan context. The research aim was accomplished through a quantitative approach by conducting a questionnaire survey with the participation of 37 respondents. Collected data was analysed through descriptive analysis. The findings identified three major causes of construction disputes in the Sri Lankan context contract-related factors, financial and economic factors, and task factors. Further, negotiation was found the most commonly used ADR method in Sri Lanka followed by arbitration and adjudication. Findings indicated that DT such as MS Office Packages, Virtual Online Dispute Resolution (ODR), Building Information Modelling (BIM), and Artificial Intelligence (AI) have high levels of effectiveness in enhancing ADR processes. BIM and Virtual ODR were highly valued for their ability to facilitate visualisation and remote dispute resolution respectively. The study suggests that DT applications can significantly improve ADR processes, enhancing efficiency and decision-making in dispute resolution, and calls for further research on global applicability and ethical implications.

Keywords: *Alternative Dispute Resolution; Construction Industry; Digital Technologies; Disputes; Sri Lanka.*

1. INTRODUCTION

Disputes are inevitable among construction stakeholders due to behavioural, contractual, and technical disagreements (Cakmak & Cakmak, 2013; Patil et al., 2019). These disputes are not only resource-intensive but also hostile and costly (Senarath & Francis, 2021). The surge in disputes leads to project delays, cost overruns, rework, potential legal cases,

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, abeywickramaaptm.19@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, Abey92@hotmail.com
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurue@uom.lk
[4] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurii@uom.lk

strained relationships, and reputation damages (El-Sayegh et al., 2020). For example, Love et al. (2010) reported that dispute costs range from 0.5% to 5% of the contract value, depending on the resolution method. Moreover, failure to manage disputes effectively will result in industrial collapses and ultimately affect the national economy (Broto & Nugraheni, 2023). Thus, it is crucial to promptly address the conflicts to prevent them from escalating into disputes, as disputes significantly hinder the successful completion of construction projects within the expected time, budget, and quality (Soni et al., 2017).

Considering the current competitive landscape in the CI, it is essential to minimise the potential for disputes and establish effective mechanisms for dispute mitigation (Senarath & Francis, 2021). ADR methods are widely acknowledged as fast and cost-effective methods for resolving disputes in out-of-court settlements (Mashwama et al., 2016; Ustuner & Tas, 2019). These ADR methods include facilitation, negotiation, conciliation, mediation, adjudication, arbitration, and hybrid models like mediation-arbitration. In the Sri Lankan CI, negotiation, mediation, dispute adjudication board and arbitration are extensively employed as ADR methods (Abeynayake & Weddikkara, 2013; Lingasabesan & Abenayake, 2022; Nitharsan & Francis, 2022). The effective implementation of ADR is crucial for alleviating the workload of the judicial system, improving the efficiency and affordability of resolving disputes, and fostering continued positive relationships between the parties involved (Illankoon et al., 2022). Saygili et al. (2022) and Vo et al. (2020) suggested that the CI has experienced significant advancements in technology, which require further research in incorporating DT in ADR. Further, Utama (2017) highlighted the global movement towards DT in resolving disputes. It offers a lower-cost, efficient, and innovative solution for cross-border disputes, transforming traditional dispute resolution methods into more innovative and technological approaches (Abbasli, 2022).

However, compared to the global initiatives Sri Lankan CI is far behind in implementing DT in ADR (Lingasabesan & Abenayake, 2022). Accordingly, this study aims to explore the applications of DT in ADR in the CI to address the challenges in the Sri Lankan context. Thus, the study objectivates to explore the causes of disputes in CI' and issues of ADR methods in SL and DT that are applicable for dispute resolution.

2. LITERATURE REVIEW

2.1 CAUSES OF CONSTRUCTION DISPUTES

Various researchers have categorised the causes of disputes in several ways. Cakmak and Cakmak (2013) categorised disputes based on responsible parties, such as contract-related, project-related, contractor-related, client-related, human behaviour-related, design-related, financial, and economic-related, material labour and equipment-related and external. Contrarily, Cheung and Pang (2013) identified three main factors contributing to construction disputes: contract incompleteness, people, and tasks. Further, they mainly categorised the disputes into process (pre-construction and construction) and project (external and internal). Table 1 illustrates the causes of disputes in the CI.

Table 1: Causes of disputes in Sri Lanka

Cause	Description	Reference
Task factors	Collaborative conflict, Risk and uncertainty	[1], [2]
Contract related	Ambiguity, Deficiency, Inconsistency, Defectiveness	[3]
Client related	Variations, Accelerations, Scope creep,	[4], [5],
Contractor related	Ambiguities, Mistakes, Vague specifications,	[6], [7]
Design related	Design errors, Poor designs, Incomplete specifications	[8], [91]
Human behaviour related	Misunderstandings, Lack of team spirit and Communication, Slow decision-making,	[1], [4], [5]
Financial and economic related	Changes to the payment date, Underestimation, Mismanagement of funds	[10]], [11]
Material, labour and equipment	Poor quality, Shortage and price fluctuations of materials plant and labour,	[12], [13], [14]
External factors	Uncertain incidents, Rework, Unrealistic expectations	[15], [16],

[1] (Cheung & Pang, 2013); [2] (Tanriverdi et al., 2021); [3] (Edirisinghe et al., 2020); [4] (Vo et al., 2020); [5] (Shash & Habash, 2021); [6] (Woodley, 2019); [7] (Mishmish & El-Sayegh, 2018); [8] (Stamatiou et al., 2019); [9] (Soni et al., 2017); [10] (Rauzana, 2016); [11] (Çakmak, 2016); [12] (Apte & Pathak, 2016); [13] (Edirisinghe et al., 2020); [14] (Equbal et al., 2017); [15] (Francis et al., 2017); [16] (Zhao, 2019)

Disputes related to task factors often arise from collaborative conflicts, where disagreements among team members on project execution methods occur (Cheung & Pang, 2013). Additionally, the risks and uncertainties inherent to the construction projects lead to conflicts. Ambiguities, deficiencies, inconsistencies, and defects in the contract documents lead to misunderstandings and eventually become disputes (Edirisinghe et al., 2020). Further, construction disputes are often caused by external factors such as adverse weather conditions, social unrest, and pandemics such as COVID-19 etc.

2.2 ALTERNATIVE DISPUTE RESOLUTION METHODS IN THE SRI LANKAN CONSTRUCTION INDUSTRY

ADR methods are affordable, time-efficient, and less adversarial, making them more accessible than traditional litigation (Ness, 2020). ADR methods help avoid project delays, preserve business relationships, and offer flexibility by allowing customised solutions that cater to specific needs (Shyamal, 2016). Negotiation is a universal dispute resolution method that allows parties to settle differences voluntarily without neutral influence (Viththakan, 2016). Arbitration is a fast, cost-efficient, and final decision-making approach for resolving construction disputes, with the Arbitration Act of Sri Lanka No. 11 of 1995 providing a legislative framework (Nihaaj, 2016). Mediation is a formalised yet flexible negotiation style, facilitated by an unbiased third-party advisor (Goski, 2021). Over 70% of parties actively pursue resolution, offering reduced time and costs, a more satisfactory outcome, and reduced further disputes. Online mediation and case law analysis may be a better alternative than traditional adjudicative procedures for complex disputes (Hardjomuljadi, 2020). The med-arb method combines elements of mediation and arbitration, aiming to resolve conflicts promptly and legally enforceable by establishing a neutral entity at the beginning of the project (Shyamal, 2016). Conciliation involves parties working with an impartial third party to address problems and reach a mutually acceptable conclusion (Palihawadana, 2020). Adjudication refers to disputes to a neutral third party for a binding decision until the dispute is resolved by arbitration or litigation (Palihawadana, 2020). Mini trial is a voluntary, non-binding procedure that treats disputes as business problems (Ustuner & Tas, 2019). The Dispute Review Board (DRB) is a proactive project management technique that anticipates and resolves disputes throughout the project, offering more reliable and appropriate solutions than litigation and other alternatives (Gulati, 2022). However, implementation of ADR methods in Sri Lankan CI is challenging. Researchers highlighted a lack of skilled practitioners, less awareness, and a non-legally binding nature as the major challenges to the successful practice of ADR (Shyamal, 2016). Table 2 extensively discusses the challenges faced by each ADR method.

Table 2: Challenges and limitations of ADR methods in Sri Lanka

ADR Method	Challenges and Limitations	References
Negotiation	Parties not compelled to use, Not legally binding, Need for skilled negotiators, Lack of neutral involvement	(Shyamal, 2016; Viththakan, 2016)
Adjudication	Necessitates thorough analysis of historical aspects Absence of legal ascent to enforce an adjudicator's decision, Comprehensive protocol	(Jayasinghe & Ramachandra, 2016)
Arbitration	Difficulty in scheduling hearings and finding arbitrators on a full-time and daily basis, lack of other venues outside Colombo, The Arbitration Act No. 11, 1995 does not specify a time limit, lack of enforcement,	(Mashwama et al., 2016; Nihaaj, 2016)
Mediation	Non-binding Nature, Dependence on the skill of the Mediator, The rigid contractual frameworks	(Iyiola & Rjoub, 2020)

Firstly, the absence of legal enforcement and the binding nature of the agreement affect negotiation and mediation, which in turn limits the effectiveness of these processes (Faghih & Akhavian, 2019; Lu et al., 2019). Secondly, adjudication and arbitration are hampered by complexity and a lack of awareness (Ranasinghe & Korale, 2011). Adjudication is not well understood by the parties involved whereas arbitration confronts difficulties with procedural nuances and a lack of specified time limits under the relevant legal frameworks. Further, arbitration is plagued by logistical challenges such as difficulties in locating arbitrators and the concentration of proceedings in Colombo, which restrict its accessibility to areas outside the country (Senarathna, 2019). Moreover, arbitration faces the challenges most compared to other ADR methods. These challenges range from procedural complexities to geographic and legal limitations which indicate the urgent need for reforms to improve the efficiency and accessibility of ADR in Sri Lanka. According to Amoah and Nkosazana (2022), implementing a regulatory framework could improve industry participants' understanding of ADR, enhance confidence, and foster a culture of sincere intentions and respect towards mediators. The literature underscores the significance of enhancing construction professionals' understanding of ADR practices to prevent significant litigation cases, emphasising the need for a neutral third party (Saeb et al., 2018).

2.3 APPLICATION OF DIGITAL TECHNOLOGIES IN CONSTRUCTION DISPUTE RESOLUTION

The increase in construction disputes has led to significant advancements in developing more effective methods of resolving disputes within the CI, particularly in ADR (Ahmad & El-Sayegh, 2021). Among them, big data analytics and AI are considered to be the most crucial tools in the CI for resolving disputes and enhancing legal information accessibility (Putera et al., 2021; Wattuhewa et al., 2023). AI has been applied in various fields, including construction and dispute resolution (Ridmika & Thayaparan, 2021). For instance, Game theory, an AI concept, has been used in Intelligent Negotiation Support (INS), which can save time and reduce costs through simplified result presentation and minimum time requirements (Abidoye et al., 2022; Zeleznikow, 2021). Further data mining techniques are used to analyse historical legal cases to identify contract terms and judicial decision patterns related to disputes (Ahmed et al., 2022; Fatima et al., 2014). Text mining is also being used to refine unstructured large-capacity text data, extracting keywords and identifying connected meanings (Fatima et al., 2014). In addition, 'Machine Learning' and 'Artificial Neural Networks' have been used to predict resolutions for disputes, revealing the factors that will affect resolutions and potential prediction models (Ayhan et al., 2022). Nonetheless, smart contracts and Virtual ODR procedures are crucial in digitally reviving contractual legal relationships, monitoring term fulfilment, and automatically triggering execution (Abbasli, 2022; Chaisse & Kirkwood, 2022; Utama, 2017). Blockchain technology and societal digitalisation can also help overcome limitations in SCs. BIM is increasingly recognised for its potential to facilitate construction by standardising legal aspects and providing a digital representation of building elements (Jamil & Fathi, 2020). A dedicated protocol for BIM in dispute resolution could enhance contract systems and stakeholder engagement across project phases. BIM models can visually represent construction processes, facilitating quick recovery of necessary data for effective dispute resolution (Muhammad & Nasir, 2022).

3. RESEARCH METHODOLOGY

This study followed the quantitative research approach to accomplish its objectivity, generalisability, and statistical rigour, enabling measurable insights into the adoption and impact of digital ADR tools across the construction industry. It is highly systematic offering robust and replicable results that can be generalised to broader contexts. Accordingly, as the first step, a thorough literature review was undertaken to understand the origin of disputes, challenges to the implementation of ADR and the use of DT to enhance the efficacy of ADR. Secondly, following the survey research strategy, an online questionnaire survey was conducted. Given the population size of 37 responses were received recording a response rate of 56% and the selected sample encompasses the entire population, ensuring complete representation of dispute resolution of each ADR method. Herein, two distinct sampling techniques were used to draw the sample. Firstly, using the stratified sampling method, three strata were formed from the population of dispute resolution practitioners based on the primary party they serve in a dispute. The three strata were client, contractor, and consultant. Subsequently, the simple random sampling method was applied to select 22 members from each stratum for the sample. Thus, the questionnaire was distributed to the sample of 66 industry practitioners in the form of a Google® Form through emails. Consequently, the findings were analysed using descriptive analysis and the results were presented through statistical calculations, graphs, and tables. Further, Equation 1 was used to calculate the Relative Important Index (RII).

$$RII = \frac{\Sigma W}{AXN} \qquad (Eq.\ 01)$$

Where;

W= Weight given to each factor by the respondents in a range from 1 to 5

A=Highest weight (5)

N=Total no of respondents

4. RESEARCH FINDINGS AND DISCUSSION

4.1 CAUSES OF CONSTRUCTION DISPUTES IN SRI LANKA

The study identifies and evaluates potential construction disputes through a questionnaire, graded based on their significance in the Sri Lankan CI, and presents the identified causes and their relative importance. Subsequently, RII was calculated using Equation 1 and the causes were ranked based on the RII scores as shown in Figure 1.

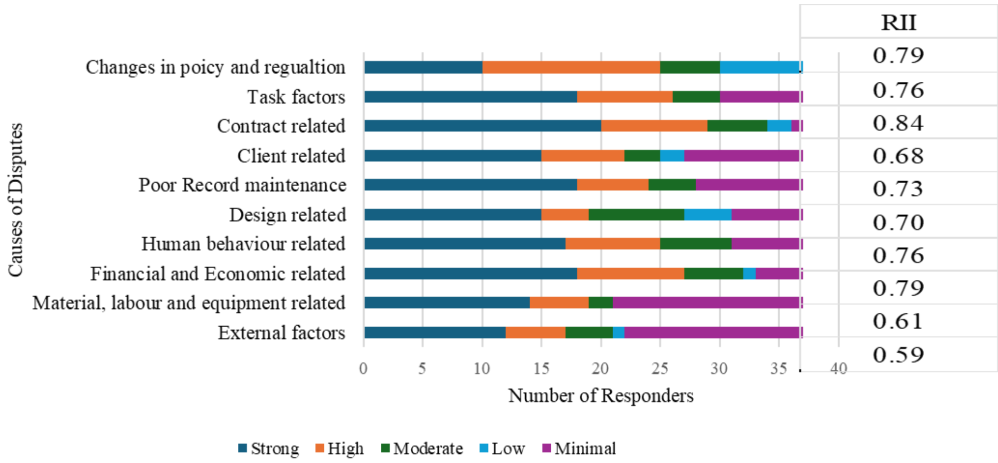


Figure 1: Significance of the causes of disputes in the Sri Lankan CI

The RII scores indicate the degree of significance attributed to each cause of dispute. According to the benchmark study by Holt (2014) having an RII score above 0.6 is an indication of relevance of the studied factors. Accordingly, eight out of the nine studied causes of disputes reported a RII above 0.600, indicating their relevance to the Sri Lankan context. However, the 'external factors' reported an RII value of 0.589 and ranked in ninth place indicating that external factors are not significant in causing construction disputes in Sri Lanka. Further, the results acknowledge 'contract-related' causes as the most significant causes of disputes in the Sri Lankan CI, with the highest RII of 0.843. The 'financial/economic related' causes are ranked in the second place with a RII of 0.795. This highlights the substantial influence of financial management and economic conditions on construction projects. The RII value of 0.762 is shared by both 'task factor' and 'human behaviour-related' causes, placing them in a tie for third place. Disputes concerning the clients have been ranked fifth with a RII of 0.730 whereas the 'design-related' causes hold the sixth position with a RII of 0.697 indicating that design-related causes are vulnerable to disputes but not among the primary concerns. Further, factors to 'human behaviour' and 'material, labour, and equipment' are less significant in terms of causing construction disputes as they are ranked in seventh and eighth places respectively with RII scores of 0.681 and 0.605. However, as Woodley (2019) discussed the design-related issues are subjective considering the procurement roots. Thus, they can still significantly impact a project when they do occur.

4.2 Alternative Dispute Resolution Methods in the Sri Lankan Construction Industry

The next section of the questionnaire focused on the ADR methods practised in the construction industry. Accordingly, respondents were provided with a list of six ADR methods which were identified through the literature review and checked their experience of the practice. Figure 2 shows the results.

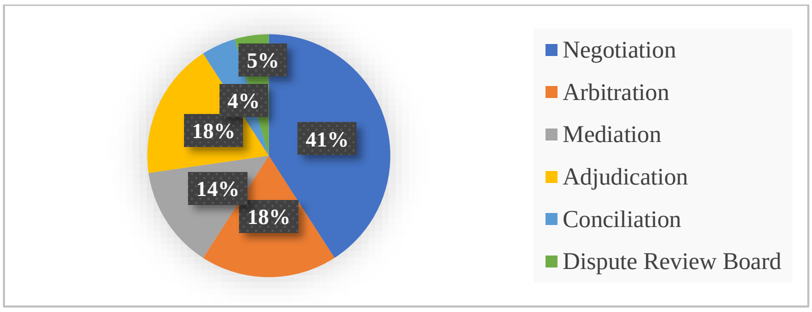


Figure 2: Ranking of ADR methods in the Sri Lankan CI

Accordingly, negotiation is the most used ADR method aligning with global trends that favour negotiation for its flexibility, speed, and less formal nature (Li & Cheung, 2022). This preference is consistent with the cultural inclination in Sri Lanka towards non-confrontational methods of dispute resolution (Viththakan, 2016). On the other end of the spectrum, conciliation and DRB are the least used methods reflecting their suitability in more structured environments such as large-scale construction projects (Liyanawatta et al., 2023). Arbitration and adjudication which are considered formal and costly are equally practised (Jayasinghe & Ramachandra, 2016; Palihawadana, 2020). Mediation reports moderate use due to its ability to preserve business relationships a valued aspect in many cultures (Iyiola & Rjoub, 2020). Sri Lanka's CI lacks innovative ADR methods including Facilitation, Standing Neutral, and Med-Arb due to a lack of awareness and familiarity with these techniques.

4.3 Application of Digital Technologies in Construction Dispute Resolution in Sri Lanka

The last section of the questionnaire focused on using DT in ADR. Accordingly, as the first step, respondents' opinion on the impact of DT in ADR was questioned. Figure 3 illustrates the responses according to a five-point Likert scale.

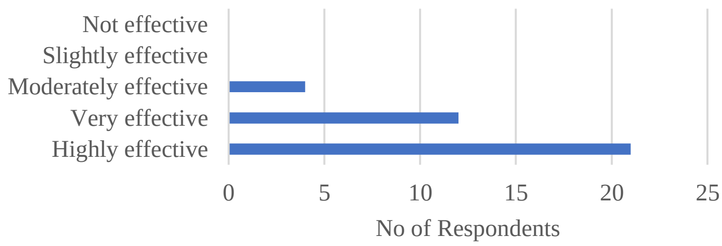


Figure 3: Impact of DT in ADR

The study shows that over 89% of respondents in the Sri Lankan CI highly or very highly endorse the use of DT in ADR, highlighting its effectiveness in improving the efficiency and effectiveness of ADR methods.

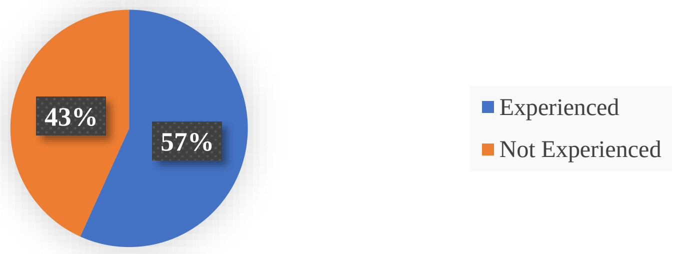


Figure 4: Experience in DT in dispute resolution

Results revealed a positive shift towards embracing DT in ADR. However, 43% of the respondents who still have not experienced DT in ADR indicate the potential areas for growth in training and technology adoption. Consequently, the respondents were provided with a list of frequently practising DT in ADR and asked to rate them based on their effectiveness. Subsequently, RII was calculated using Equation 1 and the causes were ranked based on the RII scores as shown in Table 3.

Table 3: Effectiveness of DT in ADR

Digital Technology	**Scale**					**RII**	**Rank**
	1	**2**	**3**	**4**	**5**		
BIM	5	4	7	7	14	0.714	3
Artificial Intelligence	9	3	5	11	9	0.643	4
Blockchain	6	8	6	9	8	0.627	5
Smart Contract	10	5	7	4	11	0.605	6
Big Data Analytics	15	1	9	5	7	0.535	7
Virtual ODR	0	7	4	7	19	0.805	2
Artificial Neural Networks	16	6	4	4	7	0.492	8
MS Office Packages	1	6	3	5	22	0.822	1

Accordingly, MS Office Packages have the highest RII score among all technologies, with an RII of 0.822, placing in the top rank. Virtual ODR follows in line, with an RII of 0.805, placing it in second place. This demonstrates a solid appreciation for its ability to remotely facilitate the dispute resolution processes. BIM ranks third, with a RII of 0.714.

The CI dramatically benefits from BIM, as it plays a crucial role in visualising and enables effective decision-making. Further, BIM is highly valued in promoting teamwork and its openness in construction conflicts. Artificial Intelligence, with an RII of 0.643, is ranked fourth, signifying its increasing yet unrealised capacity to automate and improve decision-making in construction projects. Blockchain technology ranks fifth, with a RII of 0.627. While the use of blockchain technology in ADR in the CI shows promise in enhancing transparency and trust in transactions, its application is still in the early stages of development. Smart contracts rank sixth with a RII of 0.605. This indicates the relevance of automating contractual obligations and the potential to reduce causes of disputes. However, the application of smart contracts in ADR is still in the early stages in the Sri Lankan context. big data analytics ranks seventh with an RII of 0.535, while artificial neural network implementation in dispute resolution is moderate due to its complexity and large dataset management proficiency.

5. CONCLUSIONS AND RECOMMENDATIONS

The CI faces disputes that cause several negative impacts such as project delays and cost overruns. However, traditional ADR methods struggle with complexity, unavailability of expert mediators, and logistical constraints. Consequently, the evolving nature of the CI necessitates advancements in dispute resolution methods. However, in the Sri Lankan context, in-depth investigations are lacking in incorporating DT into ADR processes to improve accessibility, transparency, and efficiency. Following a quantitative approach, this study conducted a survey involving 37 respondents to fill the research gap. The key findings of the study indicate that DT such as MS Office Packages, Virtual ODR, BIM, and AI have high levels of effectiveness in enhancing ADR processes. BIM and virtual ODR were highly valued for their ability to facilitate visualisation and remote dispute resolution respectively. Moreover, the integration of SC and BC is also highlighted mainly to notify parties about notices and letters. Despite their potential, Big data analytics and artificial neural networks showed lower effectiveness and implementation levels in the Sri Lankan context. Based on these findings the study concludes that there is a significant potential for enhancing ADR processes through targeted DT applications, particularly in improving efficiency and decision-making in dispute resolution. The study has limitations including a small sample size and geographical focus. It is recommended for future researchers to develop strategies to apply DT in ADR to address the unique challenges of the Sri Lankan CI. Furthermore, it is necessary to identify the possible DT for effective implementation of ADR methods considering the disadvantages of each method. This will guarantee the seamless incorporation and optimise the advantageous outcomes. Further research could investigate global applicability, longitudinal studies, and legal and ethical implications of DT in ADR.

6. REFERENCES

Abbasli, T. (2022). Can online dispute resolution prevail over the traditional methods of resolution? *Baku State University Law Review*, *8*(1), 21- 43. https://lr.bsulawss.org/files/archive/volume8/issue1/8BSULawRev1.2.pdf

Abeynayake, M. & Weddikkara, C. (2013). *Special features, experiences and new trends in arbitration in the construction industry of Sri Lanka*. The Second World Construction Symposium 2013: Socio-Economic Sustainability in Construction, Colombo, Sri Lanka. (pp. 389-398). https://ciobwcs.com/downloads/WCS2013-Proceedings.pdf

Abidoye, R. B., Fam, F., Oshodi, O. S., & Oyetunji, A. K. (2022). Impact of light rail line on residential property values – A case of Sydney, Australia. *International Journal of Housing Markets and Analysis*, *15*(3), 691–708. https://doi.org/10.1108/IJHMA-03-2021-0033

Ahmad, I., & El-Sayegh, S. (2021). Digital technology and integration in construction: The UAE context. In S. M. Ahmed, P. Hampton, S. D. Azar, & A. Saul (Eds.), *Collaboration and Integration in Construction, Engineering, Management and Technology: Proceedings of the 11th International Conference on Construction in the 21st Century, London*, 2019. (pp. 643–648).

Ahmed, M., AlQadhi, S., Mallick, J., Kahla, N. B., Le, H. A., Singh, C. K., & Hang, H. T. (2022). Artificial neural networks for sustainable development of the construction industry. *Sustainability*, *14*(22), 14738. https://doi.org/10.3390/su142214738

Amoah, C., & Nkosazana, H. (2022). Effective management strategies for construction contract disputes. *International Journal of Building Pathology and Adaptation*, *41*(6), 70–84. https://doi.org/10.1108/IJBPA-01-2022-0004aeb

Apte, B., & Pathak, S. (2016). Review of types and causes of construction claims. *International Journal of Research in Civil Engineering, Architecture and Design*, *4*(2), 43–50. https://www.academia.edu/download/47194250/08_Review_of_Types_and_Causes_of_Construction_Claims.pdf

Ayhan, M., Dikmen, I., & Birgonul, M. T. (2022). Comparing performances of machine learning techniques to forecast dispute resolutions. *Teknik Dergi*, *33*(5), 12577–12600. https://doi.org/10.18400/tekderg.930076

Broto, A. B. D., & Nugraheni, A. S. C. (2023). Effectiveness of out-of-court dispute resolution in construction disputes in Indonesia. *International Journal of Business, Economics and Law*, *28*(3), 49-52. https://ijbel.com/wp-content/uploads/2023/03/IJBEL28.ISU-3_221.pdf

Çakmak, P. I. (2016). Causes of disputes in the Turkish construction industry: Case of public sector projects: *ITU Journal of the Faculty of Architecture*, *13*(3), 109–118. doi.org/10.5505/itujfa.2016.69885

Cakmak, P. I., & Cakmak, E. (2013). An analysis of causes of disputes in the construction industry using analytical hierarchy process (AHP). *AEI 2013:* Building Solutions for Architectural Engineering, *Proceedings of the 2013 Architectural Engineering National Conference*. (pp.93–101). https://doi.org/10.1061/9780784412909.010

Chaisse, J., & Kirkwood, J. (2022). Smart courts, smart contracts, and the future of online dispute resolution. *Standford Journal of Blockchain Law & Policy*, *5*(3), 62–92. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4344466

Cheung, S. O., & Pang, K. H. Y. (2013). Anatomy of construction disputes. *Journal of Construction Engineering and Management*, 1*39*(1), 15–23. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000532

Edirisinghe, W. M. V. R., Marsh, D., Borthwick, F., & Cotgrave, A. (2020). An investigation into the significant causes of disputes in the Sri Lankan construction industry. . In T. Leathem (Ed.), *EpiC Series in Built Environment: Associated Schools of Construction Proceedings of the 56th Annual International Conference, 1*. (pp.347–355).

El-Sayegh, S., Ahmad, I., Aljanabi, M., Herzallah, R., Metry, S., & El-Ashwal, O. (2020). Construction disputes in the UAE: Causes and resolution methods. *Buildings, 10*(10). https://doi.org/10.3390/BUILDINGS10100171

Equbal, A., Banerjee, R., Khan, Z. R., & Dixit, R. B. (2017). Construction disputes in construction work sites and their probable solutions. *International Journal of Civil Engineering and Technology*, *8*(3), 74–81. http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=3

Faghih, A., & Akhavian, R. (2019). A game-theory approach to construction dispute resolution through mediation. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *11*(4), 5019004. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000325

Fatima, A., Sekhar, T. S., & Hussain, S. M. A. M. (2014). Analysis of construction dispute resolution process using artificial neural networks. *International Journal of Innovative Research and Development*, *3*(7), 81- 86. https://doi.org/10.1061/(ASCE)LA.1943-44540.006516

Francis, M., Ramachandra, T., & Perera, S. (2017). Revisiting causes of disputes: perspectives of project participants, phases of project and project characteristics. *Proceedings of The 6th World*

Construction Symposium 2017: What's New and What's Next in the Built Environment Sustainability Agenda?, Colombo, Sri Lanka. (pp.367-376).

Goski, S. M. (2021). Heading off litigation in construction disputes: Mediation as another tool in the alternative dispute resolution toolbox. *Dispute Resolution Journal*, *75*(3), 155–165. https://www.proquest.com/openview/80ec95fb9070eaaa533b3724afad91e2/1?pq-origsite=gscholar&cbl=25210

Gulati, R. (2022). Constructive ways for dispute resolution: employing alternative dispute resolution (ADR) techniques for the reclamation of justice. *Journal of Social Sciences*, *1*(1), 1–14. https://wahacademia.com/index.php/journal/article/view/1

Hardjomuljadi, S. (2020). Use of dispute avoidance and adjudication boards. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *12*(4), 3720004. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000431

Holt, G. D. (2014). Asking questions, analysing answers: Relative importance revisited. *Construction Innovation*, *14*(1), 2–16. https://doi.org/10.1108/CI-06-2012-0035

Illankoon, I. M. C. S., Tam, V. W. Y., Le, K. N., & Ranadewa, K. A. T. O. (2022*).* Causes of disputes, factors affecting dispute resolution and effective alternative dispute resolution for Sri Lankan construction industry. *International Journal of Construction Management*, *22*(2), 218–228. https://doi.org/10.1080/15623599.2019.1616415

Iyiola, K., & Rjoub, H. (2020). Using conflict management in improving owners and contractors relationship quality in the construction industry: The mediation role of trust. *Sage Journals*, *10*(1),. https://doi.org/10.1177/2158244019898834.

Jamil, A. H., & Fathi, M. S. (2020). Enhancing BIM-based information interoperability: Dispute resolution from legal and contractual perspectives. *Journal of Construction Engineering and Management*, *146*(7), 5020007. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001868

Jayasinghe, H. M., & Ramachandra, T. (2016). Adjudication practice and its enforceability in the Sri Lankan construction industry. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *8*(1), 451-465. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000178

Li, K., & Cheung, S. O. (2022*).* Are we ready for a rational discussion? The existence of biases in construction dispute negotiation. *IOP Conference Series: Materials Science and Engineering*, *1218*(1),), 012022. DOI 10.1088/1757-899X/1218/1/012022

Lingasabesan, V., & Abenayake, M. (2022). Opportunities and challenges in conducting virtual alternative dispute resolution (ADR) methods in the Sri Lankan construction industry. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, & S. Gunathilaka (Eds.), *Proceedings of the 10th World Construction Symposium*, 24- 26 June 2022, Sri Lanka. (pp.657–667). https://doi.org/10.31705/WCS.2022.53

Liyanawatta, T. N., Abeynayake, M. D. T. E., & Sumanarathna, P. M. S. U. (2023). Barriers for implementing dispute review board (DRB) method to Sri Lankan construction industry. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, T. Ramachandra, & K.A.T.O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium*, 21-22 July 2023, Sri Lanka. (pp. 260–268). https://doi.org/10.31705/WCS.2023.22

Love, P., Davis, P., Ellis, J., & On Cheung, S. (2010). Dispute causation: identification of pathogenic influences in construction. *Engineering, Construction and Architectural Management*, *17(*4), 404–423. https://doi.org/10.1108/09699981011056592

Lu, W., Wang, S., & Liu, B. (2019). Resolving construction disputes through mediation within arbitration proceedings in China. *International Journal of Architecture, Engineering and Construction*, *8*(1), 9–18. http://dx.doi.org/10.7492/IJAEC.2019.002

Mashwama, N. X., Aigbovboa, C., & Thwala, W. D. (201). Evaluating the impact of construction dispute and the use of ADR in the Swaziland construction industry. *Creative Construction Conference 2016, Budapest, Hungary*, 25-28 June 2016. (pp. 91-99). https://2016.creative-construction-conference.com/

Mishmish, M., & El-Sayegh, S. M. (2018). Causes of claims in road construction projects in the UAE. International *Journal of Construction Management*, *18*(1), 26–33. https://doi.org/10.1080/15623599.2016.1230959

Muhammad, R., & Nasir, A. R. (2022). Integrating BIM in construction dispute resolution: development of a contractual framework. *Buildings*, *12*(11), 18-28. https://doi.org/10.3390/buildings12111828

Ness, A. D. (2020). Neutral evaluation: Another tool in the ADR toolbox. *The Construction Lawyer*, *40*(4), 7- 11.. https://www.jamsadr.com/files/uploads/documents/articles/ness-andrew-construction-lawyer-neutral-evaluation-10-2020.pdf

Nihaaj, N. M. M. (2016*). Critical analysis of arbitration method used in the construction industry in Sri Lanka* [Unpublished Master thesis]. University of Moratuwa, Sri Lanka. http://dl.lib.mrt.ac.lk/handle/123/13045

Nitharsan, N., & Francis, M. (2022). Adaptability of blockchain-based E-Procurement system in Sri Lankan construction projects. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, & S. Gunathilaka (Eds.), *Proceedings of the 10th World Construction Symposium*, 24- 26 June 2022, Sri Lanka. (pp. 63-75). https://ciobwcs.com/2022-papers/

Palihawadana, H. I. (2020). *Efficacy of adjudication as a dispute resolution mechanism: the case of road projects in Sri Lanka* [Unpublished Master thesis]. University of Moratuwa, Sri Lanka.

Patil, S. K., Iyer, K. C., & Chaphalkar, N. B. (2019). Influence of extrinsic factors on construction arbitrators' decision making. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *11*(4), 73-80. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000318

Putera, N. S. F. M. S., Saripan, H., Hassan, R. A., & Abdullah, S. M. (2021). Artificial intelligence for construction dispute resolution: Justice of the future. *International Journal of Academic Research in Business and Social Sciences*, *11*(11), 139- 151. https://doi.org/10.6007/IJARBSS/v11-i11/11263

Ranasinghe, A., & Korale, J. C. (2011). Adjudication in construction contracts. *Engineer, 44*(2), 73- 81. http://iesl.nsf.ac.lk/bitstream/handle/1/1750/Engineer-2011-44(2)_73.pdf?sequence=2

Rauzana, A. (2016). Causes of conflicts and disputes in construction projects. *Journal of Mechanical and Civil Engineering*, *13*(05), 44–48. https://doi.org/10.9790/1684-1305064448

Ridmika, K. I., & Thayaparan, M. (2021). Applicability of artificial intelligent techniques for effective communication in green construction. *Proceedings of the International Conference on Industrial Engineering and Operations Management, Rome, Italy*, 2- 5 August 2021. (pp. 2269–2279).Saeb, A., Mohamed, O. Bin, Danuri, M., & Zakaria, N. B. (2018). Critical factors for selecting a neutral to support alternative dispute resolution methods in the construction industry. *Civil Engineering Journal*, *4(*1), 11–23. http://dx.doi.org/10.28991/cej-030965

Saygili, M., Mert, I. E., & Tokdemir, O. B. (2022). A decentralized structure to reduce and resolve construction disputes in a hybrid blockchain network. *Automation in Construction*, *134*(2), 104056. https://doi.org/10.1016/j.autcon.2021.104056

Senarath, P., & Francis, M. (2021). Dispute avoidance from the perspective of procurement methods: A conceptual focus. In Y.G. Sandanayake, S. Gunatilake, & K.G.A.S. Waidyasekara (Eds.), *Proceedings of the 9th World Construction Symposium*, 9-10 July 2021, Sri Lanka. (pp.256-268) http://dl.lib.uom.lk/handle/123/16589

Senarathna, D. R. (2019*). The Impact of judicial intervention on arbitral process in the construction industry of Sri Lanka* [Unpublished Master thesis]. University of Moratuwa, Sri Lanka. http://dl.lib.uom.lk/handle/123/15830

Shash, A. A., & Habash, S. I. (2021). Disputes in construction industry: Owners and contractors' views on causes and remedies. *Journal of Engineering, Project, and Production Management*, *11*(1), 37–51. https://doi.org/10.2478/jeppm-2021-0005

Shyamal, M. J. (2016). S*uccess of adjudication as a primary ADR method in Sri Lankan construction industry* Unpublished Master thesis]. University of Moratuwa, Sri Lanka. http://dl.lib.uom.lk/handle/123/12322

Soni, S., Pandey, M., & Agrawal, S. (2017). Conflicts and disputes in construction projects: An overview. *International journal of engineering research and applications*, *7*(6), 40–42. https://doi.org/10.9790/9622-0706074042

Stamatiou, D. R. I., Kirytopoulos, K. A., Ponis, S. T., Gayialis, S., & Tatsiopoulos, I. (2019). A process reference model for claims management in construction supply chains: The contractors' perspective. *International Journal of Construction Management, 19*(5), 382–400. https://doi.org/10.1080/15623599.2018.1452100

Tanriverdi, C., Atasoy, G., Dikmen, I., & Birgonul, M. T. (2021). Causal mapping to explore emergence of construction disputes. *Journal of Civil Engineering and Management*, *27*(5), 288–302. https://doi.org/10.3846/jcem.2021.14900

Ustuner, Y. A., & Tas, E. (2019). An examination of the mediation processes of international ADR institutions and the evaluation of the Turkish construction professionals' perspectives on mediation. *Eurasian Journal of Social Sciences*, *7*(4), 11–27. DOI: 10.15604/ejss.2019.07.04.002

Utama, G. S. (2017). Online dispute resolution: A revolution in modern law practice. *Business Law Review*, *3*(1). https://law.uii.ac.id/wp-content/uploads/2017/04/V-01-No-03-online-dispute-resolution-a-revolution-in-modern-law-practice-gagah-satria-utama.pdf

Viththakan, K. P. (2016). *Analysis of disputes towards effectiveness of negotiation in the Sri Lankan construction industry: contractors' perspective* Unpublished Master thesis]. University of Moratuwa, Sri Lanka. http://dl.lib.uom.lk/handle/123/12353

Vo, K. D., Nguyen, P. T., & Nguyen, Q. L. H. T. T. (2020). Disputes in managing projects: A case study of construction industry in Vietnam. *The Journal of Asian Finance, Economics and Business*, *7*(8), 635–644. https://doi.org/10.13106/jafeb.2020.vol7.no8.635.

Wattuhewa, R. M., Waidyasekara, K., & Dilakshan, R. (2023). Importance of utilising big data analytics in enhancing construction data management. *Proceedings of 13th International Conference on Business and Information, (522-532)*. https://ssrn.com/abstract=4475444

Woodley, C. (2019). Will digitalisation end construction disputes? *Construction Research and Innovation*, *10*(1), 15–17. https://doi.org/10.1080/20450249.2019.1589140

Zeleznikow, J. (2021). Using artificial intelligence to provide intelligent dispute resolution support. *Group Decision and Negotiation, 30*(4), 789–812. https://doi.org/10.1007/s10726-021-09734-1

Zhao, W. (2019). The root cause of claims and disputes in construction industry and solution analysis. *PM World Journal, 8*(5). http://www.pmworldjournal.com/

Karunanayaka, R.R., Kumarathunga, J.U. and Gamage, I., 2024. Incorporating smart interior design concepts in Sri Lankan apartment construction. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 581-593. DOI: https://doi.org/10.31705/WCS.2024.46. Available from: https://ciobwcs.com/papers/

INCORPORATING SMART INTERIOR DESIGN CONCEPTS IN SRI LANKAN APARTMENT CONSTRUCTION

Rashmika Rasanjalee Karunanayaka[1], Janani Uvasara Kumarathunga[2] and Iresha Gamage[3]

ABSTRACT

Smart interior design can be interpreted as the integration of technology, innovative materials, and sustainable approaches in creating functional and aesthetically pleasing living spaces. In response to the global shortage of affordable housing, countries have begun to explore the potential of smart interior design for space-saving and cost-effective construction. This concept is still novel in Sri Lanka, where the retreat of the construction industry due the economic crisis has caused a recession in apartment construction. Thus, this research serves as a preliminary study that aims to investigate the adoptability of space-saving smart interior design concepts in Sri Lankan apartment construction, with an emphasis on the constraints faced and strategies to overcome them. The study adopted a qualitative research approach and primarily, a comprehensive literature review was conducted to define the implication of space-saving smart interior design along with the upsides of applying this technique into apartment construction. Semi-structured interviews were conducted to identify the main constraints when incorporating this concept in Sri Lanka considering both design-stage and implementation-stage. A significant obstacle uncovered was the lack of demand for the use of this concept in Sri Lanka, stemming largely from the lack of awareness of its benefits. This study recommends that the concept of smart living should be promoted through education, small-scale construction and government intervention. The strategies proposed through this study serve towards enhancing the preparedness of incorporating this concept in Sri Lanka so that the benefits of the concept may be obtained while overcoming the constraints.

Keywords: *Apartments; Construction industry; Smart interior design; Space-saving.*

1. INTRODUCTION

Sri Lanka is likely to face a severe shortage of apartment units by next year and into the future due to the current state of financial and economic instability (Hettiarachchi & Dhanji, 2024; Hewage, 2022). The nation's overall residential land price has dropped by 62.90% because people are no longer interested in investing in land and are demotivated to build houses owing to the high rates of interest for housing loans (The Island, 2022). Through a study of the real estate industry of Sri Lanka, Madushani and Piyadasa (2019)

[1] Assistant Quantity Surveyor, Compass Project Consulting, Sri Lanka, rash97karu@gmail.com
[2] Quantity Surveyor, Nawaloka Construction Company (Pvt) Ltd, Sri Lanka, janauvasara@gmail.com
[3] Doctoral Researcher, Western Sydny University, NSW, Australia, 90959259@westernsydney.edu.au

demonstrated that the rapid development of Colombo and other suburbs has triggered an increase in the purchase of luxury and semi-luxury apartments in Sri Lanka.

In order to face the high demand for apartment units and the concurrent shortage of apartment construction, there is a need to investigate a solution to minimise the land impact, cost of apartment construction, and carbon footprint while simultaneously enhancing the living standards of Sri Lankan apartment users. It is noteworthy that finance is the most influential factor that steers customers' purchasing decisions toward buying apartments rather than buying land and building a house (Madushani & Piyadasa, 2019; Kaluthanthri & Jayawardhana, 2022). Traditional homes were built in large sizes by allocating several small single-purpose rooms for each function. The interior design of traditional homes of the last decade has focused on one function for each type of furniture and shape (Canepa, 2017). However, it is debatable if that represents the most cost-effective and sustainable course of action. The premise of this study is that smart interior design can increase the sustainability of a residential space, particularly apartment buildings. The study focuses on apartment buildings on account of the rising demand within Sri Lanka in that category, in conjunction with the dearth of research regarding space-optimisation specific to apartment buildings.

"Smart interior design" refers to the integration of technology, innovative materials, and sustainable practices to create functional and aesthetically pleasing living spaces (Ashour & Rashdan, 2023). One of the categories of smart interior designs known as 'space-saving smart interior' refers to the use of innovative design, techniques and technology to maximise the use of limited living space, while still maintaining functionality and aesthetic appeal (Taylor, 2022). This concept not only reduces land use and improves sustainability, but also promotes reduced building-material consumption by minimising the size of structural elements and maximising the effective use of space (Barbosa et al., 2015). Nevertheless, as cost reduction alone is not a guarantee of sustainability and longevity, smart interior design must be utilised in such a way that occupant comfort and long-term satisfaction with the living space are also ensured. In Kenya, The Kibera Soweto East Housing government project which was launched in 2012 was only focused on reducing costs when coming up with the interior plans and layouts and not on the improvement of the quality of life and living standards of residents. This ultimately resulted in more than half of the apartments getting sold or rented out by the owners, and the residents moving back to the slums (UN-Habitat, 2008). After extensive research, it was recommended that using multi-functional smart interior design could have overcome this problem (Wawira et al., 2019). However, in Sri Lanka, there is still no specific research that has been carried out surrounding the incorporation of space-saving smart interior designs in apartment construction. Consequently, in the context of Sri Lanka, this concept is still a novel one. Therefore, this study will be carried out to fill the aforementioned gap by investigating constraints when applying this concept to the Sri Lankan apartment construction sector. The aim of this research is to conduct a preliminary investigation on the adoptability of space-saving smart interior design concepts in Sri Lankan apartment construction, with an emphasis on the constraints faced and strategies to overcome them.

2. LITERATURE REVIEW

2.1 APARTMENT INDUSTRY IN SRI LANKA

The Department of Census and Statistics of Sri Lanka reports that the nation has experienced a significant uptick in urbanisation and population growth in recent years (Department of Census and Statistics, 2022; Department of Census and Statistics of Sri Lanka, 2012). This has caused the construction of apartments in Sri Lanka to progress steadily, driven by the growing demand for housing in urban areas. In Sri Lanka, apartments can be divided into several categories ranging from Luxury apartments (which are the most high-end category of apartments in Sri Lanka), to Mid-range, and to Economy apartments which are designed for the more budget-conscious buyers (Lanka Property Web, 2021). The number of housing units approved for construction in Sri Lanka increased by 21.8% in 2019, with apartment units accounting for a significant portion of the increase (The Central Bank of Sri Lanka, 2020). The report also notes that the construction of multi-storied buildings, including apartments, increased by 56.4% in 2019 compared to the previous year (The Central Bank of Sri Lanka, 2020).

2.2 SMART INTERIOR DESIGN AND ITS SIGNIFICANCE

In 1989, the Intelligent Building Institute of the United States defined Smart Homes as an efficient environment which prioritises occupant effectiveness, operational efficiency, and technological usage through integrated and optimised systems, structures, services and management (GhaffarianHoseini et al., 2011). In another aspect, it can be defined as a building which essentially programs itself by observing occupants' behaviour patterns and environment instead of being programmed for only a specific action (Batov, 2015). With the fast-paced technological revolution of the 21st century, Internet of Things (IoT) technologies have made it possible to collect and analyse all the building services data without human intervention and visualise the energy or environmental data of end users (Jia et al., 2019). Smart interior design can be interpreted as the future of design where the integration of smart material, furniture, devices, and sensors enable functions to be controlled and communicated through IP network and mobile applications, to a reliable analysis system that is capable of responding quickly to inhabitant requests and deciding the most efficient way of providing a convenient, comfortable, safe, and productive environment which enhances the quality of life of the occupants (Rashdan, 2016).

2.2.1 Space-Saving Smart Interior Design

Space-saving smart interior designs can be considered a sub-set of smart interior designs, owing to a few key differences. Whereas the concept of smart interior design refers to the use of design strategies and techniques that maximise the functionality, comfort, and aesthetic appeal of a space, 'Space-saving smart interior designs' serve a more specific function and refers to the use of design strategies and techniques that focus on optimising the use of limited space (Radha, 2022). This concept involves incorporating features such as multi-functional furniture, built-in storage, and flexible layouts that can be easily adapted to different needs and uses (Husein, 2021).

2.2.2 Space-Saving Smart Interior Design for Apartment Projects

Rapid population growth and a shortage of land has resulted in limited space in resident quarters, affecting the living quality and mental health of occupants (Thøgersen, 2017). The crowded and cluttered nature of small apartments causes residents to feel trapped, stressed and claustrophobic. The reason for this is not only the limited floor area but also the furniture and other items that occupy floor space (Husein, 2021). Thøgersen (2017) stated that multipurpose spaces require smart and space-saving furniture solutions to make the place more liveable, not crowded and claustrophobic. Intensive use of three-dimensional space is another strategy that can be used to utilise vertical space more efficiently. Several countries have implemented space-saving smart interior designs in apartment construction. Japan has applied space-saving design as a solution for high population density. Japanese architects have been known for their expertise in designing small apartments with smart interior design concepts (Brown, 2023). The Hong Kong government has introduced guidelines for small flat designs, promoting space-saving smart interior design concepts as a solution for high density (Sima, 2015). With limited land availability, the Housing and Development Board (HDB) of Singapore has been incorporating smart interior designs in their public housing projects to maximise the use of space (Jahan et al., 2024). There are several countries that use space-saving smart interior designs for space-saving purposes but also for financial reasons. For instance, Indian developers are turning to space-saving design strategies to maximise profits and minimise expenses in the construction of small apartments (Kahre et al., 2022). Similarly in the Philippines, developers are implementing space-saving smart interior designs to reduce construction costs and provide affordable housing to the masses (Ma et al., 2021).

2.3 Upsides of Smart Interior Design

Incorporating smart interior design solutions to building systems is gaining popularity because of the technology's capability to learn and even anticipate occupants' needs and preferences. According to Ashour and Rashdan (2023), smart interior design can potentially create spaces that are functional, sustainable, aesthetically pleasing and highly responsive to occupant needs. They found that this potential can be achieved by excelling in four key criteria: integration, communication, adaptability, and control. Table 1 elaborates the upsides of incorporating space-saving smart interior designs in apartment construction.

Table 1: Upsides of incorporating space-saving smart interior designs in apartment construction

Upsides of incorporation		Reference(s)
Compact and space-saving based advantages	Enhance the functionality of the space	(Manewa, 2012), (Goessler & Kaluarachchi, 2023)
	Minimise the need for additional compartments	(Al-Shatnawi, 2020)
	Enhance the use of vertical space	(GhaffarianHoseini et al., 2011)
	Provide more space for social gathering areas	(Goessler & Kaluarachchi, 2023), (Thøgersen, 2017)
	Provide multiactivity spaces for small apartment residents	(GhaffarianHoseini et al., 2011), (Goessler & Kaluarachchi, 2023)
	Efficient use of corners	(Manewa, 2012)
	Provide greater amount of storage space	(Rashdan, 2016), (Jia et al., 2019), (Radha, 2022)
Quality and style-based advantages	Enhance performance due to systematic integration	(GhaffarianHoseini et al., 2011), (Goessler & Kaluarachchi, 2023)
	Increase lifestyle comfort	(Thøgersen, 2017), (Radha, 2022)

Upsides of incorporation		Reference(s)
	Allow to maintain healthy indoor air quality	(Thøgersen, 2017), (Jia et al., 2019)
	Using visual tricks to enhance spaciousness	(Jia et al., 2019)
	Increase demand by adding modern architectural features	(Hamid & Embi, 2016), (Batov, 2015), (Radha, 2022)
	Enhance futuristic vision in interior design	(GhaffarianHoseini et al., 2011), (Su et al., 2023)
	Increase flexibility	(GhaffarianHoseini et al., 2011), (Goessler & Kaluarachchi, 2023)
Price-based advantages	Potential to lower cost of construction	(Omar, 2018), (Aloudeh et al., 2023), (Su et al., 2023)
	Reduce size of structural elements	(Goessler & Kaluarachchi, 2023), (Su et al., 2023)
	Reduce the floor area while providing same functionality	(Goessler & Kaluarachchi, 2023)
	Potential to make apartment units more affordable	(Manewa, 2012), (Aloudeh et al., 2023), (Su et al., 2023)
Psychological-based advantages	Provide better phycological condition by avoiding being compact	(Manewa, 2012), (Rashdan, 2016)
	Provide flexibility within the house to move components in need of more space	(Al-Shatnawi, 2020)
Environmental-based advantages	Increase energy efficiency	(Omar, 2018), (Batov, 2015), (Akadiri et al., 2012)
	Reduce the land use	(Hamid & Embi, 2016)
	Promote sustainability	(Aloudeh et al., 2023), (Rashdan, 2016), (Akadiri et al., 2012)
	Allow less building material consumption	(Omar, 2018), (Rashdan, 2016), (Su et al., 2023)
	Reduce carbon footprint	(GhaffarianHoseini et al., 2011), (Hamid & Embi, 2016)

2.4 CONSTRAINTS WHEN APPLYING SMART INTERIOR DESIGN

While singular smart design amenities (devices such as sensors, displays, logic controllers, transmitters etc.) are being increasingly utilised in modern homes (Ashour & Rashdan, 2023), the concept of a ‘smart home’ is still relatively novel in most parts of the world. According to Liu and Chen (2023), although smart-home products of the present are technologically innovative, some are impractical for everyday use. As a result, these products perform poorly in the market since their introduction. Educating end-users is evidently a major challenge in the way of incorporating smart interior design. According to Christiansson (2007), the development of smart interior design concepts thus far has been driven mostly by information revolution and the rapid evolution of technology, rather than client’s requirement. Although end-users stand to benefit significantly through these innovations, their limited knowledge on intelligent buildings creates a gap between user requirements and the services provided (Liu et al., 2010). Although smart homes have the potential to reduce costs indirectly by minimising resource wastage, optimising space usage, increasing comfort etc., there are significant direct costs attached to the technology. As noted by Ni et al. (2023), in addition to the high initial cost, maintenance costs of smart home systems are relatively high. Users may be hesitant to make large investments in unproven concepts. The risk of data theft and privacy violation is another major constraint, according to Ni et al. (2023). As the home environment is one with needs extremely high standards of confidentiality, smart homes could potentially become dangerous sources for data theft. These constraints are exacerbated by the lack of a unified quality control standard to monitor product-quality, after-sales service and maintenance (Liu & Chen, 2023; Ni et al., 2023).

3. METHODOLOGY

The literature review was conducted by acquiring and scrutinising journal articles, conference proceedings, newspaper articles, and reports relating to smart interior designing. While many past studies have dwelled into the benefits and applicability of smart interior design, very few focus specifically on 'space-saving' smart interior design. Even fewer such studies have been conducted in the context of Sri Lanka. Thus, this research was conducted as an exploratory study to investigate the potential of incorporating space-saving smart interior design into Sri Lankan apartment construction, by determining the upsides, constraints and strategies for incorporation of this technology.

The study follows a qualitative research approach instead of quantitative, as it allows for a more in-depth preliminary analysis surrounding the concept of smart interior design in Sri Lanka. The qualitative approach is particularly beneficial in dealing with emerging and complex topics such as space-saving smart interior designs, where limited understanding and data are available in the Sri Lankan context (Rahman, 2016). Due to the exploratory nature of the study, data was gathered through semi-structured interviews where suitable candidates were chosen using non-random selective sampling. It was decided that selective sampling would be best since it enables the selection of the most pertinent responders in a judgmental manner (Saunders et al., 2019). Since the focus area of the research is a novel concept to Sri Lanka, the guideline entailed more open-ended questions. This allowed respondents to reveal their beliefs, experiences, and knowledge without restriction. Altogether, the study employed an interpretivism research paradigm, meaning that because the respondents' answers are based on their present knowledge, experience, and comprehension, they are subjective.

Fifteen (15 nr.) interviewees were chosen from three focused populations: Tenants, professionals from interior design consultation and manufacturing companies, and professionals from apartment development organisations. Five candidates from each category were chosen as the sample size for this study. This sample size allowed for an abundance of varying responses to be collected while also achieving data saturation. Five (5 nr.) tenants of different age groups that live in luxury and semi-luxury apartments in urban areas of Colombo were interviewed. Further, five (5 nr.) professionals from interior design consultation and manufacturing companies were interviewed. These candidates were chosen from reputed companies, on the basis of expertise (over 5 years of experience) and knowledge of smart interior design, the construction industry and the housing market. However, it must be noted that due to the novelty of the smart interior design concept, 4 out of the 5 interviewees selected were chartered architects. The remaining interviewees were five (5 nr.) professionals from apartment development organisations. Manual content analysis was used on the data gathered from semi-structured interviews. Finally, the conclusions of the research were derived by harmonising all findings of the research.

4. RESEARCH FINDINGS

4.1 CONSTRAINTS IN INCORPORATING SPACE-SAVING SMART INTERIOR DESIGN IN SRI LANKA

Interviewees' opinions were gathered regarding potential constraints when incorporating space-saving smart interior design into apartment industry of Sri Lanka. It must be noted that the tenants were interviewed first, to gather more details of constraints from the perspective of potential end-users. By interviewing the construction professionals and developers later, data was collected regarding strategies to overcome these constraints. Based on the responses, the listed constraints were sub-categorised as design-stage constraints and implementation constraints. 'Design-stage constraints' are constraints that can occur when applying this concept into designs of apartment construction. 'Implementation constraints' are constraints that can arise when constructing designs of the apartment construction including space saving smart interior designs into reality. This category was further divided into social, economic, legal, technological, and other constraints. Table 2 entails a summary of the constraints identified through analysis. It is evident that the most significant constraint to incorporation is the lack of awareness among the general public regarding smart concepts. This social constraint may even be a root cause for other major constraints such as the lack of demand, less popularity, and lack of familiarity.

Table 2: Constraints towards incorporating space-saving into apartment construction

		Constraints	No. of responses
Design stage		Interior designs may vary based on user requirements	7
		Premium charges are added when developers consult interior designers regarding space-saving smart interior designs	1
		Space-saving not being a priority for users and developers	4
Implementation stage	Legal	Government tax and importing restrictions	5
		No laws imposed by the government to save spaces	3
		Apartment rules and regulations	1
	Economic	Less demand	5
		High risk involving when manufacturing	2
		Manufactures can't add considerable profit margin	4
		Cost of design is high	3
		Additional effort, time and cost are incurred in buying process	2
	Social	Cultural barriers	4
		Less popularity of vertical living	4
		Less awareness among the people about smart concept	8
		Difficulty of finding reliable manufactures	4

Constraints		No. of responses
	Spending patterns	2
	Behavioural and thinking patterns	3
Technological and others	Less availability of accessories	3
	Less durable	2
	Not created required maintenance skills yet	2
	Difficulty to use for elderly people	1
	Requires more maintenance because of more accessories	2
	Transforming or folding up furniture causes constrained, cluttered, and cramped feelings.	1
	Less familiar with smart technology	2

4.2 SUMMARY OF PROPOSED STRATEGIES TO OVERCOME THE IDENTIFIED CONSTRAINTS

Table 3 illustrates the strategies that this study proposes to combat the constraints identified previously. All three categories of interviewees were persistent that awareness programs are necessary to educate the public regarding space-saving smart interior design. Most tenants commented that user-friendly interfaces and maintenance guidelines would reduce the resistance to change when purchasing smart-home devices. Professionals in the apartment industry suggested that to build the users' faith in smart interior designs, products of high-quality functions, durability and user-friendly interfaces should be promoted in Sri Lanka.

Table 3: Strategies to overcome constraints

Constraints				Proposed strategies
Design stage		Interior designs may vary based on user requirements.	S1	Conduct surveys comparing space-saving smart interior designs and apartment-user requirements.
		Premium charges are added when developers consult interior designers regarding space-saving smart interior designs Space-saving not being a priority for users and developers	S2	Increasing awareness to normalise the concept and alert regarding its benefits. Provide interior design selection in 3D or animated visualisation.
Implementation stage	Legal	Government tax and importing restrictions No laws imposed by the government to optimise spaces. Apartment rules and regulations.	S3	Provide suitable creative designs in line with apartment restrictions.
	Economic	Less demand High risk involved when manufacturing	S4	Promote space-saving smart interior designs into residential buildings to increase awareness regarding its benefits.

	Constraints		Proposed strategies
	Manufactures can't add considerable profit margin Cost of design is high Additional effort, time and cost are incurred in buying process.	S5	Conduct market research on financial feasibility.
Social	Cultural barriers	S6	Include smart living concepts in education.
	Less popularity of vertical living	S7	Conduct awareness programs.
	Less awareness among the people about smart concept Difficulty of finding reliable manufactures.	S8	Designers and developers should promote the concept with the aim of developing a trend for space-saving smart interior designs
	Spending patterns Behavioural and thinking patterns.	S9	Increase the availability of the space-saving smart interior designs in show rooms
Technological and others	Less availability of accessories	S10	Increase the availability of raw materials through local sourcing
	Less durable Not created required maintenance skills yet Difficulty to use for elderly people	S11	Manufacture with locally-sourced, durable alternative materials that are suitable for the Sri Lankan context
	Requires more maintenance because of more accessories Transforming or folding up furniture causes constrained, cluttered, and cramped feelings.	S12	Manufacture with smooth and user-friendly mechanisms suitable for all ages
	Less familiarity with smart technology	S13	Provide maintenance guidelines when purchasing

5. DISCUSSION

Space-saving smart interior design is a concept that, despite its novelty in the context of Sri Lanka, can provide great benefits for the country's housing industry. The lack of research surrounding space-saving smart interior design in the Sri Lankan context is a gap that must be bridged in order to utilise this concept to its full potential. Past studies revealed that smart design, including space-saving smart interior design in particular, holds the potential to significantly improve the quality of life of occupants while enhancing the value of apartments by reducing unnecessary costs, optimising space and improving responsiveness towards user-needs. Since this is an exploratory study, the upsides of this technology were explored first in order to establish the need for the research that followed.

In Sri Lanka, the rising cost of land and construction has driven people towards buying apartments. The dilemma within the country, however, is the halt in apartment construction owing to the economic crisis. To summarise the upsides of space-saving smart interior design: it allows for even a smaller space to be utilised in the most efficient manner possible, thus negating the need for arduous and lengthy construction and introducing technologies which cater to occupant comfort. It is, therefore, an ideal solution that creates a win-win situation for buyers and apartment developers. The literature review uncovered several constraints relating to applicability of smart interior design. Although these studies were neither specific to 'space-saving' smart interior design nor conducted in the Sri Lankan context, they are comparable to the findings of the semi-structured interviews. One major constraint identified through interviews was that interior designs may vary based on user requirements. Liu et al. (2010) also noted that the limited understanding of this technology could create gaps between user requirements and the provided services. The proposed strategy S1 recommends surveys to be conducted to gain a better understanding of user requirements. A similar approach was suggested by Liu et al. (2010), who cited a 2006 Danish research project that proposed a method to minimise product-knowledge gaps providing a platform for clients to input their user-requirements for intelligent buildings, so that developers can use that data. It was found that cost is the most crucial deciding factor for end-users, as all the interviewees attested. The findings of Omar (2018), Su et al. (2023) and others mentioned in the literature review establish the potential cost-related upsides of smart interior designs. Alternatively, several of the identified constraints mention the cost implications of incorporating such a novel technology without proof-of-concept. These concerns are echoed by Ni et al. (2023) in the literature review, due to the high initial cost and the subsequent maintenance costs. As an exploratory study of this concept, this research concludes that there are many indirect costs that can be saved through space-saving smart interior design. On the other hand, there are direct costs associated with these newer technologies. Further research must be conducted focused on quantitative cost-benefit analyses of space-saving smart interior design. Having identified the potential constraints and suggesting strategies for overcoming them, this research acts as a preliminary study which can enhance the adoptability of this technology in Sri Lanka.

6. CONCLUSIONS

The aim of this research was to conduct a preliminary investigation on the adoptability of space-saving smart interior design concepts in Sri Lankan apartment construction, with an emphasis on the constraints faced and strategies to overcome them. The findings of the literature review revealed five categories of upsides: compact and space-saving based advantages, quality and style-based advantages, price-based advantages, psychological-based advantages, and environmental-based advantages. Semi-structured interviews were conducted to identify the constraints in adopting space-saving smart interior design. Constraints of two basic categories were identified: design-stage constraints and implementation-stage constraints. Implementation-stage constraints were further divided as legal, economic, social, technological and other constraints. Following the identification of the constraints, strategies to overcome those constraints were also provided. According to the standpoint of the tenants, conducting island-wide awareness programs and increasing the availability of space-saving smart interior designs in manufacturers'' show rooms, exhibitions, etc. will enhance the awareness among end-users and buyers. Industry professionals were of the opinion that social and economic constraints can be avoided by creating a sufficient demand for the concept through awareness. Accordingly, the following recommendations can be made for the implementation of space-saving smart interior design in apartment construction:

- Promote smart-living concept through education – Government is required to take action to promote this concept among community to enhance the affordability of small living spaces and to avoid apartment construction shortage in future as a result of recession.
- Promote space saving smart interior designs in residential buildings – Designers can help to reduce energy consumption and promote eco-friendly living.
- Create a trend among people for space-saving smart interior designs – Developers can gain higher profits from investments by reducing construction costs and increasing the overall desirability of living spaces.

While this study serves as a preliminary study, it can be a stepping stone towards further research which quantitatively analyses the cost implications of space-saving smart interior design and conducts a cost-benefit analysis. There are limitations to this study in terms of the niche subject, as it focused solely on apartment buildings. However, several findings and proposed strategies can be reasonably applied to other residential spaces as well. Thus, this study can benefit more research on the subject of space-saving interior design, when being applied to other residential spaces. Although the findings of this study were derived from the Sri Lankan context, they can also be reasonable applied in the context of countries with similar economic, and social conditions including similar population density, and real-estate trends. Overall, the findings of this study and the recommended strategies serve towards creating awareness, and enhancing the preparedness of incorporating this novel concept to Sri Lanka so that the construction industry of Sri Lanka can realise its benefits while overcoming the obstacles.

7. REFERENCES

Akadiri, P. O., Chinyio, E., & Olomolaiye, P. (2012). Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. *Buildings*, 2(2), 126–152. https://doi.org/10.3390/buildings2020126

Aloudeh, R., Elmardi, M., & Sheta, W. (2023). A sustainable approach to improve the interior design of existing space: the case of the BUID main lobby. In K. Al Marri, F. Mir, S. David, & A. Aljuboori (Eds.), *BUiD Doctoral Research Conference 2022* (pp. 167–178). Springer. https://doi.org/10.1007/978-3-031-27462-6_16

Al-Shatnawi, S. (2020). *A framework to evaluate smart homes* [Master's thesis, Eastern Mediterranean University, Gazimağusa, North Cyprus]. Institutional repository. http://hdl.handle.net/11129/5365

Ashour, A. F., & Rashdan, W. (2023). Smart technologies in interior design. *The International Journal of Designed Objects*, *18*(1), 39–59. https://doi.org/10.18848/2325-1379/cgp/v18i01/39-59

Barbosa, J. A. S. D., Araújo, C., Mateus, R., & Bragança, L. (2015). Smart interior design of buildings and its relationship to land use. *Architectural Engineering and Design Management*, *12*(2), 97–106. https://doi.org/10.1080/17452007.2015.1120187

Batov, E. I. (2015). The distinctive features of "Smart" buildings. *Procedia Engineering*, 111, 103–107. https://doi.org/10.1016/j.proeng.2015.07.061

Brown, A. (2023, August 29). *Small spaces, Part II: Japanese ideas for small and tiny homes.* All About Japan. Retrieved June 24, 2024, from https://allabout-japan.com/en/article/11165/

Canepa, S. (2017). Living in a flexible space. *IOP Conference Series: Materials Science and Engineering*, 245, 052006. https://doi.org/10.1088/1757-899x/245/5/052006

Christiansson, P. (2007). *ICT enhanced buildings potentials*. In *Bringing ITC knowledge to work - Proceedings of 24th CIB W78 conference, Maribor, Slovenia*, 27-29 June 2007. (pp. 373-378). https://itc.scix.net/data/works/att/w78-2007-056-156-Christiansson.pdf

Department of Census and Statistics of Sri Lanka. (2012). *Census of Population and Housing in Sri Lanka*. Department of Census and Statistics of Sri Lanka. http://www.statistics.gov.lk/PopHouSat/CPH2012Visualization/htdocs/index.php?usecase=indicator&action=Map&indId=10

Department of Census and Statistics (2022). *National Accounts of Sri Lanka*. Ministry of Finance, Economics Stabilization and National Policies.

GhaffarianHoseini, A., Ibrahim, R., Baharuddin, M. N., & Ghaffarianhoseini, A. (2011). Creating green culturally responsive intelligent buildings: Socio-cultural and environmental influences. *Intelligent Buildings International*, *3*(1), 5–23. https://doi.org/10.3763/inbi.2010.0002

Goessler, T., & Kaluarachchi, Y. (2023). Smart adaptive homes and their potential to improve space efficiency and personalisation. *Buildings*, *13*(5), 1132. https://doi.org/10.3390/buildings13051132

Hamid, A. B. A., & Embi, M. R. (2016). Review on application of building information modelling in interior design industry. *MATEC Web of Conferences, 66,* 00003. https://doi.org/10.1051/matecconf/20166600003

Hettiarachchi, T. W., & Dhanji, M. (2024). The challenges of sustainable affordable housing construction during the Sri Lankan economic crisis. *International Journal of Research and Innovation in Social Science*, *8*(2), 1868–1875. https://doi.org/10.47772/ijriss.2024.802131

Hewage, I. (2022, May 6). Acute shortage of housing, luxury apartments by next year?. *Daily News.* https://dailynews.lk/2022/05/06/business/278351/acute-shortage-housing-luxury-apartments-next-year

Husein, H. A. (2021). Multifunctional furniture as a smart solution for small spaces for the case of Zaniary Towers apartments in Erbil city. *International Transaction Journal of Engineering, Management, Applied Sciences and Technologies*, *12*(1). https://doi.org/10.14456/ITJEMAST.2021.8

Jahan, I., Hossain, S., & Aayaz, R. (2024). Optimizing small spaces: A comprehensive study on interior design challenges, perceptual experiences and innovative solutions. In *7th International Conference on Civil Engineering for Sustainable Development (ICCESD 2024), Khulna, Bangladesh*, 7 - 9 February 2024. Khulna University of Engineering & Technology. http://www.iccesd.com/proc_2024/Papers/702.pdf

Jia, M., Komeily, A., Wang, Y., & Srinivasan, R. S. (2019). Adopting internet of things for the development of smart buildings: A review of enabling technologies and applications. *Automation in Construction*, 101, 111–126. https://doi.org/10.1016/j.autcon.2019.01.023

Kahre, A., Roy, D., & Nanda, T. P. (2022). *Alternate construction technologies for mass housing: Challenges to adoption in India.* (Working paper no. 408). Indian Council for Research on International Economic Relations.

Kaluthanthri, P., & Jayawardhana, K. (2022). Exploring the complexities of millennial housing choices: An analysis of the influence of neighborhood factors. *Sri Lankan Journal of Real Estate*, *19*(02), 93–122. https://doi.org/10.31357/sljre.v19i02.6356

Lanka Property Web. (2021). *Properties for sale in Sri Lanka.* Lanka Property Web. Retrieved October 3, 2021, from https://www.lankapropertyweb.com/house_prices.php

Liu, J., & Chen, C. (2023). Research on the practice and future trend of interior design based on the background of smart home. In M. F. S. M. Don., P. T. Zabielskis, Xudong Liu, & Xiao Liu (Eds.) *Proceedings of the 2nd International Conference on Culture, Design and Social Development (CDSD 2022), Nanjing, China*, 2-4 December 2022. (pp. 10–17). https://doi.org/10.2991/978-2-38476-018-3_3

Liu, K., Nakata, K., & Harty, C. (2010). Pervasive informatics: theory, practice and future directions. *Intelligent Buildings International*, *2*(1), 5–19. https://doi.org/10.3763/inbi.2009.0041

Ma, Z., Jôrgensen, B. N., & Billanes, J. D. (2021). 3-Smart buildings and urban spaces. In J. R. Vacca (Ed.), *Solving urban infrastructure problems using smart city technologies,* (pp. 55–87). Elsevier. https://doi.org/10.1016/b978-0-12-816816-5.00003-6

Madushani, K. H. A., & Piyadasa, R. U. K. (2019). An empirical investigation on factors influencing to consumers' purchasing decision towards the luxury apartments in Colombo and suburbs, Sri Lanka. In *Proceedings of the 12th International Conference of Faculty of Architecture Research Unit (FARU), Colombo,* 3 December 2019. (pp.125-133). University of Moratuwa, Sri Lanka. http://dl.lib.uom.lk/handle/123/16576

Manewa, R. (2012). *Economic considerations for adaptability in buildings* [PhD dissertation, Loughborough University]. Loughborough Institutional Repository. https://core.ac.uk/download/pdf/288385028.pdf

Ni, X., Kong, Y., & Xie, L. (2023). Research on application of smart home in interior design. *Art And Performance Letters*, *4*(1). https://doi.org/10.23977/artpl.2023.040107

Omar, O. (2018). Intelligent building, definitions, factors and evaluation criteria of selection. *Alexandria Engineering Journal*, *57*(4), 2903–2910. https://doi.org/10.1016/j.aej.2018.07.004

Radha, R. K. (2022). Flexible smart home design: Case study to design future smart home prototypes. *Ain Shams Engineering Journal*, 13(1), 101513. https://doi.org/10.1016/j.asej.2021.05.027

Rahman, M. S. (2016). The advantages and disadvantages of using qualitative and quantitative approaches and methods in language "Testing and Assessment" research: A literature review. *Journal of Education and Learning*, *6*(1), 102. https://doi.org/10.5539/jel.v6n1p102

Rashdan, W. (2016). The impact of innovative smart design solutions on achieving sustainable interior design. In *Proceedings of 11th International Conference on Urban Regeneration and Sustainability Alicante, Spain,* 12 - 14, July 2016. https://doi.org/10.2495/sc160521

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students eBook* (8th ed.). Pearson Publications. Retrieved from https://elibrary.pearson.de/book/99.150005/9781292208794

Sima, L. (2015). A study on small apartment design in China: Evaluation on the impressions of and preferences for the floor plans. *Journal of Asian Architecture and Building Engineering*, *14*(2), 307–314. https://doi.org/10.3130/jaabe.14.307

Su, Y., Cai, J., Zhang, J., Qiu, X., & Jiang, D. (2023). Research on cost control of prefabricated concrete building design stage. *Journal of Physics: Conference Series*, *2519*(1), 012011. https://doi.org/10.1088/1742-6596/2519/1/012011

Taylor, J. (2022, March). *Space-smart furniture: trends, products and innovations.* INDESIGNLIVE : The Home of Architecture and Design in Asia-Pacific. Retrieved from https://www.indesignlive.com/singapore/segments

The Central Bank of Sri Lanka. (2020). *Annual Report 2020*. The Central Bank Annual Report 2020. https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/publications/annual_report/2020/en/15_Appendix.pdf

The Island. (2022, August 21). Apartment selling prices rise 45% alongside construction costs. *The Island*. https://island.lk/apartment-selling-prices-rise-45-alongside-construction-costs/

Thøgersen, K. (2017). *Small spaces need smart solutions : Designing furniture for small spaces in connection with human wellbeing.* Norwegian University of Science and Technology. Retrieved from https://www.scribd.com/document/440628228/Small-Spaces-Need-Smart-Solutions-Kristoffer-Th%C3%B8gersen

UN-Habitat. (2008). *UN-Habitat and the Kenya Slum Upgrading Programme - Strategy Document* Retrieved from https://unhabitat.org/un-habitat-and-the-kenya-slum-upgrading-programme-strategy-document

Wawira, N. G., Maina, S., & Munene, M. (2019). *Flexibility of interior spaces for low cost housing in Kenya : A case study of the Kibera Soweto East housing project in Nairobi, Kenya*. [Doctoral Dissertation, University of Nairobi] https://doi.org/10.13140/RG.2.2.22797.97760

Lu, Y., Karunasena, G. and Liu, C., 2024. Influence of behavioural constructs on building practitioner's minimal compliance with residential building energy performance standards in Australia. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 594-606. DOI: https://doi.org/10.31705/WCS.2024.47. Available from: https://ciobwcs.com/papers/

INFLUENCE OF BEHAVIOURAL CONSTRUCTS ON BUILDING PRACTITIONER'S MINIMAL COMPLIANCE WITH RESIDENTIAL BUILDING ENERGY PERFORMANCE STANDARDS IN AUSTRALIA

Yi Lu[1], Gayani Karunasena[2], and Chunlu Liu[3]

ABSTRACT

Energy performance standards for residential buildings are essential in promoting the residential building industry's energy efficiency. Dwellings are commonly designed at the standards' minimum compliance level, which puts the industry at risk of achieving its energy-efficiency goal. One of the causes of this minimal compliance is related to building practitioners' behavioural constructs during the compliance process: Attitudes (ATT), Subjective Norms (SN), Perceived Behavioural Control (PBC) and Personal Norms (PN). This paper aims to investigate how these behavioural constructs influence minimal compliance. The data are drawn from a questionnaire survey of 73 residential building practitioners who actively deal with compliance requirements in the design stage in Australia. A framework predominantly based on the Theory of Planned Behaviour was analysed via structural equation modelling technique to illustrate the influence paths of the behavioural constructs and the extent of the influence. The results show that SN, PBC and PN positively influence behavioural intention, then the intention positively influences minimal compliance outcome. Furthermore, ATT shows the strongest extent in influencing the minimal compliance outcome, while exhibiting the lowest current performance. These findings inform policymakers of suitable interventions to trigger behaviour change toward going beyond minimal compliance. By illustrating the pathways and the degree to which behavioural constructs influence minimal compliance, policymakers can be more effectively guided on appropriate interventions to encourage behaviour change that exceeds minimal compliance.

Keywords: *Building Practitioner; Compliance Behaviour; Energy Performance Standard; Minimal Compliance; Residential Building.*

[1] PhD candidate, School of Architecture and Built Environment, Deakin University, Geelong 3220, Australia, yi.lu@deakin.edu.au

[2] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Geelong 3220, Australia, gayani.karunasena@deakin.edu.au

[3] Professor, School of Architecture and Built Environment, Deakin University, Geelong 3220, Australia, chunlu.liu@deakin.edu.au

1. INTRODUCTION

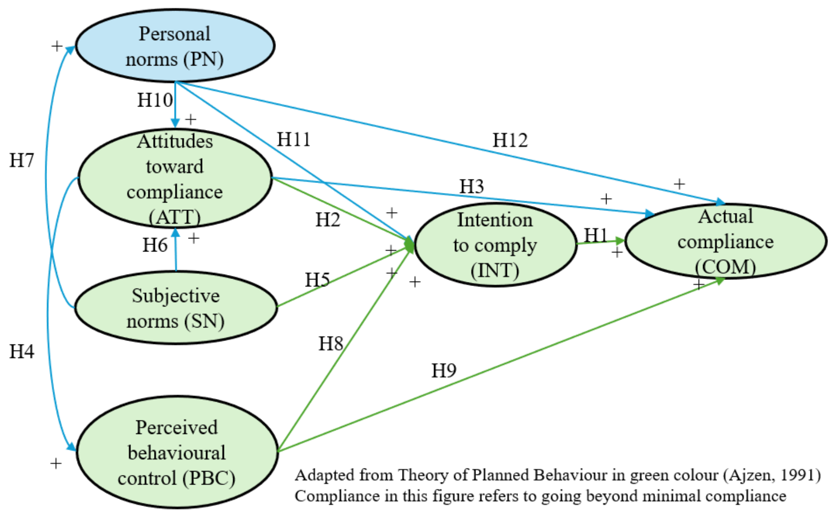
Increasing energy efficiency is a fast-track roadmap for carbon mitigation and improving residential buildings' energy performance to achieve a sustainable future. Amongst the existing regulatory instruments to promote building energy efficiency in the residential sector, the minimum building energy performance standards are recognised as an essential policy tool. However, minimal compliance in the design phase with the energy performance standards for residential buildings is commonly observed in many countries including Australia, the USA and South Korea (Shim et al., 2018; Moore et al., 2019; Lu et al., 2022). The outcome of minimal compliance is not enough for a net zero and sustainable residential building industry. Minimal compliance is defined as modest involvement with mandatory requirements. The behaviour of minimal compliance appears good in the letter of the law but does not solve the problems warranting the setting of the requirements (Chimboza, 2023). The issue of minimal compliance in the current context puts the residential building industry at risk of achieving its net zero and sustainability targets (Moore et al., 2019). Amongst other reasons, recent studies elucidate that this difficulty in going beyond minimal compliance is caused by building practitioners' various compliance behaviour constructs (attitudes toward going beyond minimal compliance, subjective norms, perceived behavioural control and personal norms).

Understanding minimal compliance is crucial for policymakers as wrongfully targeted interventions have the risk of reducing the impact of policy intervention and can concurrently generate extravagant costs. However, there is a scarcity of in-depth investigation of building practitioners' minimal compliance behaviour in the existing studies (Lu et al., 2024a). Therefore, this study aims to investigate how the behavioural constructs influence building practitioners' minimal compliance with building energy performance standards in the design stage where they encounter compliance requirements. By demonstrating the paths and extent of behavioural constructs in influencing minimal compliance, policymakers can be better informed of suitable interventions to trigger behaviour change toward going beyond minimal compliance.

2. LITERATURE REVIEW

In Australia, the Nationwide House Energy Rating Scheme (NatHERS) was established as a mechanism for assessing building energy performance. According to the simulation output of the house design, an energy star rating of the modelled heating and cooling loads is provided, ranging from zero (worst) to ten stars (best). The minimum building energy performance standard before changes to the National Construction Code (NCC) 2022 was to achieve a NatHERS six stars for new housing. Latest data shows that 79.76% of new Victorian (Australian) housing was designed only to achieve the minimum NatHERS 6-star standard, 7.24% went beyond seven stars and only 1.36% achieved an environmentally and economically optimal 7.5 stars ("States and territories", 2023). Studies underlined that residential buildings demonstrating minimal compliance with the energy performance standard "*often struggle to deliver occupant comfort despite relatively high energy consumption and capital costs, let alone achieving their intended efficiency goals*" (State of South Australia, 2014). Amongst the various causes of minimal compliance, building practitioners' discrete behavioural constructs demonstrated in the compliance process are non-neglectable (Lu et al., 2024b). However, previous studies did not demonstrate how each behavioural construct influences the building practitioner's compliance outcome, nor did they specify the extent of these constructs' influence on the compliance outcomes (Lu et al., 2024a). To pave the way toward the industry's efficiency goal, it is important to use robust compliance behaviour theories to fill this research gap.

The Theory of Planned Behaviour (TPB) was developed by Ajzen (1991). For two reasons, TPB is one of the most robust and widely accepted theories in explaining and predicting human behaviour (Hagger & Hamilton, 2024). Firstly, TPB is particularly useful in predicting compliance behaviour where individuals require both the motivations and capacities, skills or resources to perform the behaviour. Nevertheless, the majority of other compliance theories [e.g. (Nielsen & Parker, 2012)] only emphasise motivational factors but overlook the capacity to perform in correspondence to one's motivations (de Bruijn et al., 2023). Secondly, multiple studies have successfully applied TPB to understand and explain compliance behaviour relating to waste management or worker safety in the construction sector (Li et al., 2018; Liu et al., 2022). Despite the distinct advantages, several studies argued that there is a necessity to integrate personal normative factors into TPB to predict compliance behaviour (Cooper, 2017; Li et al., 2018). Accordingly, the authors (Lu et al., 2024a) developed a theoretical framework integrating TPB and the component of personal norms to underpin the current investigation (Refer to Figure 1).



Hypotheses developed:
H1: There is a positive relationship between a building practitioner's intention to go beyond minimal compliance and their actual compliance behavior.
H2: There is a positive relationship between a building practitioner's favourable attitudes toward going beyond minimal compliance and their intention to go beyond minimal compliance.
H3: There is a positive relationship between a building practitioner's favourable attitudes toward going beyond minimal compliance and their actual compliance behaviour.
H4: There is a positive relationship between a building practitioner's favourable attitudes toward going beyond minimal compliance and their perceived behavioural control.
H5: A building practitioner's subjective norms relate positively to their intention to go beyond minimal compliance.
H6: A building practitioner's subjective norms relate positively to their attitudes toward going beyond minimal compliance.
H7: A building practitioner's subjective norms relate positively to their personal norms.
H8: A building practitioner's perceived behavioral control has a positive effect on their intention to go beyond minimal compliance.
H9: A building practitioner's perceived behavioral control has a positive effect on their actual compliance behaviour.
H10: A building practitioner's personal norms relate positively to their attitudes toward going beyond minimal compliance.
H11: A building practitioner's personal norms relate positively to their intention to go beyond minimal compliance.
H12: A building practitioner's personal norms relate positively to their actual compliance behaviour.

Figure 1: Theoretical framework

The green part of Figure 1 is the original behavioural constructs and influence paths as per TPB. The blue part demonstrates the additional construct of personal norms and paths. Each hypothesis is explained briefly in the remainder of this paragraph. As for hypothesis H1, Zapata-Lancaster and Tweed (2014) and State of South Australia (2014) stated that building practitioners' intention to exceed minimal compliance leads to their design techniques to materialise a high-performing residential building. In terms of hypotheses H2-4, State of South Australia (2014) implied that building practitioners' unfavourable attitude toward going beyond minimal compliance with energy performance standards influences their reluctant behavioural intention. In particular, the building practitioner's perception of the increased costs of high-energy performance design could lead to a reluctance to exceed minimal compliance (Lemprière, 2016). In addition, building practitioners' perceived profits e.g. receiving competitive advantage can also enhance the intention of surpassing code minimum (Lee & Yik, 2004). Moreover, research showed that attitudes positively influence perceived behavioural control regarding households' adherence to waste prevention programs (Corsini et al., 2018). Additionally, Bagozzi et al. (1990) and Li et al. (2022) suggested that attitudes can positively impact behaviour itself in a direct manner. Regarding hypotheses H5-7, May (2004) concluded that the desire to gain a societal reputation was an important consideration in building practitioners' compliance intention. Additionally, Hurlimann et al. (2018) showed that social benefits including reputation and respect increased intention to exceed minimal compliance. Other than social reputation, subjective norm was demonstrated via building practitioners' perceived peer pressure from other building practitioners (Enker & Morrison, 2019) and clients' requests (Zapata-Lancaster & Tweed, 2014). Furthermore, subjective norms serve as antecedents to personal norms. As outlined by Liu et al. (2020), subjective norms help verify the social correctness of safety compliance behaviours among building practitioners, aiding in their assessment of whether their personal beliefs and norms are advantageous to them. Previous research (Li et al., 2011) has demonstrated that subjective norms exert a positive influence on attitudes. In terms of hypotheses H8 and H9, building practitioners' perceived capability was shown to influence their compliance intention. May (2004) found building practitioners' capability to comply essentially affected their motivation to comply. Similarly, Moore and Higgins (2016) suggested that insufficient expertise impeded building practitioners' willingness to move beyond the code minimum. Furthermore, these perceived constraints might influence actual compliance performance. The State of South Australia (2014) indicated that building practitioner's inadequate skills negatively impacted the achievement of going beyond minimal compliance. Shergold and Weir (2018) further argued that building practitioners' minimal compliance was due to their poor comprehension of standards. The last three hypotheses H10-12 relate to normative motivation deriving from internal moral alignment with the policy's substantive goals (Gibbs, 2012). Murtagh et al. (2016) showed that architects and designers with strong internalised alignment with energy conservation and low carbon vision were more likely to deploy more energy-efficient strategies to their designs. Moreover, Enker and Morrison (2019) found that building practitioners' agreement degree with energy performance assessment guidance embedded in the standards affected their intention to comply. As per the Norm Activation Theory (Schwartz, 1977), personal norms positively influence actual behaviour. Liu et al. (2020) highlighted how construction workers' personal norms positively affect their safety compliance behaviour. Li et al. (2018) discovered a positive relationship between personal norms and attitudes.

3. METHODOLOGY

3.1 QUESTIONNAIRE DESIGN

Based on the theoretical framework (refer to Figure 1), the questionnaire measured each behavioural construct. The design followed the recommendations of Ajzen (2002) and Francis et al. (2004) and included adapted items of personal norms from Li et al. (2018). The indicators were measured on a 5-point Likert Scale. 1 represents the lowest and 5 represents the highest. As summarised in Table 1, the measurement indicators were operationalised with relation to minimal compliance with the NatHERS, i.e. delivering a project at seven stars and higher.

Table 1: Measurement indicators of compliance behaviour constructs in the questionnaire

Construct	Indicator
Attitudes (ATT) [An evaluative predisposition towards compliant behaviour as a function of its determinant personal consequences]	ATT1: Perceived economic benefits ATT2: Perceived economic costs
Subjective norms (SN) [Perceived pressure or motivation from those significant referents]	SN1: Requests from clients SN2: Expectations from building industry colleagues and peers
Perceived behavioural control (PBC) [A person's "understanding of their capacity to achieve a compliant behaviour"]	PBC1: Self-efficacy in terms of confidence to go 7 stars and higher PBC2: Self-efficacy in terms of perceived easiness to go 7 stars and higher PBC3: Perceived controllability in going 7 stars and higher
Personal norms (PN) [Self-expectations based on people's internalized values, deriving either from internalized moral agreement with the policy objective or the policy content]	PN1: Moral agreement with environmental protection PN2: Moral agreement with carbon emissions reduction PN3: Agreement regarding whether going beyond 7 stars is correct PN4: Agreement regarding whether going beyond 7 stars can lead to emissions reduction PN5: Agreement regarding whether going beyond 7 stars can lead to energy consumption reduction
Intention to go beyond minimal compliance (INT) [The extent to which practitioners are willing to try, and the extent of efforts practitioners are planning to deploy for compliance]	INT: Willingness and efforts devoted to executing compliance
Actual compliance (COM) [The extent to which practitioners are willing to try, and the extent of efforts practitioners are planning to deploy for compliance.]	COM: Actual compliance outcome delivered since 2010

3.2 CONTEXT AND SAMPLE

The research was conducted in the State of Victoria in Australia. Increasing energy efficiency in the residential building industry has long been recognised as a key strategy amongst Australia's climate change mitigation policies. Since the energy performance standards prescribed in the NCC in Australia are amended with slight variations in different states and territories, the authors selected Victoria because all dwellings in Victoria are effectively approved via the NatHERS approach (Law, 2023), which ensures research findings' consistency. This study used cluster sampling. The research included building practitioners who are actively involved in the initial phase of the compliance process. Per the categories from the National Registration Framework (Australian Building Codes Board [ABCB], 2021), these building practitioners included architects, designers/draftspersons, builders, construction supervisors, and thermal performance assessors. Survey invitations to this survey were emailed between February and June 2023. A total of 73 respondents participated in the study (refer to Figure 2). Ensuing the 10-time rule (Hair et al., 2011), the minimum sample size should be larger than ten times the largest number of paths pointed at any construct in the structural model, which is 40 in this study. Thus, 73 samples sufficed for further analysis.

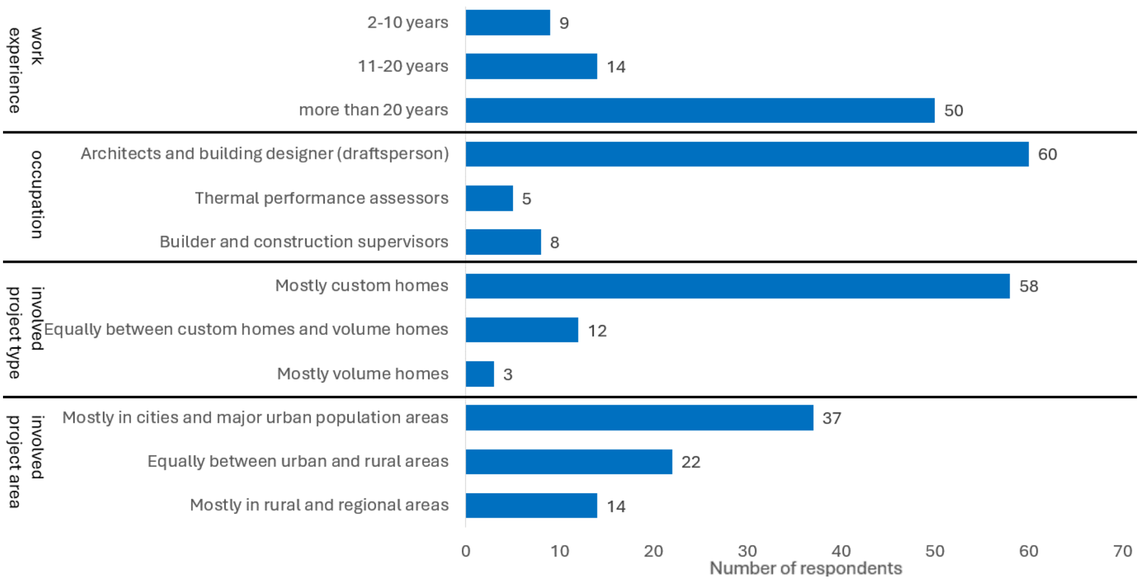


Figure 2: Profile of the 73 building practitioners

3.3 DATA ANALYSIS

The collected data was analysed using the Structural Equation Modelling (SEM) method in SmartPLS 4.0. SEM has two types: Partial least squares SEM (PLS-SEM) and covariance-based SEM (CB-SEM). The study adopted PLS-SEM. First, PLS-SEM is appropriate for small sample sizes. The study sample (n=73) was small, which was deemed unsuitable for the CB-SEM method requiring over 200 cases. Thus, PLS-SEM was considered appropriate. Second, this study intended to test the theoretical framework from a prediction perspective, and the PLS-SEM approach has advantages in exploratory research and is prediction-oriented. Analysis of the SEM modelling results comprises several steps (Hair et al., 2021), as illustrated in Table 2.

Table 2: Analysis steps pertaining to the PLS-SEM modelling technique

Steps	Sub-steps	Analysis technique
1. Evaluation of the modelling results	1a. Evaluating quality of measurement model, i.e. the relationship between constructs and indicators	Factor analysis through reliability and validity tests via computing: Factor loading: >0.7 Composite reliability: >0.7 Average variance extracted (AVE): >0.5 Heterotrait-monotrait (HTMT) ratio: <0.85
	1b. Evaluating the quality of the structural model i.e. the relationship between constructs	Ensuring no collinearity issue exists via computing VIF: <5 Evaluating the theoretical and predictive power of the model via computing: Interpretable variance of endogenous constructs (R^2): >0.1 (if >0.2, indicating high predictive power, especially in behavioural studies) Stone-Geisser's (Q^2): >0 (suggesting the predictive relevance of the structural model)
2. Interpretation of the modelling results	2a. Influence paths (Section 4.1)	Path analysis via computing: path coefficient (β) *p*-value: <0.1
	2b. Extent of influence (Section 4.2)	Importance-performance map

As Table 2 shows, the analysis mainly involves two steps. Step 1 was related to the evaluation of the quality of the modelling results. The detailed parameters for indicating sufficient quality are demonstrated in the third column. After ensuring the quality in step 1, the authors proceeded with the step 2. In sub-step 2a, path analysis was used to illustrate the degree and significance of the relationships between constructs, via computing path coefficient (β) and p-value. Generally, when the p-value is lower than 0.05, the path coefficient is statistically significant. However, as Dahiru (2008) noted, the threshold value of p-value at 0.05 is merely a convention in hypothesis testing. Researchers can make the significant test less stringent moving the p-value borderline to 0.1, as is seen in recent studies (Bag & Gupta, 2017; Tian et al., 2021; Sopha et al., 2024). Hence, the current research placed 0.1 as the p-value threshold. In sub-step 2b, to explore the extent of behavioural constructs and indicators' influences on actual compliance outcome, and identify which construct needs to be targeted more urgently to improve compliance outcome, the analysis of th eimportance-performance map was also conducted.

4. INFLUENCE PATH AND EXTENT OF BEHAVIOURAL CONSTRUCTS

Following the analysis steps in Table 2, the quality of the modelling results was evaluated. The factor loadings of most indicators were bigger than the threshold value of 0.7, ensuring the reliability of indicators. There were only two exceptions. The factor loading of the indicator PBC3 was 0.578, which was below the threshold of 0.7. According to Francis et al. (2004), the variable of perceived behavioural control must include two dimensions i.e. (i) controllability (PBC3), and (ii) self-efficacy (PBC1 and PBC2).

Therefore, the authors chose to accept PBC 3 despite its low loading index. A similar approach was used by Nielsen and Parker (2012). Another indicator PN5 had a factor loading of 0.699, which was below the cutoff of 0.7. Hair et al. (2019) argued that in exploratory research, a coefficient greater than 0.6 was also deemed acceptable. Hence, this indicator was deemed reliable and was kept. The other parameters (composite reliability, AVE, HTMT ratio, R^2 and Q^2) all met the required threshold. Since the model quality is confirmed, the next section reports the main results.

4.1 INFLUENCE PATHS

Table 3 reports the influence paths of the behavioural constructs.

Table 3: Results of the hypotheses test

Hypothesis of influence path	Path coefficient (β)	*P*-value	Interpretation
H1: INT -> COM	0.133	0.077	Supported
H2: ATT -> INT	-0.045	0.307	**Not supported**
H3: ATT -> COM	0.333	0.003	Supported
H4: ATT -> PBC	0.254	0.047	Supported
H5: SN -> INT	0.187	0.085	Supported
H6: SN -> ATT	0.300	0.007	Supported
H7: SN -> PN	0.503	0.000	Supported
H8: PBC -> INT	0.235	0.033	Supported
H9: PBC -> COM	0.191	0.050	Supported
H10: PN -> ATT	0.346	0.001	Supported
H11: PN -> INT	0.408	0.006	Supported
H12: PN -> COM	0.120	0.124	**Not supported**

As Table 3 shows, the influence path between attitudes and actual compliance outcome was supported, while the path between attitudes and intention was not supported. This finding suggests that, when building practitioners have favourable attitudes toward going higher energy stars than the minimum six stars, they are more likely to directly deliver beyond minimal compliance projects. It further implies that their level of effort to deliver higher energy star houses is low. In addition, the results supported the influence path between personal norms and intention. However, the path between personal norms and actual compliance was not supported. Rather, personal norms indirectly influence actual compliance either through intention or attitudes. This finding implied that building practitioners who have high agreement with NatHERS guidance or moral obligation with industry net zero vision, will not necessarily deliver the houses exceeding minimum requirements. Furthermore, the influence path between attitudes and perceived behavioural control was supported, meaning that building practitioners with favourable attitudes generally perceive going beyond compliance as easy.

While the direct influence path between attitudes and compliance outcome findings appears contrasting to the original TPB which posits that attitude only indirectly influences behaviour through intention, it is consistent with several empirical studies. For instance, in a study examining the attitude-behaviour relationship about recycling, Schultz and Oskamp (1996) found attitudes' direct influence on recycling behaviour.

Earlier studies supported these findings (Bagozzi & Yi, 1989; Bagozzi et al., 1990). According to these studies, when a behaviour needs a high level of effort, then the mediating effect of intention will be high, hence no direct relationship between attitude and actual behaviour can be found. In contrast, if the level of effort needed to execute the behaviour is little, the mediating role of intention will be weak, and attitude can predict the behaviour directly. In the current study, most of the responding building practitioners are those who work on custom homes. They do not need to rely on standardised designs and thus are more likely to deliver innovative energy-efficient designs. In other words, the level of effort needed for these building practitioners to go beyond minimal compliance is relatively low. Therefore, their attitudes directly influence the compliance outcome. Furthermore, the positive and significant influence of subjective norms on attitudes is also confirmed. This influence path is not present in the original TPB as well. However, this additional relationship was also supported by Courneya and McAuley (1995) who found that the more one feels that important others think one should carry out the behaviour, the more favourable one's attitude toward executing the behaviour should be.

4.2 EXTENT OF INFLUENCE

The extent of influence of each behavioural construct and indicator on minimal compliance was explored, and their current performance was identified (refer to Figure 3).

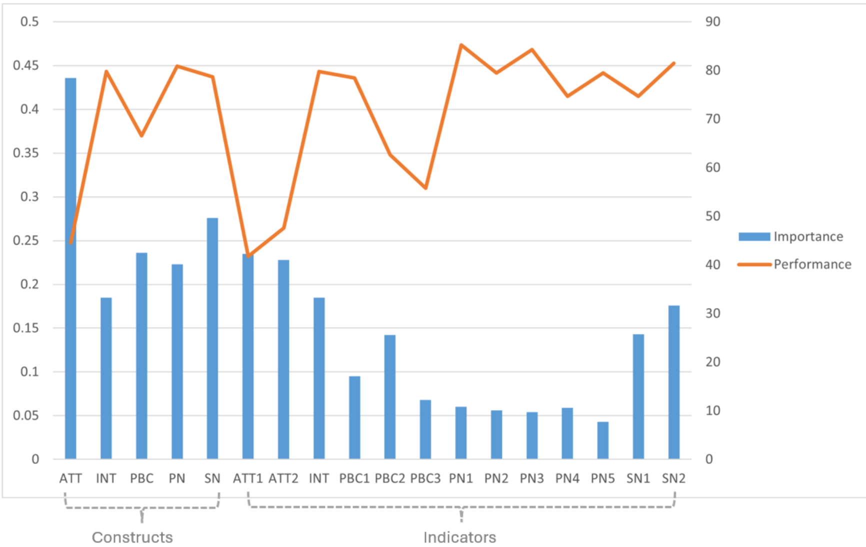


Figure 3: Importance-performance map of the behavioural constructs and indicators

As Figure 3 displays, in explaining minimal compliance, building practitioner's attitude has the largest influence, followed by subjective norm, perceived behavioural control, personal norm and intention. However, the performance of ATT is the lowest. Further, as indicated by the bottom part of Figure 3, indicators ATT1 and ATT2 have the highest influence on minimal compliance. It implies reducing compliance costs or increasing profits are strong motivating strategies to enhance attitudes, and can thus further encourage more people to go beyond minimal compliance. Victorian authorities can thus introduce more financial incentives such as the 7 Stars Home Rebate provided by ABCB (2021) to building practitioners who design houses at higher compliance levels, thus lowering building practitioners' perceived costs and generating more favourable attitudes toward going beyond minimal compliance. Further, the low value of indicators PBC1-3 indicates that targeting perceived behavioural control (e.g., training to increase building practitioner's knowledge regarding energy-efficient design techniques) may not be a very effective intervention strategy as people thought.

As highlighted, the study suggests that the most effective path to improve energy compliance was to increase attitude. Gunningham's notion of economic license supported this recommendation (Gunningham et al., 2003). As similarly highlighted in research conducted in the UK, Singapore, and Indonesia (Sun et al., 2015; Shan et al., 2020; Fitriani & Ajayi, 2023), enhanced governmental incentives, such as subsidies to mitigate the added costs of developing projects beyond a 7-star rating, are pivotal for motivating building practitioners to adopt more energy-efficient practices.

5. CONCLUSIONS AND THE WAY FORWARD

This study provides an in-depth investigation regarding building practitioners' behaviour in going beyond minimal compliance with residential building energy performance standards in the Australian context. The study results support the positive and significant influence paths between SN, PBC, PN and INT, INT and COM, as well as ATT and COM. The study reveals that, amongst the performance of all building practitioners' behavioural constructs, attitude toward going beyond minimal compliance is the lowest. Nevertheless, attitude influences minimal compliance to the largest extent than any other construct. The contributions of this study are two-fold. Theoretically, it contributes to the existing literature on the role of social and psychological factors regarding behaviour going beyond minimal compliance. The theoretical framework extends the original TPB and enriches the understanding of minimal compliance behaviour. Practically, the study implies the prioritised urgency and effectiveness in targeting attitudes for promoting compliance level, thus providing guidance to building authorities in promoting a high-performing residential building industry.

There are limitations. While the use of PLS-SEM has increased over decades for effectively exploring complex relationships among variables and predicting outcomes, it has several limitations such as biased parameter estimates and the lack of measurement error estimation (Lee et al., 2021). These limitations could potentially affect the robustness of the findings if hypothesis testing and parameter estimation precision are critical. Nevertheless, the researcher has calculated model fit indices and criteria. The results ensure the validity of the developed PLS-SEM model. Furthermore, compared to CB-SEM, PLS-SEM achieves greater statistical power at all sample sizes, but particularly smaller sample sizes as in the current study (Hair Jr et al., 2017). Hence, PLS-SEM was deemed the most suitable method for this research, providing a robust framework for analysing complex relationships within the data while accommodating the study's sample size feature.

Having identified the influence paths and extent of the behavioural constructs affecting minimal compliance, this study lays a foundation to examine external policy interventions' effectiveness in triggering behaviour change. As an ongoing research, the authors are in the process of extending this study's findings to assess the amount of behaviour change under different policy scenarios.

6. REFERENCES

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

Ajzen, I. (2002). *Constructing a TpB questionnaire: Conceptual and methodological considerations.* https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=0574b20bd58130dd5a961f1a2db10fd1fcbae95d

Australian Building Codes Board (ABCB). (2021). *National registration framework for building practitioners-model guidance on BCR recommendations*. https://www.abcb.gov.au/sites/default/files/resources/2022/BCR-rec1-2-National-registration-framework.pdf

Bag, S., & Gupta, S. (2017). Antecedents of sustainable innovation in supplier networks: A South African experience. *Global Journal of Flexible Systems Management*, *18*, 231-250. https://doi.org/10.1007/s40171-017-0158-4

Bagozzi, R. P., & Yi, Y. (1989). The degree of intention formation as a moderator of the attitude-behavior relationship. *Social Psychology Quarterly*, 266-279. https://doi.org/10.2307/2786991

Bagozzi, R. P., Yi, Y., & Baumgartner, J. (1990). The level of effort required for behaviour as a moderator of the attitude-behaviour relation. *European Journal of Social Psychology*, *20*(1), 45-59. https://doi.org/10.1002/ejsp.2420200105

Chimboza, T. M. (2023). *ICT organisations' minimal compliance with affirmative actions regulations: Case of the Broad-Based Black Economic Empowerment (B-BBEE) ICT sector code in South Africa* [Doctoral dissertation, University of Cape Town]. http://hdl.handle.net/11427/38466

Cooper, B. (2017). What drives compliance? An application of the theory of planned behaviour to urban water restrictions using structural equation modelling. *Applied Economics*, *49*(14), 1426-1439. https://doi.org/10.1080/00036846.2016.1218430

Corsini, F., Gusmerotti, N. M., Testa, F., & Iraldo, F. (2018). Exploring waste prevention behaviour through empirical research. *Waste Management*, *79*, 132-141. https://doi.org/10.1016/j.wasman.2018.07.037

Courneya, K. S., & McAuley, E. (1995). Cognitive mediators of the social influence-exercise adherence relationship: A test of the theory of planned behavior. *Journal of Behavioral Medicine*, *18*, 499-515. https://doi.org/10.1007/BF01904776

Dahiru, T. (2008). P-value, A true test of statistical significance? A cautionary note. *Annals of Ibadan Postgraduate Medicine*, *6*(1), 21-26. https://doi.org/10.4314/aipm.v6i1.64038

de Bruijn, A. L., Feldman, Y., Reinders Folmer, C. P., Kuiper, M. E., Brownlee, M., Kooistra, E., Olthuis, E., Fine, A., & Van Rooij, B. (2023). Cross-theoretical compliance: An integrative compliance analysis of COVID-19 mitigation responses in Israel. *Administration & Society*, *55*(4), 635-670. https://doi.org/10.1177/00953997221140899

Enker, R. A., & Morrison, G. M. (2019). Behavioral facilitation of a transition to energy efficient and low-carbon residential buildings. *Buildings*, *9*(11), 226. https://doi.org/10.3390/buildings9110226

Fitriani, H., & Ajayi, S. (2023). Barriers to sustainable practices in the Indonesian construction industry. *Journal of Environmental Planning and Management*, *66*(10), 2028-2050. https://doi.org/10.1080/09640568.2022.2057281

Francis, J., Eccles, M. P., Johnston, M., Walker, A., Grimshaw, J. M., Foy, R., Kaner, E. F., Smith, L., & Bonetti, D. (2004). *Constructing questionnaires based on the theory of planned behaviour: A manual for health services researchers*. Centre for Health Services Research, University of Newcastle. https://openaccess.city.ac.uk/id/eprint/1735/1/TPB%20Manual%20FINAL%20May2004.pdf

Gibbs, C. (2012). Corporate citizenship and corporate environmental performance. *Crime, Law and Social Change*, *57*, 345-372. https://doi.org/10.1007/s10611-012-9365-2

Gunningham, N., Kagan, R. A., & Thornton, D. (2003). *Shades of green: Business, regulation, and environment*. Stanford University Press. https://www.sup.org/books/title/?id=5879

Hagger, M. S., & Hamilton, K. (2024). Longitudinal tests of the theory of planned behaviour: A meta-analysis. *European Review of Social Psychology*, *35*(1), 198-254. https://doi.org/10.1080/10463283.2023.2225897

Hair, J. F., Ringle, C. M., & Sarstedt, M. (2011). PLS-SEM: Indeed a silver bullet. *Journal of Marketing Theory and Practice*, *19*(2), 139-152. https://doi.org/10.2753/MTP1069-6679190202

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. *European Business Review*, *31*(1), 2-24. https://doi.org/10.1108/EBR-11-2018-0203

Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2021). *A primer on partial least squares structural equation modeling (PLS-SEM)*. Sage publications. https://www.researchgate.net/publication/354331182_A_Primer_on_Partial_Least_Squares_Structural_Equation_Modeling_PLS-SEM

Hair Jr, J. F., Matthews, L. M., Matthews, R. L., & Sarstedt, M. (2017). PLS-SEM or CB-SEM: Updated guidelines on which method to use. *International Journal of Multivariate Data Analysis*, *1*(2), 107-123. https://doi.org/10.1504/IJMDA.2017.087624

Hurlimann, A. C., Browne, G. R., Warren-Myers, G., & Francis, V. (2018). Barriers to climate change adaptation in the Australian construction industry–Impetus for regulatory reform. *Building and Environment*, *137*, 235-245. https://doi.org/10.1016/j.buildenv.2018.04.015

Law, T. (2023). An increasing resistance to increasing resistivity. *Architectural Science Review*, *66*(2), 108-121. https://doi.org/10.1080/00038628.2021.1916428

Lee, C. C., Ting, L. J., Yeh, W. C., & Yu, Z. (2021). The influence of the technical dimension, functional dimension, and tenant satisfaction on tenant loyalty: An analysis based on the theory of planned behavior. *International Journal of Strategic Property Management*, *25*(6), 469–484. https://doi.org/10.3846/ijspm.2021.15566

Lee, W. L., & Yik, F. W. H. (2004). Regulatory and voluntary approaches for enhancing building energy efficiency. *Progress in Energy and Combustion Science*, *30*(5), 477-499. https://doi.org/10.1016/j.pecs.2004.03.002

Lemprière, M. (2016). Using ecological modernisation theory to account for the evolution of the zero-carbon homes agenda in England. *Environmental Politics*, *25*(4), 690-708. https://doi.org/10.1080/09644016.2016.1156107

Li, J., Wang, Y., & Liu, C. (2022). Spatial effect of market sentiment on housing price: Evidence from social media data in China. *International Journal of Strategic Property Management*, *26*(1), 72-85. https://doi.org/10.3846/ijspm.2022.16255

Li, J., Zuo, J., Cai, H., & Zillante, G. (2018). Construction waste reduction behavior of contractor employees: An extended theory of planned behavior model approach. *Journal of Cleaner Production*, *172*, 1399-1408. https://doi.org/10.1016/j.jclepro.2017.10.138

Li, N. W., Ma, Y., & Niu, L.-X. (2011). Research on miners' deliberate violation behavior intentions based on theory of planned behavior. *Zhongguo Anquan Kexue Xuebao*, *21*(10), 3-9.

Liu, J., Wang, Y., & Wang, Z. (2022). Effect of pressure on construction company compliance attitudes: Moderating role of organizational ethical climate. *Journal of Construction Engineering and Management*, *148*(11). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002400

Liu, Q., Xu, N., Jiang, H., Wang, S., Wang, W., & Wang, J. (2020). Psychological driving mechanism of safety citizenship behaviors of construction workers: Application of the theory of planned behavior and norm activation model. *Journal of Construction Engineering and Management*, *146*(4). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001793

Lu, Y., Karunasena, G., & Liu, C. (2022). A systematic literature review of non-compliance with low-carbon building regulations. *Energies*, *15*(24), 9266. https://doi.org/10.3390/en15249266

Lu, Y., Karunasena, G., & Liu, C. (2024a). Conceptual cross-theoretical assessment model for practitioners' compliance behavior with building energy codes. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *16*(1), 04523039. https://doi.org/doi:10.1061/JLADAH.LADR-1019

Lu, Y., Karunasena, G., & Liu, C. (2024b). Preliminary study on building practitioners' compliance behaviour with 7-star house energy ratings in Australia: Perceptions of industry experts. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-09-2023-0279

May, P. J. (2004). Compliance motivations: Affirmative and negative bases. *Law & Society Review*, *38*(1), 41-68. https://doi.org/10.1111/j.0023-9216.2004.03801002.x

Moore, T., Berry, S., & Ambrose, M. (2019). Aiming for mediocrity: The case of Australian housing thermal performance. *Energy Policy*, *132*, 602-610. https://doi.org/10.1016/j.enpol.2019.06.017

Moore, T., & Higgins, D. (2016). Influencing urban development through government demonstration projects. *Cities*, *56*, 9-15. https://doi.org/10.1016/j.cities.2016.02.010

Murtagh, N., Roberts, A., & Hind, R. (2016). The relationship between motivations of architectural designers and environmentally sustainable construction design. *Construction Management and Economics*, *34*(1), 61-75. https://doi.org/10.1080/01446193.2016.1178392

Nielsen, V. L., & Parker, C. (2012). Mixed motives: Economic, social, and normative motivations in business compliance. *Law & Policy*, *34*(4), 428-462. https://doi.org/10.1111/j.1467-9930.2012.00369.x

Schultz, P. W., & Oskamp, S. (1996). Effort as a moderator of the attitude-behavior relationship: General environmental concern and recycling. *Social Psychology Quarterly*, 375-383. https://doi.org/10.2307/2787078

Schwartz, S. H. (1977). Normative influences on altruism. *Advances in Experimental Social Psychology*, *10*, 221-279. https://doi.org/10.1016/S0065-2601(08)60358-5

Shan, M., Liu, W. Q., Hwang, B. G., & Lye, J. M. (2020). Critical success factors for small contractors to conduct green building construction projects in Singapore: Identification and comparison with large contractors. *Environmental Science and Pollution Research*, *27*, 8310-8322. https://doi.org/10.1007/s11356-019-06646-1

Shergold, P., & Weir, B. (2018). *Building Confidence: Improving the effectiveness of compliance and enforcement systems for the building and construction industry across Australia*. Commonwealth of Australia. https://www.industry.gov.au/sites/default/files/July%202018/document/pdf/building_ministers_forum_expert_assessment_-_building_confidence.pdf

Shim, J., Song, D., & Kim, J. (2018). The economic feasibility of passive houses in Korea. *Sustainability*, *10*(10), 3558. https://doi.org/10.3390/su10103558

Sopha, B. M., Asih, A. M. S., & Agriawan, J. I. (2024). Adopters and non-adopters of drones in humanitarian operations: An empirical evidence from a developing country. *Progress in Disaster Science*, *21*, 100314. https://doi.org/10.1016/j.pdisas.2024.100314

State of South Australia (2014). *National energy efficient building project*. https://www.energymining.sa.gov.au/__data/assets/pdf_file/0009/658494/NEEBP-final-report-November-2014.pdf

States and territories (2023). CSIRO. https://ahd.csiro.au/dashboards/energy-rating/states/

Sun, M., Geelhoed, E., Caleb-Solly, P., & Morrell, A. (2015). Knowledge and attitudes of small builders toward sustainable homes in the UK. *Journal of Green Building*, *10*(2), 215-233. https://doi.org/10.3992/jgb.10.2.215

Tian, H., Iqbal, S., Anwar, F., Akhtar, S., Khan, M. A. S., & Wang, W. (2021). Network embeddedness and innovation performance: A mediation moderation analysis using PLS-SEM. *Business Process Management Journal*, *27*(5), 1590-1609. https://doi.org/10.1108/BPMJ-08-2020-0377

Zapata-Lancaster, G., & Tweed, C. (2014). Designers′ enactment of the policy intentions. An ethnographic study of the adoption of energy regulations in England and Wales. *Energy Policy*, *72*, 129-139. https://doi.org/10.1016/j.enpol.2014.04.033

Gurusinghe, H.R., Gallage, S.D. and Dalugoda, T.P., 2024. Influence of BOI approvals on cost and time aspect of apartment construction in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 607-618. DOI: https://doi.org/10.31705/WCS.2024.48. Available from: https://ciobwcs.com/papers/

INFLUENCE OF BOI APPROVALS ON COST AND TIME ASPECT OF APARTMENT CONSTRUCTION IN SRI LANKA

H.R. Gurusinghe[1], S.D. Gallage[2], and T.P. Dalugoda[3]

ABSTRACT

This study investigates the influence of the Board of Investment (BOI) approval process on the cost and time aspects of apartment construction projects in Sri Lanka. The research aims to identify the specific challenges and factors associated with BOI approvals that impact project timelines and budgets. Utilising semi-structured interviews and a questionnaire survey, the study gathers insights from industry experts and practitioners, revealing that the BOI approval process varies with project types and involves diverse requirements such as UDA, SLTDA, and environmental approvals. Despite recent BOI initiatives to expedite approvals, delays persist, often leading to the expiration of BOI concessions and subsequent cost increases. A comprehensive framework was developed to summarise these findings, highlighting the critical cost and time-related factors at different project stages. The implications for industry practitioners include better preparation for BOI-related challenges, while academia and policymakers can use these insights to enhance understanding and refine regulatory processes. Limitations include a limited sample size and a focus on qualitative data. Future research could expand the scope and incorporate quantitative methods to validate and extend these findings.

Keywords: *Apartment Projects; Board of Investment (BOI); Construction Delays; Cost Overruns; Foreign Direct Investment (FDI).*

1. INTRODUCTION

Urbanisation has significantly impacted land availability, particularly in urban areas, leading to a growing scarcity of developable land (Gallage et al., 2022). This scarcity has driven increased interest among developers and investors in apartment projects, which offer a viable solution to the limited land resources. Apartment constructions not only optimise land use yet meet the rising demand for housing in densely populated cities (Mensah, 2014). The Board of Investment (BOI) in Sri Lanka plays a crucial role in facilitating these projects by providing various concessions, including tax reductions, to attract both local and foreign investments (Board of Investment of Sri Lanka, 2024). These incentives make apartment projects more appealing compared to other types of construction projects, as they help lower overall costs and enhance profitability (Jayasekara, 2014).

[1] Quantity Surveyor, ALEC Engineering, Abu Dhabi Emirate, UAE, himashrashmika1996@gmail.com
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sasankag@uom.lk
[3] Student, Department of Building Economics, University of Moratuwa, Sri Lanka, dalugoda.19@uom.lk

However, despite the benefits, the BOI approval process is often associated with high levels of bureaucracy. This can lead to delays in construction, as the process involves extensive documentation and approval stages, such as investment and engineering approvals, CUSDEC documentation, and more (Board of Investment of Sri Lanka, 2024). While these procedures are meant to ensure compliance and quality, they can also pose significant challenges, particularly in terms of time and cost overruns (Siraj & Fayek, 2019).

Notably, there is a gap in existing research regarding the specific impacts of the BOI's bureaucratic procedures on construction projects. While previous studies have highlighted the challenges posed by political aspects, inflation, and a lack of new technologies on foreign direct investment (Botric & Skuflic, 2006; Eryigit & Shafaq, 2021), none have specifically focused on the BOI's procedural effects on construction timelines and costs. This study aims to fill this gap by investigating the influence of BOI approvals on the cost and time aspects of apartment construction in Sri Lanka. By identifying the challenges posed by the BOI process, the research seeks to develop a framework to identify benefits offered to the investors and reveal the challenges associated with the BOI's bureaucratic procedures.

2. LITERATURE REVIEW

2.1 BOARD OF INVESTMENT, SRI LANKA

The construction industry is one of the major industries that refers to all types of activities connected to assembling and renovating immobile structures and facilities (Nam & Tatum, 1997). According to Ibrahim et al. (2010), the construction industry plays a massive role in converting the needs of people into physical projects by transforming their objectives into reality. Three major trends can be identified with the recent developments in the construction industry of the Asian region, namely, increment of vertical integration in the packaging of construction projects, larger private sector involvement in the infrastructure projects and increase of foreign participation in local constructions (Raftery et al., 1998). One of the strategies that developing countries can follow to boost the economic growth of the country is to attract foreign direct investment to the country (Mondal, 2003).

BOI of Sri Lanka is the department that gives supplementary help not only to foreign investors but also to local investors who contribute towards the economy of the country in a number of ways. BOI provides TAX and non-TAX incentives to local and foreign investors to motivate them to invest in the relevant industries (LawPlus Ltd, 2021). The Board of Investment of Sri Lanka is one of the leading investment promotion agencies in Asia since its primary function is to do investment Promotion (Board of Investment of Sri Lanka, 2024). The Sri Lankan government is keen on offering a favourable investment environment by allowing employers to import materials and machinery for a duty-free mechanism, fast-track the BOI approval process for the investors, and further offering tax concessions (Board of Investment of Sri Lanka, 2024).

2.2 CHALLENGES FOR APARTMENT CONSTRUCTION PROJECTS IN SRI LANKA

Apartments are units of multi-owned properties where different individuals own various units, sharing common areas such as pools, lifts, and gyms (Anthonisz & Perry, 2015). In

Sri Lanka, the Urban Development Authority (2001) projected that an additional 800,000 homes will be needed in the next 40-50 years, on top of the existing one million homes. However, apartment construction presents more challenges compared to other building types (Gavit et al., 2015). The complexity of the apartment construction process is fraught with significant uncertainties (Lee et al., 2012). According to Iqbal et al. (2015), these issues can arise due to funding problems, regulatory changes, weather conditions, payment delays, construction-related accidents, and design defects. Most apartment projects in Sri Lanka face time overruns and exceed expected budgets. Fraser and Silva (2016) noted that factors such as required design changes by the consultant or client, adverse weather conditions, accidents, and material price fluctuations contribute to these time and cost overruns.

Additionally, due to its unique nature, construction hazards pose significant challenges to the apartment construction industry. Given that apartment construction projects in Sri Lanka take several years to complete, one major uncertainty is the risk of exchange rate fluctuations, where the value of Sri Lanka's currency changes relative to other countries or economic zones (Board of Investment of Sri Lanka, 2024). Musarat et al. (2020) identified various factors affecting material cost deviations, including supply and demand, raw material costs, labour costs, import duties, and exchange rates. Furthermore, the procurement of construction projects faces global challenges (Ayopo et al., 2019), which are particularly relevant for apartment construction in Sri Lanka.

3. METHODOLOGY

The primary purpose of this research is to assess the impact of BOI approvals on the cost and timeline of apartment construction projects in Sri Lanka. A mixed-methods approach was chosen to achieve this, combining qualitative and quantitative research techniques. This approach is advantageous because it leverages the strengths of both qualitative and quantitative methods, compensating for their individual limitations (Creswell & Clark, 2018).

The research design incorporated semi-structured interviews and a questionnaire survey. Semi-structured interviews were selected due to their flexibility and ability to elicit detailed insights into complex processes, such as the BOI approval's effects on construction projects (Bryman, 2016). These interviews provided a platform for participants to discuss incentives, challenges, and strategies related to BOI incentives in detail. The questionnaire survey complemented the qualitative data by allowing for the collection of quantitative data from a larger sample, thus enhancing the generalisability of the findings (Kumar, 2014).

For data analysis, the study employed manual content analysis for the qualitative data obtained from the interviews. Content analysis is an effective method for systematically examining communication content, allowing for extracting meaningful patterns and themes from the text (Elo & Kyngäs, 2008; Neuendorf, 2017). This technique helped identify key issues and challenges associated with BOI procedures, as reported by participants.

The quantitative data from the questionnaire survey were analysed using the Relative Importance Index (RII) method. RII is useful for ranking the significance of various factors and systematically prioritising issues based on their perceived impact on project cost and time. Respondents rated these factors, enabling the research to quantify their relative importance and focus on the most critical areas affecting project outcomes.

By integrating qualitative insights with quantitative data, this mixed-method approach provides a comprehensive understanding of the BOI approval process's influence on apartment construction projects in Sri Lanka, helping to identify key challenges and potential solutions.

4. FINDINGS AND ANALYSIS

4.1 INTERVIEW FINDINGS

The purpose of conducting semi-structured interviews in this research was to address a gap in the literature, which generally lacks specific insights into construction-related issues associated with the BOI approval process. While the literature review highlighted general challenges, it did not delve into the practical issues stakeholders face in apartment construction projects. Many professionals are involved in these projects, but most have limited experience. Since not all projects receive BOI concessions, professionals with over ten years of experience handling BOI-approved projects are scarce. Therefore, the interviews were specifically conducted with Quantity Surveyors and BOI officers with at least a decade of experience with BOI projects. Quantity Surveyors were chosen for their extensive involvement in the documentation related to BOI procedures, while BOI officers provided insights into the overall approval process. This targeted approach ensured that the research captured nuanced, expert perspectives on the challenges and incentives associated with the BOI approval process, thus informing the subsequent phases of data collection and analysis. Table 1 below provides a summary of the interviewees.

Table 1: Details of respondents

Interviewee	Designation	Type of Organization	Experience Related to Construction	Experience Related to BOI Projects
R1	Ch. QS	Contractor	29 years	12 years
R2	Ch. QS	Consultant	10 years	10 years
R3	Ch.QS	Contractor	14 years	10 years
R4	QS	Contractor	19 years	12 years
R5	Ch.QS	Contractor	33 years	13 years
R6	BOI Officer	BOI	14 years	24 years
R7	BOI Officer	BOI	11 years	21 years

4.2 BOI APPROVAL PROCESS AND MATERIAL IMPORTATION PROCEDURES FOR CONSTRUCTION PROJECTS

The interview findings revealed that obtaining BOI approval for construction projects involves specific applications, such as the Investment and Site applications, which vary based on the project type, including infrastructure, agriculture factories, apartments, hotel buildings, and educational buildings. R6 and R7 noted that these applications cover details including project location, minimum investment, duration for investment, and site specifics. Additionally, required approvals, such as those from the Urban Development

Authority (UDA), Sri Lanka Tourism Development Authority (SLTDA) for hotel projects, and environmental clearances, differ depending on the project's nature.

The respondents highlighted that the BOI process for importing material quantities remains consistent, regardless of whether materials are imported all at once or in multiple lots. However, R2 emphasised that importing in smaller batches can lead to additional time and costs due to the need for repeated documentation. R7 confirmed that after the Engineering Department of the BOI approves the total quantity requirement, this approval is sent to the Inland Revenue Department. If materials are imported in batches, separate approvals are issued for each lot.

4.3 SPECIAL BENEFITS OF OBTAINING BOI CONCESSION FOR APARTMENT CONSTRUCTION PROJECTS

The semi-structured interviews revealed specific benefits of obtaining BOI concessions, particularly relevant to apartment construction projects. R1 and R2 noted that BOI-approved projects enjoy an accelerated approval process, which is crucial for apartment construction, where timely approvals can significantly impact project timelines. For instance, faster bank approvals for Letter of Credit (LC) facilitate the procurement of essential materials and machinery, expediting the construction process. Additionally, the quick clearance procedures for imported materials and machinery are particularly beneficial in ensuring that construction progresses without unnecessary delays.

R4 highlighted that BOI projects are supported by well-prepared documentation, which minimises disputes related to documentation errors. This is especially important in apartment construction, where complex documentation involving various stakeholders is often required. According to R6, the availability of BOI lands for lease or rent can provide strategic locations for apartment projects, enhancing their market appeal.

R7 emphasised that the benefits offered by BOI can vary depending on the country's economic situation, with more concessions provided during economic downturns to encourage investment. This flexibility can benefit apartment developers seeking cost-effective opportunities during challenging economic periods. Additionally, BOI provides visa facilities for foreign employees, which is beneficial in apartment construction projects requiring specialised skills not available locally. However, R7 noted that the BOI's 2:1 ratio of local to foreign labour may not always be feasible due to skill shortages, making the visa facilities particularly valuable in such cases.

4.4 INFLUENCE OF BOI PROCEDURE AND STAKEHOLDER INVOLVEMENT IN CONSTRUCTION PROJECTS

In the planning stage, the BOI procedure significantly influences project progress. According to BOI officers R6 and R7, after submitting essential documents such as the Investment application, Site application, Preliminary planning clearance, Project proposal, and Investor profile, a fixed application fee of approximately 275 USD is required. An acknowledgment letter is issued, and the approval letter, which details the concessions and conditions, is typically provided within 60 days. However, R6 noted that delays can occur if additional requirements such as site inspections or environmental approvals are necessary. The key stakeholders in this stage include the Investment Department, which appraises the project; the Engineering Department, which assesses site suitability; the Environment Department, which addresses environmental concerns; and the Legal Department, which ensures compliance with standards.

During the construction stage, the BOI's role is crucial in approving materials, particularly those on a negative list. R6 highlighted that additional documentation is required for materials on this list to prove that local alternatives are insufficient, which can delay the approval process. R2, R3, and R4 discussed how stakeholders, including the Contractor, Employer or Employer's Representative, Consultant Quantity Surveyor, and various BOI departments, collaborate to prepare and verify the necessary approvals, clear materials, and manage transportation logistics. Delays can arise from complex documentation, detailed calculations, or staff shortages, especially during challenging periods such as a pandemic, as pointed out by R5.

In the handover stage, the Monitoring Department ensures compliance with BOI conditions. R6 and R7 explained that this involves verifying material usage, adherence to investment commitments, and the proper completion of project documentation. The Monitoring Department may continue to follow up after completion, and if conditions are not met, the employer might be required to pay duties on duty-free materials. R2 emphasised that stakeholders at this stage ensure that all final documentation aligns with BOI requirements, facilitating a smooth project conclusion.

4.5 QUESTIONNAIRE FINDINGS

Survey methods are essential for gathering data from respondents representing the target population using close-ended questions. This research used a questionnaire to rank factors identified in the literature and semi-structured interviews. The questionnaire included three sections: respondent background information, factors affecting time and cost in different project stages, and challenges related to BOI regulations. It was distributed among 50 Sri Lankan construction industry professionals, with 38 responses received. The data were analysed using the Relative Importance Index (RII) to address the study's primary objective. Figure 1 below summarises the respondents who participated in the questionnaire survey.

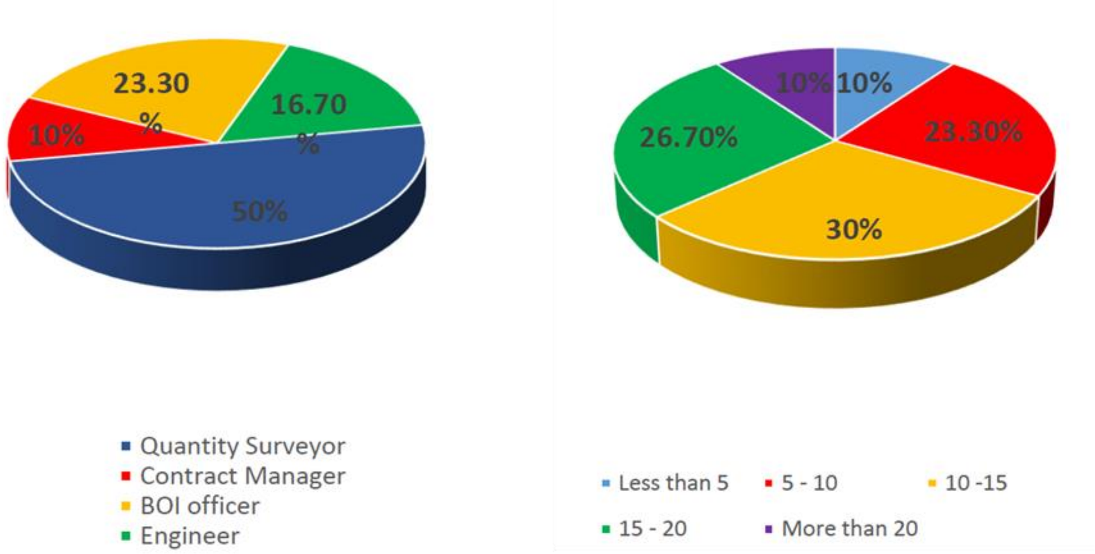


Figure 1: Summary of questionnaire survey participants

4.5.1 Factors Affecting Project Time Across Different Stages

The questionnaire survey revealed several key factors influencing project timelines at various stages in Sri Lankan construction projects under the BOI process. The impact of these factors was measured using the Relative Importance Index (RII) based on industry expert responses. A summary of the findings is provided in Table 2.

Table 2: Factors affecting time management of apartment construction projects

No	Affecting factor	RII	Rank
1	**During Pre-Construction Stage**		
1.1	Delays occurred in obtaining UDA approval	0.840	1
1.2	Lack of technical people within the BOI	0.707	2
1.3	Delays occurred in obtaining investment application	0.700	3
1.4	Delays occurred in obtaining site approval from BOI	0.687	4
1.5	Delays occurred in obtaining environment approval from BOI	0.667	5
1.6	Delays occurred in obtaining the site application	0.667	5
1.7	Lack of awareness of the BOI guidelines and documentation	0.660	7
1.8	Delays occurred in obtaining preliminary planning clearance	0.647	8
1.9	Complexity of the approval procedure	0.573	9
1.10	Staff shortage in BOI	0.453	10
2	**During Construction Stage**		
2.1	Variations to the material type after those materials are importing	0.953	1
2.2	Getting confirmation documents (From local suppliers) for negative listed materials	0.907	2
2.3	Getting approval for negative listed material	0.887	3
2.4	Lack of dollar reserves	0.873	4
2.5	Investment approval delays	0.867	5
2.6	Applying incorrect quantities to the documents	0.793	6
2.7	Engineering approval delays	0.720	7
2.8	Lack of awareness of the BOI guidelines and documentation	0.673	8
2.9	CUSDEC delays	0.667	9
2.10	Complexity of the procedure	0.647	10
2.11	Huge calculation requirement for the document approvals	0.633	11
2.12	Additional re-checking of the documents by Employer and BOI	0.560	12
2.13	Complexity of the drawings	0.480	13
2.14	Staff shortage in BOI	0.473	14

During the pre-construction stage, the primary factors affecting project time included the requirement for additional staff to register the project under BOI, initial one-time payments, and costs associated with BOI applications. Among these, the need for additional staff emerged as the most significant, with an RII of 0.6867, indicating its substantial impact on project timelines compared to projects without BOI concessions. The initial one-time payment for BOI and the costs for BOI applications followed, with RII values of 0.6067 and 0.5533, respectively. Additionally, obtaining UDA approval was highlighted as a critical factor, also scoring 0.5533 in RII, indicating its importance in the pre-construction phase.

In the construction stage, the survey identified several critical factors impacting project timelines. The most significant was "Variations to the material type after those materials are imported," which had the highest RII of 0.9533. This was closely followed by challenges related to obtaining confirmation documents from local suppliers for negative-listed materials, which had an RII of 0.9067. Getting approval for these materials also posted significant delays, with an RII of 0.8867. The lack of dollar reserves and investment approval delays were additional major concerns, scoring 0.8733 and 0.8667 in RII, respectively. These issues reflect the complexities of navigating BOI regulations and their impact on the construction timeline.

Other notable factors included applying incorrect quantities to documents (RII 0.7933), engineering approval delays (RII 0.7200), and a general lack of awareness about BOI guidelines and documentation (RII 0.6733). These factors contributed to delays in project execution and highlighted areas where better training and more accurate documentation could mitigate time overruns. The factors such as additional re-checking of documents by employers and BOI (RII 0.5600), complexity of drawings (RII 0.4800), and staff shortages within BOI (RII 0.4733) were identified as less impactful but still noteworthy. These issues often led to delays in final approvals and project closure.

4.5.2 Factors Affecting Project Cost at Different Stages

The questionnaire survey revealed several factors impacting the cost of projects under the BOI process in Sri Lankan construction projects. These factors were identified at different stages of the project, including pre-construction, construction, and handover, with their impact measured using the Relative Importance Index (RII). Table 3 outlines the RII values of each factor that was identified.

Table 3: Factors affecting cost management of apartment construction projects

No	Affecting factor	RII	Rank
1	**During Pre-Construction Stage**		
1.1	Additional staff requirements for registering the project	0.687	1
1.2	Initial one-time payment for the BOI	0.607	2
1.3	Cost for the BOI application	0.553	3
1.4	Obtaining the UDA approval	0.553	3
2	**During Construction Stage**		
2.1	Requirement of storage facilities	0.940	1
2.2	Have to purchase the materials locally due to the dollar issue	0.920	2
2.3	Double handling, if the materials received earlier	0.920	2
2.4	Delays due to the BOI process increase material price	0.893	4
2.5	Cost for preliminaries will increase due to delays	0.867	5
2.6	Additional charge by the clearing agent	0.673	6
2.7	Annual BOI charge	0.673	6
2.8	Charge for the CUSDEC document	0.560	8
2.9	Cost for the investment and engineering applications	0.513	9

No	Affecting factor	RII	Rank
3	**Handover Stage**		
3.1	Custom duty payment due to non-compliance	0.847	1
3.2	Tax for the unused goods or re-export the goods	0.840	2

During the pre-construction stage, four major factors were identified as affecting project costs. The most significant was the "Additional staff requirement for registering the project under BOI," which had an RII of 0.6867. This indicates a substantial cost impact, particularly compared to projects without BOI concessions. The "Initial one-time payment for the BOI" followed, with an RII of 0.6067, highlighting its considerable financial burden on projects. The costs associated with the "BOI application" and "Obtaining UDA approval" were also significant, both with an RII of 0.5533, indicating their role in increasing project costs at this stage.

In the construction stage, nine factors were identified as influencing project costs. The most critical factor was the "Requirement of storage facilities if the materials are received early," with a high RII of 0.9400. This reflects the need for additional infrastructure to accommodate early deliveries, leading to increased costs. The need to "Purchase materials locally due to the Dollar issue" and "Double handling, if the materials are received earlier" were significant, both with an RII of 0.9200. These issues are closely related to financial constraints and logistical challenges, leading to higher costs. "Delays due to the BOI process" causing "Material price increases" was another significant factor, with an RII of 0.8933, indicating the financial impact of procedural delays. Additionally, "Cost for preliminaries will increase due to delays" had an RII of 0.8667, highlighting how time overruns can lead to higher costs. Other factors such as "Additional charge by the clearing agent," "Annual BOI charge," and costs associated with "CUSDEC documents and engineering applications" were also noted, though with relatively lower RII values.

At the handover stage, two factors were identified as significantly impacting costs. The most critical was the need to "Pay custom duty since the conditions of the contract with BOI were not fulfilled," which had an RII of 0.8467. This indicates substantial costs incurred due to non-compliance with BOI contract conditions. The requirement to "Pay tax for unused goods or re-export the goods" was another significant cost factor, with an RII of 0.8400, highlighting the financial implications of handling unused materials at the project's conclusion.

Drawing on the findings from both interviews and questionnaire surveys with industry experts, the framework given below in Figure 2 identifies key issues at the pre-construction, construction, and handover stages, highlighting their impact on project delays and cost overruns. This comprehensive framework aims to provide project managers and stakeholders with a structured approach to anticipate, evaluate, and mitigate these challenges, thereby enhancing project efficiency and cost-effectiveness. By integrating these insights, the framework serves as a practical tool to improve project outcomes and ensure compliance with BOI regulations.

Criteria to be a BOI project	**Pre-construction stage**	**Construction stage**	**Handover stage**
	Incentives/benefits	**Incentives/benefits**	**Incentives/benefits**
- Solutions for the unemployment - Affect to the economic growth of the country - Approved under Section 17 of BOI Law - minimum investment threshold of USD 3 Mn or upwards - Approved under Section 16 of BOI Law - minimum investment requirement is USD 250,000	- BOI lands can be obtain for the construction. - BOI also involve with getting UDA approvals.	- TAX concessions - The approval procedure will accelerate (Letter of credit, CUSDEC) - Disputes caused by the improper documentation will be minimized - Provide visa facility to export foreign employees - Allow to export heavy machineries which are not locally available - Material clearing is easy with the BOI process	- ·Employer can complete the project lower cost - Customer can buy the apartments at lower cost than the projects without BOI concessions - Can sell the apartment units for a competitive price in the market.
Regulations/ acts	**Challenges**	**Challenges**	**Challenges**
- The Inland Revenue Act No. 24 of 2017 - Companies Act No. 7 of 2007 - BOI Act No. 4 of 1978 as amended and its Regulations - Exchange Control Act No. 24 of 1953 and its Regulations - Strategic Development Projects Act No. 14 of 2008 as amended - Finance Act No. 12 of 2012 Part (iv) as amended (Hub Operation Regulations) - The Customs Ordinance (Chapter 235) - The Merchant Shipping Act, No. 52 of 1971	- UDA approvals get delay - Additional staff requirement for registering the project under BOI - Pandemic situations	- Variation in imported material type under BOI concessions. - Difficulty obtaining confirmation documents from local suppliers for restricted materials. - Delays in obtaining investment applications. - Need for storage facilities if materials arrive early. - Compulsion to purchase materials locally due to dollar issues. - Potential material price increases due to BOI process delays. - Risk of BOI concession period ending before project completion. - Impacts of pandemic situations. - High documentation requirements for BOI registration. - Strict limitations on wastage: no wastage for countable items, 10% allowance for measured items.	- Had to pay the custom duty since the conditions of contract with BOI not fulfilled. - Has to pay the tax for the unused go or re-export the goods

Figure 2: Framework

5. CONCLUSIONS

The research aimed to investigate the influence of the BOI approval process on the cost and time aspects of apartment construction projects in Sri Lanka. This study set out to identify the challenges and factors associated with BOI approvals that impact project timelines and budgets. The research successfully met its objectives through semi-structured interviews and a questionnaire survey by gathering insights from industry experts and practitioners.

Key findings revealed that the BOI approval process varies with project types, contrary to the uniform approach suggested in existing literature. Interviewees highlighted that, requirements such as UDA approvals, SLTDA approvals, and environmental clearances differ across projects. Additionally, despite recent BOI initiatives to streamline approvals, delays persist due to issues including contractor inefficiencies, material quality concerns, and project complexity. These delays can result in the expiration of BOI concessions, increasing project costs.

The questionnaire survey further identified critical cost-related factors at different project stages, such as additional staffing for BOI registration and unexpected material cost fluctuations. These findings were integrated into a comprehensive framework, summarising the key challenges and their impact on project cost and time.

The implications of these findings are significant for industry practitioners, academia, and policymakers. For practitioners, understanding the nuances of the BOI process can help mitigate delays and cost overruns. Academia can use these insights to further explore the complexities of regulatory impacts on construction projects. Policymakers, particularly those involved with the BOI, can leverage these findings to refine approval processes, ensuring they are efficient and supportive of project success.

However, the study has limitations, including a limited sample size and a focus on qualitative data, which may introduce bias. The findings are also specific to Sri Lanka and may not be generalisable to other contexts. Future research could expand the sample size, incorporate more comprehensive quantitative methods, and explore comparative studies across regions to validate and broaden the understanding of the BOI approval process's impact. Additionally, examining the long-term effects of BOI approvals and other influencing factors including market dynamics and technological advancements would provide a more comprehensive perspective.

6. REFERENCES

Anthonisz, S., & Perry, C. (2015). Effective marketing of high-rise luxury condominiums in a middle-income country like Sri Lanka. *Journal of Work-Applied Management*, *7*(1), 61–83. https://doi.org/10.1108/JWAM-10-2015-002

Ayopo, O. O., Ohis, A. C., & Wellington, T. D. (2019). Challenges of construction procurement: A developing nation's perspective. In *International Conference of Socio-economic Researchers ICSR 2016 Serbia.* (pp. 205-218). Scientific Society Akroasis Serbia. https://www.researchgate.net/profile/Oluwabukunmi-Ogunsanya/publication/337636417.pdf

Board of Investment of Sri Lanka. (2024). *Annual report 2022*. Board of Investment of Sri Lanka. https://investsrilanka.com/wp-content/uploads/2024/04/BOI-AR-Eng-2022-v16B-012_compressed-1_compressed.pdf

Botrić, V., & Škuflić, L. (2006). Main determinants of foreign direct investment in the southeast European countries. *Transition Studies Review*, *13*(2), 359–377. https://doi.org/10.1007/s11300-006-0110-3

Bryman, A. (2016). *Social research methods*. Oxford University Press.

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). SAGE.

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing*, *62*(1), 107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x

Eryigit, M., & Shafaq, A. Q. (2021). Factors affecting foreign direct investment: The Afghanistan case. *Studies of Applied Economics*, *39*(2), 2. https://doi.org/10.25115/eea.v39i2.3351

Fraser, N., & Silva, M. (2016). A study on causes and effects of risk in large scale building construction projects in Colombo, Sri Lanka. In *1st International Conference in Technology Management*. (pp. 87-91). Department of Management of Technology, University of Moratuwa. https://www.researchgate.net/profile/Samanthi-Weerabahu/publication/323336195.pdf

Gallage, S. D., Devapriya, K. A. K., & Perera, B. A. K. S. (2022). A framework for the better integration of the crucial economic factors of Sri Lankan urban renewal projects. *Intelligent Buildings International*, *14*(4), 414–432. https://doi.org/10.1080/17508975.2021.1902256

Gavit, S. C., Pitroda, D., & Makwana , A. H. (2015). Risk management in high rise construction projects: A Review. *International Journal of Science and Engineering Research*, *9*(6), 1536-1544. https://www.academia.edu/download/91805245/IRJET_V9I6271.pdf

Ibrahim R.B., A., Roy, M. H., Ahmed, Z., & Imtiaz, G. (2010). An investigation of the status of the Malaysian construction industry. *Benchmarking: An International Journal*, *17*(2), 294–308. https://doi.org/10.1108/14635771011036357

Iqbal, S., Choudhry, R. M., Holschemacher, K., Ali, A., & Tamošaitienė, J. (2015). Risk management in construction projects. *Technological and Economic Development of Economy*, *21*(1), 65–78. https://doi.org/10.3846/20294913.2014.994582

Jayasekara S.D. (2014), Determinants of foreign direct investment in Sri Lanka. *Journal of the University of Ruhuna*, 2, 4-13. https://www.researchgate.net/profile/S-G-Sisira-Jayasekara/publication/286192336_.pdf

Kumar, R. (2011). *Research Methodology: A Step-by-Step Guide for Beginners* (3rd ed.). SAGE.

LawPlus Ltd. (2021). *Investment Promotion in Thailand: BOI and EEC 2021*. Lexology. https://www.lexology.com/library/detail.aspx?g=3491bbc6-dc66-4fd4-ae55-4f139a70f147

Lee, H.S., Kim, H., Park, M., Ai Lin Teo, E., & Lee, K.-P. (2012). Construction risk assessment using site influence factors. *Journal of Computing in Civil Engineering*, *26*(3), 319–330. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000146

Mensah, J. T. (2014). Carbon emissions, energy consumption and output: A threshold analysis on the causal dynamics in emerging African economies. *Energy Policy*, *70*, 172–182. https://doi.org/10.1016/j.enpol.2014.03.038

Mondal, W. I. (2003). Foreign direct investment in Bangladesh: an analysis of perceptions of prospective investors. *Studies in Economics and Finance*, *21*(1), 105–115. https://doi.org/10.1108/eb028771

Musarat, M. A., Alaloul, W. S., & Liew, M. S. (2021). Impact of inflation rate on construction projects budget: A review. *Ain Shams Engineering Journal*, *12*(1), 407–414. https://doi.org/10.1016/j.asej.2020.04.009

Nam, C. H., & Tatum, C. B. (1997). Leaders and champions for construction innovation. *Construction Management and Economics*, *15*(3), 259–270. https://doi.org/10.1080/014461997372999

Neuendorf, K. A. (2017). *The Content Analysis Guidebook*. SAGE.

Raftery, J., Pasadilla, B., Chiang, Y. H., Hui, E. C. M., & Tang, B.S. (1998). Globalization and construction industry development: Implications of recent developments in the construction sector in Asia. *Construction Management and Economics*, *16*(6), 729–737. https://doi.org/10.1080/014461998372024

Siraj, N. B., & Fayek, A. R. (2019). Risk identification and common risks in construction: Literature review and content analysis. *Journal of Construction Engineering and Management*, *145*(9), 03119004. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001685

Urban Development Authority. (2001). *Concept Plan*. Urban Development Authority.

Lukson, E.E., Ranadewa, K.A.T.O., Parameswaran, A., Wijerathna, M.R.D.P. and Kodituwakku, D., 2024. Integrated project delivery implementation among construction SMEs in Sri Lanka: Barriers and strategies. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 619-633. DOI: https://doi.org/10.31705/WCS.2024.49. Available from: https://ciobwcs.com/papers/

INTEGRATED PROJECT DELIVERY IMPLEMENTATION AMONG CONSTRUCTION SMES IN SRI LANKA: BARRIERS AND STRATEGIES

E. Edman Lukson[1], K.A.T.O. Ranadewa[2], Agana Parameswaran[3] , M.R.D.P. Wijerathna[4], and Dasuni Kodituwakku[5]

ABSTRACT

Small and Medium-sized Enterprises (SMEs) are vital to Sri Lanka's economy, particularly in the construction sector, which largely relies on traditional procurement methods. This reliance results in persistent issues due to industry fragmentation. To address these challenges, it is vital to investigate the applicability of Integrated Project Delivery (IPD), a procurement method tailored to address the needs of construction SMEs. Despite its potential benefits, comprehension and implementation of IPD within the Sri Lankan construction industry remain limited due to the intricate nature of SMEs. Hence, the study aims to investigate the strategies to minimise barriers to IPD implementation within construction SMEs in Sri Lanka through a qualitative approach. A total of 15 semi-structured interviews with Sri Lankan construction industry experts were conducted. The literature review identified a range of barriers, including financial, technical, legal, and cultural challenges, which were further explored through these interviews. The research highlighted the lack of advanced strategies within Sri Lanka's construction SMEs to address these challenges effectively. Significant barriers to IPD implementation, such as narrow-mindedness, reluctance to change, and copyright issues, were validated and identified through the manual content analysis. The study proposes several strategies to facilitate IPD implementation, including introducing new guidelines from the Construction Industry Development Authority (CIDA), setting minimum parameters for team selection, implementing various versions of IPD rather than a pure IPD approach, and addressing conflict points early. The research offers valuable insights for both academia and industry practitioners, presenting strategies to enhance the efficiency, quality, and sustainability of construction SMEs through the adoption of IPD.

Keywords: *Barriers; Construction Small and Medium-sized Enterprises (SMEs); Integrated Project Delivery (IPD); Sri Lanka; Strategies.*

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, edmanlukson@gmail.com

[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, tharushar@uom.lk

[3] PhD Scholar, School of Engineering, Design and Built Environment, Western Sydney University, Australia, aganaparameswaran@gmail.com

[4] Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, dewminir@uom.lk

[5] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, ldasuni@uom.lk

1. INTRODUCTION

The construction industry is vital for moving the economy of the country forward and acts as a measure of development (Eze *et al.*, 2020; Uhanovita et al., 2023). In most nations, the construction sector is divided into a limited number of large companies and a large number of small and medium enterprises (SMEs) (Ranadewa et al., 2021; Tezel *et al.*, 2018). Hence, SMEs are significant for economic development as they are involved in creating jobs, reducing poverty, and helping large enterprises (Agwu & Emeti, 2014; Shelton *et al.*, 2016). According to Fulford and Standing (2014), large companies are not interested in having more employees and are used to subcontracting certain works to SMEs.

Various procurement techniques have been created throughout time in the industry to address the shortcomings of prior approaches. Common procurement procedures have a key flaw in that they do not guarantee the project's productivity level (Jayasena & Senevirathna, 2012). Further authors added that lower productivity is caused by failure to meet schedules and budgets, inadequate information in construction drawings, and material waste. Integrated Project Delivery (IPD) was created to address these issues.

IPD is a unique and creative approach to project management (Mei et al., 2017). However, according to Sive (2009) and Ling et al. (2020), there is a lack of research elaborating on the present situation of IPD implementation in the construction industry and the causes of slow implementation of IPD. Kahvandi et al., (2017) stated for the successful adoption of IPD, project stakeholders need to have familiarity, experience, and knowledge about the IPD as the role of stakeholders is different from traditional procurement methods and lack of familiarity prevents construction firms from using IPD. The absence of IPD training is considered one of the barrier factors to implementing IPD because it is a new concept to the construction industry (Durdyev et al., 2019). According to Autodesk Whitepaper (2008), the Requirement of a new legal framework is a major reason for the slow adoption of IPD in construction (cited in Roy et al., 2018). As IPD emphasises mutual trust between the parties and requires several agreements signed between parties, the adoption of IPD in construction is needed for new laws and regulations (Ghassemi & Becerik-Gerber, 2011; Ilozor, 2012).

As SMEs are prone to economic changes which leads the SMEs to unable to engage resources for innovation (Alves et al., 2011) and lack of trust by large clients towards the SMEs (Briscoe et al., 2001), reduce the use of IPD in construction SMEs. In developing countries adopting IPD in construction is not widely spread due to the lack of knowledge about eliminating barriers and the absence of interest (Rached et al., 2014), especially where cost overrun, time delays, and low productivity are issues (Durdyev et al., 2019). Therefore, it is vital to investigate those barriers and identify reasons for not materialising the adoption of IPD (Sommer et al., 2014). In developed countries, IPD has been adopted already, yet its adoption in developing countries is still in the very early stages (Mei et al., 2017). As a result, research is required to identify challenges related to IPD and determine the viability of IPD adoption in construction SMEs. Nevertheless, it is possible that issues faced by construction SMEs can be mitigated through the adoption of IPD. There is research available about the possibility of implementing IPD for construction companies but there is a lack of research discussing implementing IPD for construction SMEs. It is essential to research to investigate how to overcome the barriers to IPD implementation in construction SMEs in Sri Lanka through strategies to minimise barriers to IPD implementation in construction SMEs in Sri Lanka. Therefore, the study aims to investigate the strategies to minimise barriers to IPD implementation within construction SMEs in Sri Lanka. The objectives of the study are to investigate the barriers to IPD implementation for construction SMEs in Sri Lanka and to propose strategies to minimise these barriers.

First, a comprehensive literature review on barriers to adopting IPD for construction SMEs and strategies to adopt IPD in construction SMEs is presented. Subsequently, the methodology employed in this research is delineated. Thereafter, the analysis of findings is provided, followed by a discussion and conclusion.

2. LITERATURE REVIEW

The study aims to explore strategies to overcome barriers to the implementation of IPD within construction SMEs in Sri Lanka through a Systematic Literature Review focused on formulating research problems and synthesising answers in a systematic process based on formulated data from previous research using databases such as Scopus, Web of Science, and Google Scholar.

2.1 BARRIERS TO ADOPTING IPD FOR CONSTRUCTION SMES

In the construction sector, the implementation of IPD faces various challenges (Teng et al., 2019). Project performance is notably affected by a limited comprehension of the obstacles to IPD adoption, particularly in developing nations (Rached et al., 2014). Therefore, there is a need for research to investigate these barriers (Sommer et al., 2014). Such obstacles encompass technical, legal, financial, and cultural factors (Kent & Becerik-Gerber, 2010). Moreover, there is a dearth of research focusing on IPD within construction SMEs. Thus, Table 1 below outlines the general barriers to adopting IPD in the construction industry.

Table 1: Barriers to adopting IPD

NO	Barriers to adopting IPD	References
	Financial barriers	
1	Equitable distribution of opportunities for gain and potential for loss among stakeholders.	[2], [7], [14], [15], [16], [17]
2	Differences in the accounting of costs and profit among the client, consulting, and contracting firms.	[15]
	Technical barriers	
3	Integration of information, and knowledge management systems	[15]
4	An early definition of target goals without a fully developed design	[15]
5	Un-established/unclear BIM standards and practices	[15]
6	consistency problems due to different organizations using various IT systems	[10]
7	ownership issues and liability issues in the integrated use of technology	[8]
	Legal barriers	
8	Need for new legal framework	[1], [7], [15]
9	Criteria for selection of agencies value-based vs. cost-based	[14], [15]

NO	Barriers to adopting IPD	References
10	current contracts do not incorporate IPD parameters	[4], [8], [9], [13], [14]
11	New contract documents supporting IPD are not thoroughly tested	[8], [12]
12	Absence of proper risk or reward-sharing procedure	[3]
13	Need for a long time for changing rules needed for IPD implementation	[7], [5]
14	Problems related to insurance	[2], [11], [12], [16]
	Cultural barriers	
15	Lack of mutual respect & trust	[15]
16	Inexperience with each other & IPD	[15]
17	Awareness and willingness about IPD among owners.	[15]
18	Reluctance to change	[5], [14]
19	unawareness of alternative procurement strategies	[6]
20	the rigid culture and high uncertainty avoidance	[6]
	Other barriers	
21	Early involvement of subcontractors	[15]
22	Requirement of a competent and risk-tolerant client	[15]
23	Subjectivity in measuring quality	[15]

[1] Subaih, 2015 [2] Cohen, 2010 [3] Durdyev et al., 2019 [4] Fish, 2011 [5] Ghassemi & Becerik-Gerber, 2011[6] Joseph & Jayasena, 2008 [7] Kahvandi et al., 2017 [8] Kent & Becerik-Gerber, 2010 [9] Ling et al., 2020 [10] Moses et al., 2008 [11] Mossman et al., 2013 [12] Naismith et al., 2016 [13] Pishdad-Bozorgi & Beliveau, 2016 [14] Rached et al., 2014 [15] Roy et al., 2018 [16] Tezel et al., 2018 [17] Haiyan & Hua, 2017

The equitable distribution of gains and losses among stakeholders emerges as a primary barrier to IPD adoption. The absence of contracts integrating IPD parameters is identified as a legal barrier by many researchers. Additionally, cultural barriers, such as reluctance to change, are highlighted by several authors. Thus, the barriers to IPD adoption for a general contractor necessitate empirical testing during research.

2.2 STRATEGIES TO ADOPT IPD IN CONSTRUCTION SMES

As there are lack of research focusing on IPD for construction SMEs. some researchers have indicated that similar to large contractors, construction SMEs also implement strategies to overcome barriers in the IPD implementation. Therefore, Table 2 presents the strategies that need to be adopted by construction SMEs.

Table 2: Strategies to adopt IPD in construction SMEs

No	Strategies	References
1	pay more attention while choosing the team and contract type.	[6]
2	Increasing integration between project teams	[5]
3	made aware of the relational contract practices and the possible advantages.	[3], [5]
4	Research and Development	[4]

No	Strategies	References
5	Eliminate the power of parties to sue one another.	[2], [7], [9]
6	Use Contractors All Risk Insurance policy with modifications.	[4], [8]
7	Using methods like Price estimation, Cost benchmarking and Target Criteria Amendment and Target Cost for risk	[1], [8]

[1] AIA, 2012 [2] Cohen, 2010 [3] Eze et al., 2020 [4] Fish, 2011 [5] Gunathilake & Jayasena, 2008 [6] Kahvandi et al., 2017 [7] Naismith et al., 2016 [8] Roy et al., 2018 [9] Sive, 2009

Table 2 outlines key strategies for implementing IPD in construction SMEs, emphasising aspects such as team selection, contract types, integration among project teams, awareness of relational contract practices, and investment in research and development. These strategies draw upon various references in the field, reflecting a growing recognition of the importance of tailored approaches for SMEs in the construction sector. Identifying barriers and strategies specific to construction SMEs is crucial for optimising their performance and competitiveness in the industry. By understanding the unique challenges they face such as limited resources and capabilities, stakeholders can devise targeted solutions to enhance IPD implementation, foster collaboration, and drive sustainable growth within the SME segment of the construction sector.

3. METHODOLOGY

A comprehensive literature review was conducted to collect barriers to adopting IPD for construction SMEs and strategies to overcome the barriers and successfully adopt IPD in construction SMEs. The qualitative approach is used to achieve the aim of the study. Qualitative research allows the researcher to gain detailed knowledge as it is deeply involved in the actual experiences (Creswell, 2009). Accordingly, the data was collected through semi-structured interviews. Semi-structured expert interviews were conducted to identify the barriers to adopting IPD for construction SMEs and to propose strategies to overcome the barriers to adopting IPD for construction SMEs in Sri Lanka. A 15 number of semi-structured interviews with industry practitioners, selected through a purposive sampling method were conducted to validate and expand the literature findings. The qualitative data was analysed through manual content analysis which is among the many qualitative techniques currently accessible for analysing data and interpreting its significance is qualitative content analysis. The details of the interviewees are listed in Table 3.

Table 3: Details of the interviewees

Respondent	Designation	Educational Qualification	Industry experience	Awareness of the IPD concept	Experience in SMEs
R1	Quantity Surveyor	PhD	3 years	Well aware	Yes
R2	Contract Administrator	MSc	35 years	Aware	Yes
R3	Quantity Surveyor	BSc	4 years	Well aware	Yes
R4	Quantity Surveyor	BSc	3 years	Well aware	Yes
R5	Quantity Surveyor	MSc	7 years	Well aware	Yes
R6	Senior Lecturer	BSc	10 years	Well aware	Yes

Respondent	Designation	Educational Qualification	Industry experience	Awareness of the IPD concept	Experience in SMEs
R7	Director	BSc, MBA	30 years	Well aware	Yes
R8	Chief Quantity Surveyor	BSc	15 years	Aware	Yes
R9	Senior Cost Manager	MSc	9 years	Well aware	Yes
R10	Senior Cost Manager	MSc	11 years	Well aware	Yes
R11	Senior Lecturer	BSc	10 years	Well aware	Yes
R12	Director	BSc, MBA	27 years	Well aware	Yes
R13	Chief Quantity Surveyor	BSc	16 years	Aware	Yes
R14	Quantity Surveyor	BSc	5 years	Well aware	Yes
R15	Quantity Surveyor	BSc	4 years	Well aware	Yes

The interview guidelines consisted of three sections. The first section focuses on the general details of the experts, the second section focuses on barriers to implementing IPD in construction SMEs, and the third section concentrates on strategies for adopting IPD in these SMEs.

4. DATA ANALYSIS AND FINDINGS

4.1 IPD

IPD is a project delivery approach that integrates all the participants to improve project results by giving priority to project goals instead of their own goals (Durdyev et al., 2020). Respondents were asked about their ideas regarding IPD as the first question of the interview. According to R1, "*IPD can be classified as a contractual arrangement to overcome the challenges of trust and collaboration issues and cost overrun in projects by creating a common set of terms, expectations, and project goals*''. Terms used by the respondents to explain IPD are presented in Figure 1.

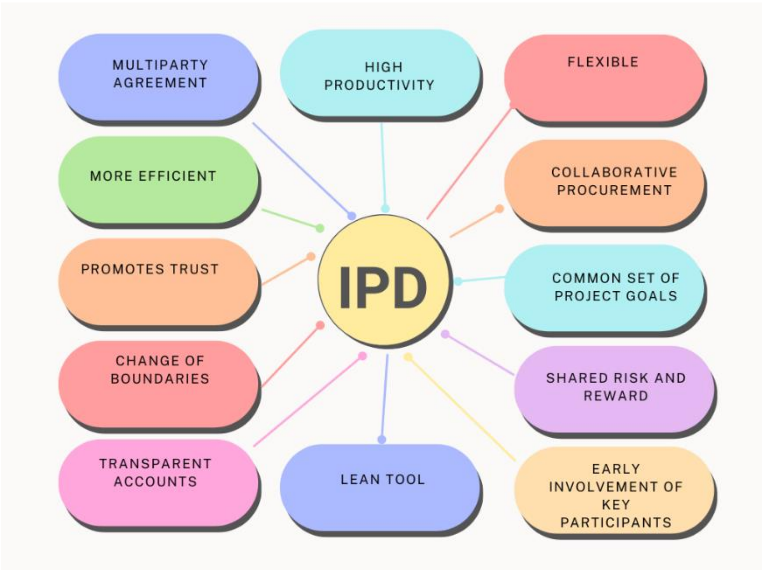


Figure 1: Terms used to define IPD

To illustrate IPD, Figure 1 illustrates the most often used terminologies to define IPD.

4.2 BARRIERS TO IMPLEMENTING IPD IN CONSTRUCTION SMES

Investigating the barriers to IPD implementation for construction SMEs in Sri Lanka is one of the research objectives. Experts were asked to discuss the barriers to IPD implementation for construction SMEs in Sri Lanka. The identified barriers from the literature were used to aid the interview process.

4.2.1 Financial Barriers

Except for **R1** and **R5,** all other experts identified the equitable distribution of opportunities for gain and potential for loss among stakeholders as barriers. **R3** stated that there is no recognised formula to distribute the gain and loss among the stakeholders. It is the challenge of selecting compensation and incentive structures corresponding to the unique project's characteristics and its participants (Cohen, 2010). However, **R1** claimed that *''just like the agreements in joint venture projects, stakeholders can identify in the multi-party agreement about the proportion of gain and loss''.* Moreover, **R5** noted that reaching an agreement about the proportion of gain and loss may be time-consuming and slow the progress but it cannot be considered a barrier. **R1, R2, R8,** and **R9** considered Differences in the accounting of costs and profit among the client, consulting, and contracting firms as a barrier. **R4** claimed that "*even though different parties have different accounting practices, IPD itself promotes transparency which could eliminate the problem of different accounting practices"*. Stakeholders can check the accounts of others and confirm the cost and profits.

4.2.2 Technical Barriers

Out of the technical barriers identified in the literature review, no experts select integration of information, and knowledge management systems and un-established/unclear BIM standards and practices as barriers for implementing IPD in construction SMEs. **R7** stated that with the technology and information tools available sharing information and knowledge management cannot be considered as a barrier. Moreover, **R11** added that *''since IPD can be practised without BIM, Un-established/unclear BIM standards and practices cannot be considered as a barrier''.* **R5** claimed that the information can be shared more efficiently with the help of BIM. However, it cannot act as a barrier to implementing IPD in construction SMEs. However, in the literature findings, Rached et al. (2014) reveal that BIM integrates all the trades and design aspects and supports the scope of work and the construction method to be used. However, the use of BIM might cause problems when small entities do not have enough expertise with such a technology.

Roy et al. (2018) claimed that the early setting of target goals without a fully developed design is the most important technical barrier. Similar to that **R2** claimed that ''Without defining the design, stakeholders may find it extremely difficult to set clear cost, time, and quality goals''. However, **R13** claimed that if it is completely a new project and nobody has done it yet, it can be a barrier, yet generally, the other projects can be benchmarked at the feasibility stage. Therefore, target goals can be set without a fully developed design.

4.2.3 Legal Barriers

Except need for a new legal framework, all other barriers identified in the literature review were considered as barriers by the 15 experts. **R3, R5,** and **R7** identified the absence of a legal framework for implementing IPD as a barrier. Similarly, Roy et al.

(2018) added that a new legal framework is a prerequisite for the successful implementation of IPD. However, **R1** claimed that instead of the new legal framework, it is advisable to have new guidelines for implementing IPD. Furthermore, **R14** added that before moving into the legal context, the contractual context needs to be given priority. Because professionals in the construction industry are not intervening in legal matters at very early stages. Because they always trying to resolve or minimise the issues contractually.

4.2.4 Cultural Barriers

During the literature review, six cultural barriers were identified. All the experts selected all identified barriers as factors that hinder the implementation of IPD in construction SMEs. Ghassemi and Becerik-Gerber (2011) trust between the different stakeholders is key to the success of an IPD project. According to **R5, ‘’***as a result of prior experiences, it has been noted that there is a great deal of mistrust amongst the participants in the Sri Lankan construction sector’’*. **R9** claimed that some of the barriers are interrelated. For example, due to the rigid culture and high uncertainty avoidance, owners are reluctant to change from traditional procurement methods to alternative procurement methods.

4.2.5 Other Barriers

R1, R2, R3, R5, and **R6** selected Early involvement of subcontractors as a barrier. **R1** believed that the IPD goals could never be achieved without including major subcontractors at the very early stage of the project. In contrast to that **R12** claimed that "*the subcontractors in the Sri Lankan construction industry are not knowledgeable enough to add anything to the IPD process’’*. Furthermore, Subcontractors engaged in specialised services including MEP works, Steelworks, etc. are the only exceptions. Figure 2 summarises the barriers selected by the 15 experts.

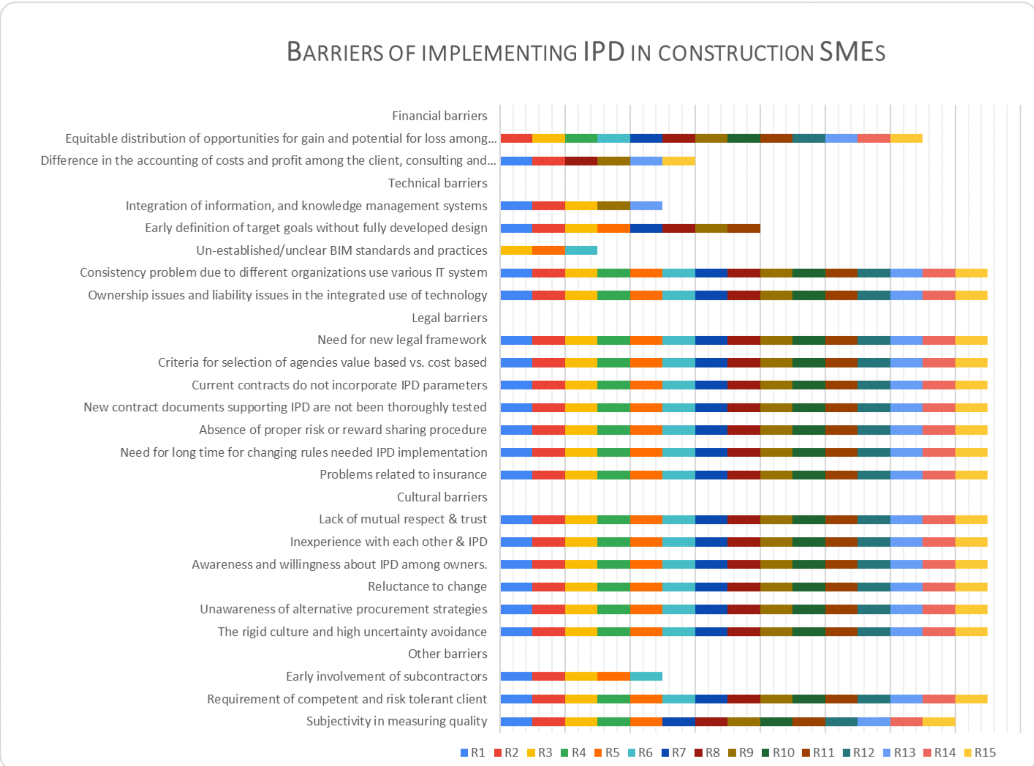


Figure 2: Barriers to adopting IPD

In addition to the barriers identified in the literature review, respondents in the construction industry identified several challenges that hinder the effective implementation of IPD. These barriers include limited access, a narrow focus on profit maximisation, tendency to shift risk -As well as organisational structure, issues such as problem-solving techniques, frequent abusive behaviour, and undesirable or hostile work environment, the lack of an established framework further complicates the adoption of IPD in addition to resistance to considering new ideas, the desire to push one's ideas alone. Obstacles that arise Reluctance or fear of customers and the challenges of discussing the benefits of IPD implementation further highlights the multifaceted barriers facing construction SMEs in adopting collaborative approaches. Overcoming these barriers requires comprehensive strategies that encourage cultural exchange, improve communication, and create an enabling environment for entrepreneurship and innovation among SMEs in manufacturing.

4.3 STRATEGIES TO IMPLEMENT IPD IN CONSTRUCTION SMES

All the respondents identified paying more attention while choosing the team as a strategy. **R1** stated that the success of IPD projects hugely depends on the parties involved and how parties work in a collaborative environment for a common goal by sharing the risks involved in the project. Therefore, high attention should be given to selecting the parties for the IPD team. ''*Minimum parameters should be set to select the parties*''. For example, select the parties who have already worked with each other. It will increase the integration between the teams and select the parties who have a good reputation in the field. In addition to that **R3** suggested that the Project team should select based on their ability to handle different parties at the same time and ability to communicate. **R6** suggested that ''*when selecting contractors for the projects based on IPD, it is a better option to go for a selective group of contractors and negotiate with them rather than open selection''.* It will enhance the trust between the involved parties. It allows the client to work with the contractor with whom they may worked for a long time collaboratively. For example, design consultants and contractors are working on a design and build project. In such a scenario as they are already in a collaborative mindset, it can be used as a strategy to implement IPD in construction SMEs.

Moreover, **R1** claimed that parties involved in the construction sector were unaware of new procurement methods such as IPD in Sri Lanka. Therefore, it is recommended to introduce Continuous Professional Development (CPD) courses to educate. **R7** added that "*Research and development related to IPD can be used to show the client the advantages of IPD implementation and how IPD can be used to gain considerable benefits in the construction*". With more and more research about IPD, familiarity and awareness about IPD as a procurement method will be increased. Furthermore, **R1** suggested that CIDA should come up with a new guideline for IPD contracts. As current contracts commonly used in Sri Lanka do not incorporate parameters for IPD, it is highly appreciable and will allow the implementation of IPD soon. ''*Most of the legal and contractual problems can be eliminated with the help of a guideline or a standard document''*.

R1 emphasised that proper communication channels should be established to implement IPD successfully by stating; "*It is better to establish a portal to share information, questions, and progress in real-time"*. It will allow all the parties to get updates about the project immediately. For example, if an architect asks an information from the client related to the project, all other parties could be aware at the same time through the common portal. As IPD is to achieve the common goal, it should be visible to every party. Even though online platforms are available to share information with the team, **R8** claimed parties in Sri Lanka wish to work in a physical environment most of the time. Therefore, it is better to have weekly meetings, and progress meetings which allow parties to know each other. With regular meetings, integration between the teams can be achieved.

Additionally, **R12** claimed that conflict points should identified and identified conflict points should addressed during the pre-contract stage. It leads to work smoothly as it is agreed between the parties involved. For example, copyright issues can be solved by including the rights of each party over the documents in the contract. Moreover, **R9** stated that '*'before the multiparty contract, a very thorough analysis should be conducted to ascertain the risks that each party would face in the project. This will ensure that the shared profit and loss are distributed fairly''*. If the incentive program was not preferred by the parties involved, it might have a substantial negative impact on the teams' morale and consequently their production. In addition, R**7** stated that the method of distributing gain and loss among parties is essential for implementing IPD. It should be decided at a very early stage of the project. However, the definition of target goals without a fully developed design is difficult. Cost benchmarking can be used to overcome this situation. It allows the parties to set a target goal based on a similar project even at the feasibility stage.

R2 and **R3** emphasised that proper documentation needs to be incorporated into IPD projects. **R14** suggested that the responsibilities of each party in every stage of the procurement process from feasibility to completion and liability period need to be identified and defined properly. "*Responsibilities should be properly documented to avoid confusion"*. The pre-contract stage is very vital for the implementation of IPD. Therefore, proper attention and more efforts should be allocated to the pre-contract stage. Furthermore, **R15** added that the implementation of IPD needs high transparency between the parties about the financial transactions. Therefore, open-book accounting is followed in IPD contracts. However, different account practices followed by different parties may bring trouble. Therefore, it is recommended to have standard accounting practices agreed upon by parties to the contract.

All the respondents disagree with the elimination of parties' power to sue one another as a strategy to adopt IPD for construction SMEs in Sri Lanka. According to **R5,** "*Elimination of the power of parties to sue one another might lead to some problems as well. Absence of the power to sue might be misused by the parties which are not familiar with the contractual conditions"*. All the respondents agreed that the Contractor's All-Risk (CAR) insurance policy can be used with some modifications due to the absence of an insurance policy for IPD. **R10** added that risks in IPD contracts are shared between the parties. Normal CAR insurance is not going to be applicable as some of the risks will be shared with the client. Therefore, the CAR policy can be used as insurance with some modifications.

R8 claimed that Government projects should start adopting IPD. It will create confidence in the IPD as a procurement method. It will motivate the private sector to engage in IPD-based projects. Investors could gain confidence through government initiatives, and it can be the starting point of the adoption of IPD among construction SMEs in Sri Lanka. In addition to that **R9** added "*different versions of IPD can be implemented rather than* *going for a pure IPD*". It will allow a partnership between the client and the contractor to have partial arrangements before going to the pure IPD.

Figure 3 summarises all the strategies identified in the literature review and new strategies revealed by experts in the interview in a structured way.

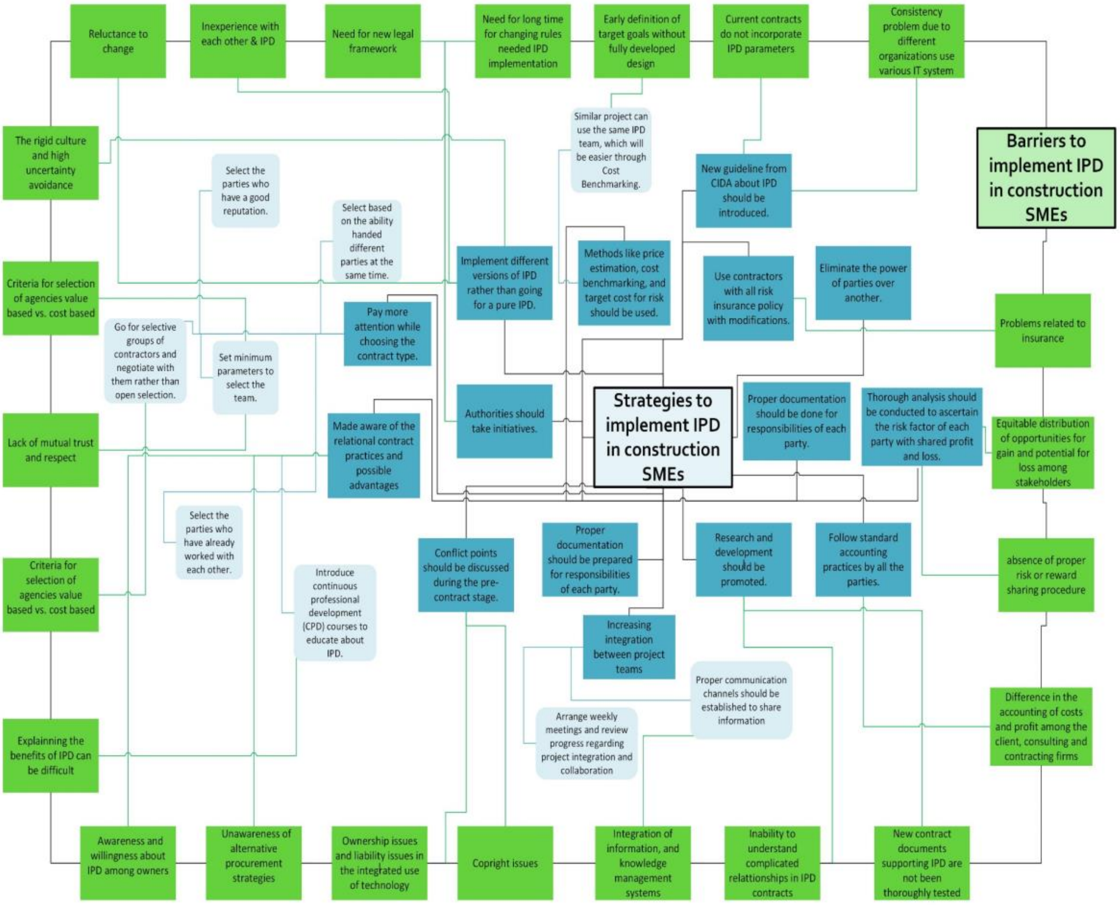


Figure 3: Strategies to implement IPD

5. DISCUSSION

The literature highlights several key barriers to the adoption of IPD, particularly within SMEs. Alves et al. (2011) note that SMEs, due to their vulnerability to economic changes, often struggle to allocate resources for innovation. Additionally, Briscoe et al. (2001) point out that a lack of trust from larger clients towards SMEs further hinders the utilisation of lean construction deployments in this sector. Building upon this, Ogunbiyi et al. (2014) proposd a strategic shift towards IPD within the overall project delivery framework, positioning it as the final tier under lean construction deployments. However, the study identifies a significant barrier to IPD adoption among SMEs: the absence of a recognised formula for the equitable distribution of gains and losses among stakeholders, echoing the concerns raised by Cohen (2010). Furthermore, Roy et al. (2018) identified early goal setting without fully developed designs as a critical technical barrier to IPD implementation. The authors emphasise the need for a new legal framework to support successful IPD implementation, a sentiment echoed by experts in the field. To overcome these barriers and ensure industry-wide adoption of IPD, Fish (2011) suggests prioritising education initiatives to enhance stakeholder understanding of the concept's importance.

Additionally, Joseph and Jayasena (2008) advocate for increased Research and Development (R&D) investment in the construction industry, particularly in regions such as Sri Lanka where R&D practices are relatively underutilised. Regarding insurance practices in IPD approaches, Fish (2011) notes the reliance on traditional insurance policies despite the lack of specific policies tailored to IPD. This underscores the need for customised insurance solutions for IPD projects, incorporating various policies to address project-specific concerns. In terms of risk management and profit-sharing in IPD contracts, AIA (2023) and Roy et al. (2018) advocate for thorough research and agreement among parties on risk allocation and benefit sharing based on their respective levels of engagement. Rached et al. (2014) further emphasised the importance of conducting comprehensive research before signing multiparty contracts to ensure fair distribution of shared savings and earnings. Finally, both the study and Fish (2011) highlight the effectiveness of multiparty agreements as a solution to IPD contracting challenges, emphasising their holistic approach compared to standard contracts, which typically focus on individual parties rather than the project as a whole.

6. CONCLUSIONS

SMEs play a pivotal role in Sri Lanka's economy, yet competitive pressures and various barriers have compelled construction SMEs to seek innovative strategies for overcoming challenges. IPD stands out as a procurement method characterised by principles such as early involvement of key stakeholders, shared risk and reward, collaborative behaviour, and open communication, prioritising project objectives over individual gains. While IPD is not currently practised in the Sri Lankan construction industry, it has gained popularity in developed countries due to its considerable benefits. This study, conducted through a cumulative process involving literature review and semi-structured interviews, aimed to identify barriers to IPD implementation in construction SMEs. The literature review pinpointed financial, technical, legal, cultural, and other barriers, which were further explored in semi-structured interviews. Similarly, strategies for implementing IPD were identified through a literature review and assessed for their applicability in Sri Lankan construction SMEs.

The research highlighted the absence of advanced strategies within Sri Lanka's construction SMEs to address their challenges. To address these barriers and ensure market survival, the study advocates for IPD as a procurement method. The research provides insights into how IPD can be adopted in construction SMEs in Sri Lanka, presenting barriers, and strategies associated with IPD adoption as key contributions. By examining the barriers to IPD implementation among construction SMEs in Sri Lanka, this paper provides valuable insights into the challenges faced by industry practitioners. This identification of barriers enables stakeholders to anticipate and address potential obstacles in their own IPD adoption efforts. Further, through the exploration of strategies to overcome these barriers, this paper offers practical guidance to construction SMEs in Sri Lanka and similar contexts. By implementing these strategies, organisations can enhance their ability to adopt and implement IPD effectively, leading to improved project outcomes and organisational performance. This paper contributes to the theory by empirically validating the barriers to IPD adoption identified in the existing literature. However, the research faced limitations due to the limited awareness of both SMEs and IPD among professionals and the extensive amount of data to analyse. Nevertheless, the data collection and analysis revealed that the implementation of IPD has the potential to resolve a significant number of problems faced by construction SMEs.

7. REFERENCES

Agwu, M.O. & Emeti, C.I., 2014. Issues, Challenges, and Prospects of Small and Medium Scale Enterprises (SMEs) in Port-Harcourt City, *European Journal of Sustainable Development*, *3*(1), 101–114. https://doi.org/10.14207/ejsd.2014.v3n1p101

AIA. (2012, March). *IPD Case Study*. AIA Minnesota, School of Architecture –University of Minnesota.

AIA. (2023, November 23). *Understanding & implementing IPD*. Integrated Project Delivery: A Guide.

Alves, T., Barros Neto, J., Heineck, L., Kemmer, S., & Pereira, P. (2011). Incentives and innovation to sustain lean construction implementation. *17th Annual Conference of the International Group for Lean Construction* (pp. 583-592), Taipei, Taiwan. Retrieved from https://www.researchgate.net/publication/282338935_Incentives_and_innovation_to_sustain_lean_construction_implementation

Autodesk Whitepaper. (2008). *Improving building industry results through integrated project delivery and building information modeling*. Autodesk, In.

Briscoe, G., Dainty, A. R. J., & Millett, S. (2001). Construction supply chain partnerships: skills, knowledge and attitudinal requirements. *European Journal of Purchasing & Supply Management*, *7*(4), 243–255. https://doi.org/https://doi.org/10.1016/S0969-7012(01)00005-3

Cohen, J. (2010). *Integrated Project Delivery: Case Studies*. American Institute of Architects.

Creswell, J. (2009). *Research design: Qualitative, quantitative and mixed methods approaches* (3rd ed.). Thousand Oaks, CA: SAGE Publications.

Durdyev, S., Hosseini, M. R., Martek, I., Ismail, S., & Arashpour, M. (2019). Barriers to the use of integrated project delivery (IPD): a quantified model for Malaysia. *Engineering, Construction and Architectural Management*, *27*(1), 186–204. https://doi.org/10.1108/ECAM-12-2018-0535

Eze, C. E., Awodele, I. A., Adegboyega, A. A., Onyeagam, O. P., & Guto, J. A. (2020). Assessment of the triggers of inefficient materials management practices by construction SMEs in Nigeria. *International Journal of Real Estate Studies*, *14*(1), 38–56. https://intrest.utm.my/index.php/intrest/article/view/134

Fish, A. (2011). *Integrated project delivery: The obstacles of implementation*. [Masters of Science, Kansas State University]. K-State Electronic Theses, Dissertations, and Reports http://hdl.handle.net/2097/8554.

Fulford, R., & Standing, C. (2014). Construction industry productivity and the potential for collaborative practice. *International Journal of Project Management*, *32*(2), 315–326. https://doi.org/https://doi.org/10.1016/j.ijproman.2013.05.007

Ghassemi, R., & Becerik-Gerber, B. (2011). Transitioning to Integrated Project Delivery: Potential barriers and lessons learned. *Lean Construction Journal*, *2011*, 32-52. https://leanconstruction.org/wp-content/uploads/2022/08/LCJ_11_sp3.pdf

Gunathilake, S., & Jayasena, S. H. (2008). Developing relational approaches to contracting: The Sri Lankan context. In R. Haigh & D. Amaratunga (Eds.), *International Conference on Building Education and Research* (pp. 1528–1541).

Haiyan, X., & Hua, L. (2017). Studying contract provisions of shared responsibilities for integrated project delivery under national and international standard forms. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *9*(3), 04517009. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000220

Ilozor, D. (2012). Building information modelling and integrated project delivery in the commercial construction industry: A conceptual study. *Journal of Engineering, Project, and Production Management*, *2*(1), 23-36. https://doi.org/10.32738/JEPPM.201201.0004

Jayasena, H., & Senevirathna, N. (2012). Adaptability of Integrated Project Delivery in a Construction Industry. *World Construction Conference 2012 – Global Challenges in Construction Industry*, Colombo, Sri Lanka.

https://www.researchgate.net/publication/338608014_Adaptability_of_Integrated_Project_Delivery_in_a_Construction_Industry

Joseph, L. A., & Jayasena, H. S. (2008). Impediments to the Development of Design and Build Procurement System in Sri Lanka. In R. Haigh & D. Amaratunga (Eds.), *International Conference on Building Education and Research* (pp. 1566–1575).

Kahvandi, Z., Saghatforoush, E., Alinezhad, M., & Noghli, F. (2017). Integrated project delivery (IPD) research trends. *Journal of Engineering, Project, and Production Management*, *7*(2), 99–114. https://doi.org/10.32738/JEPPM.201707.0006

Kent, D., & Becerik-Gerber, B. (2010). Understanding construction industry experience and attitudes toward integrated project delivery. *Journal of Construction Engineering and Management-136*(8), https://doi.org/10.1061/(ASCE)CO.1943-7862.0000188

Ling, F. Y., Xin, T. P., Shan, L., Zhe, Z., & Qiuwen, M. (2020). Adoption of integrated project delivery practices for superior project performance. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *12*(4), 05020014. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000428

Mei, T., Wang, Q., Xiao, Y., & Yang, M. (2017). Rent-seeking behavior of BIM- and IPD-based construction project in China. *Engineering, Construction and Architectural Management*, *24*(3), 514–536. https://doi.org/10.1108/ECAM-11-2015-0178

Moses, S., El-Hamalawi, A., & Hassan, T. M. (2008). The practicalities of transferring data between project collaboration systems used by the construction industry. *Automation in Construction*, *17*(7), 824–830. https://doi.org/https://doi.org/10.1016/j.autcon.2008.02.007

Mossman, A., Ballard, G., & Pasquire, C. (2013). Lean Project Delivery — innovation in integrated design & delivery. In J. Eynon (Eds.), *The Design Manager's Handbook* (1st ed., pp. 165–190). Wiley Blackwell. https://doi.org/10.13140/2.1.2713.2804

Naismith, N., Tookey, J., Hoseini, A. G., & Kekreja, R. (2016). The adoption of integrated project delivery in public sector projects in New Zealand: the way forward. In Y. Sandanayake, G. Karunasena, & T. Ramachandra (Eds.), *Greening Environment, Eco-Innovations & Entrepreneurship* (pp. 507–516). Ceylon Institute of Builders.

Ogunbiyi, O., Goulding, J. S., & Oladapo, A. (2014). An empirical study of the impact of lean construction techniques on sustainable construction in the UK. *Construction Innovation*, *14*(1), 88–107. https://doi.org/10.1108/CI-08-2012-0045

Pishdad-Bozorgi, P., & Beliveau, Y. J. (2016). Symbiotic relationships between integrated project delivery (IPD) and trust. *International Journal of Construction Education and Research*, *12*(3), 179–192. https://doi.org/10.1080/15578771.2015.1118170

Rached, F., Hraoui, Y., Karam, A., & Hamzeh, F. (2014). Implementation of IPD in the Middle East and its Challenges. Proceedings International Group for Lean Construction, (pp.293-304), Oslo, Norway. https://doi.org/10.13140/RG.2.1.3348.6724/1

Ranadewa, K.A.T.O., Y.G. Sandanayake, Y.G.S. and Siriwardena, M. (2021). Enabling lean through human capacity building: an investigation of small and medium contractors, *Built Environment Project and Asset Management*, 11(4), 594-610. https://doi.org/10.1108/BEPAM-03-2020-0045

Roy, D., Malsane, S., & Samanta, P. (2018). Identification of critical challenges for adoption of integrated project delivery (IPD). *Lean Construction Journal*, 01-15. https://leanconstruction.org/wp-content/uploads/2022/08/LCJ_17_007.pdf

Shelton, J., Martek, I. & Chen, C., (2016). Implementation of innovative technologies in small-scale construction firms: Five Australian case studies. *Engineering, Construction and Architectural Management*, *23*(2), 177-91. http://dx.doi.org/10.1108/ECAM-01-2015-0006

Sive, T. (2009). Integrated project delivery: Reality and promise, a strategist's guide to understanding and marketing IPD. Society for Marketing Professional Services Foundation, 10-17. https://www.scribd.com/document/504125811/Sive-White-Paper-IPD

Sommer, A. F., Dukovska-Popovska, I., & Steger-Jensen, K. (2014). Barriers towards integrated product development — Challenges from a holistic project management perspective. *International Journal of Project Management*, *32*(6), 970–982. https://doi.org/https://doi.org/10.1016/j.ijproman.2013.10.013

Subaih, A. (2015). Integrated Project Delivery: A paradigm shift for oil and gas projects in the UAE and the Middle East region. *Oil and Gas Facilities*, *4*(4), 64–77. https://doi.org/10.2118/171722-PA

Teng, Y., Li, X., Wu, P., & Wang, X. (2019). Using cooperative game theory to determine profit distribution in IPD projects. *International Journal of Construction Management*, *19*(1), 32–45. https://doi.org/10.1080/15623599.2017.1358075

Tezel, A., Koskela, L., & Aziz, Z. (2018). Current condition and future directions for lean construction in highways projects: A small and medium-sized enterprises (SMEs) perspective. *International Journal of Project Management*, *36*(2), 267–286. https://doi.org/https://doi.org/10.1016/j.ijproman.2017.10.004

Uhanovita A.C., N., K.A.T.O., R. and Parameswaran, A. (2023), Poka-Yoke to minimise variations: a framework for building projects, *Construction Innovation*. https://doi.org/10.1108/CI-12-2022-0343

Kanimaruthan, P., Kulatunga, U. and Thennakoon, T.M.P.N., 2024. Integrating 5D-BIM approach optimising quantity calculation efficiency in the Sri Lankan construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 634-647. DOI: https://doi.org/10.31705/WCS.2024.50. Available from: https://ciobwcs.com/papers/

INTEGRATING 5D-BIM APPROACH OPTIMISING QUANTITY CALCULATION EFFICIENCY IN THE SRI LANKAN CONSTRUCTION INDUSTRY

P. Kanimaruthan[1], U. Kulatunga[2] and T.M.P.N. Thennakoon[3]

ABSTRACT

Quantity calculation is a key component of the cost estimation process. Cost consultancy firms encounter various challenges such as higher time consumption, lower accuracy, higher expenditure for employees, and higher stress levels for estimators when conventional methods are practiced for quantity calculation. The drawbacks of quantity calculation with conventional methods can be effectively addressed through the adoption of 5D-Building Information Modelling (BIM) based quantity calculation. 5D-BIM is one of the dimensions of BIM which is beneficial in Quantity Surveying related aspects. Thus, this study aims to investigate the advancements of 5D-BIM that can be brought to the quantification approaches in the Sri Lankan context. Accordingly, a qualitatively based extensive literature synthesis has been conducted to review the concept of 5D BIM, ascertain the problems of conventional quantification methods, identify the key features of 5D BIM-based quantity calculation, and explore how the problems of conventional quantification approaches can be solved by the key features of 5D-Building Information Modelling (BIM) based quantity calculation. Following the qualitative approach, data were collected through eleven semi-structured expert interviews. Experts were selected through purposive sampling followed by snowball sampling. The data analysis was conducted through manual content analysis. Findings revealed context, features of 5D-BIM-based quantity calculation which solve the problems of conventional methods in the Sri Lankan context which includes high time consuming, lesser accuracy, minimal collaboration, inefficient for preliminary stage estimating and inefficient for cost planning with cross-reference to the findings in the literature review. In addition to the findings in the literature review respondents were suggested problems in conventional methods in Sri Lanka and how those problems can be addressed through key features of the 5D-BIM approach.

Keywords: *5D-Building Information Modelling (BIM); Conventional Quantity Calculation; Quantity Calculation; Quantity Surveyor (QS).*

[1] Graduated Quantity Surveyor, Department of Building Economics, University of Moratuwa, Sri Lanka, pkanimaruthan@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, udayangani2002@yahoo.com
[3] Temporary Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, piyumithnisansala146@gmail.com

1. INTRODUCTION

Cost estimation is an important task for determining the cost of a construction project (Ismail et al., 2016). As the project complexity increases, the cost estimation consequently becomes more difficult and time-consuming (Bettemir, 2018). Quantity calculation is an inherent and prominent component of the cost estimation process (Varma et al., 2016). Requirements of investors in providing value for money and improving the efficiency and accuracy of cost estimates have become challenges in the construction industry (Babatunde et al., 2020). Despite the importance of cost estimation and quantity calculation, the efficiency of traditional estimating methods has been questioned, especially when dealing with the increased competition within the construction industry (Babatunde et al., 2020). Improper calculation of quantities is one of the critical factors that affect the cost performance of a construction project (Doloi, 2012; Fazeli et al., 2021). More importantly, cost performance can be affected due to inaccurate quantity calculations and inaccurate BOQ Human errors have had a negative impact on the conventional quantity take-off process in various instances. Additionally, even after the identified errors have been rectified, there is no guarantee of the reliability of calculated quantities (Monteiro & Martins, 2013).

"Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility and BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle" (National Institute of Building Sciences [NIBS], 2007, P.8). Moreover, BIM represents geometric and non-geometric details of building in a digital way and can be used for various purposes (NBIMS, 2010, as cited in Stanley & Thurnell, 2014).

5D BIM facilitates quantity calculation, modification, and extrication of data incorporated within the BIM model to become a prime source of information that could be used in Quantity Surveying practices (Stanley & Thurnell, 2014). In addition, many firms identified 5D BIM as a competitive approach to cost management of construction projects (Smith, 2016). 5D BIM confers the facility for Quantity Surveyors (QSs) to generate quantities directly from a properly updated BIM model through 5D BIM-based software. As the monotonous quantification task can be simplified through 5D BIM, it offers ample time for QSs to provide more focus on other project-related specific aspects including factorising risk and pricing (Autodesk, 2007, as cited in Mayouf et al., 2019).

5D BIM offers numerous advantages to the construction industry including increased understanding of the project through digital representation (Stanley & Thurnell, 2014; Usman et al., 2019), improvement in the accuracy of quantity calculation (Usman et al., 2019; Wahab & Wang, 2022), increased collaboration among the project team (Hasan & Rasheed, 2019), integration of time, cost, and other parameters in one model (Nawari & Ravindran, 2019), early detection of clashes and design errors, mitigation of risks associated with costing and scheduling and other related benefits (Hasan & Rasheed, 2019). Further, the Quantity Surveying practice can be shifted from spending significant time in quantity calculation to validating the generated quantities with the advent of 5D BIM (Sylvester & Dietrich, 2010).

Although 5D BIM can provide numerous advantages in terms of quantity calculation, there are some problems regarding the 5D BIM-based quantity calculation. For instance, cultural resistance, inadequate qualified staff, higher initial cost, inadequate protocol and criteria, inaccurate quantifications due to inadequate design details, problems due to interoperability, and other related limitations (Hasan & Rasheed, 2019; Smith, 2014). More importantly, bulk checking of quantities is required to ensure whether the generated quantities are correct (Harrison & Thurnell, 2015; Stanley & Thurnell, 2014). However, Stanley and Thurnell (2014) have stated that through effective collaboration between relevant stakeholders in BIM modelling, some existing problems related to 5D BIM could be overcome. In addition, Harrison and Thurnell (2015) argued that through continuous usage of 5D BIM and ensuring that required inputs are provided by designers to the model, benefits from 5D BIM can be enhanced.

Olatunji and Sher (2015) emphasised that with the advent of BIM for estimation purposes, there is a requirement for research regarding advances in BIM. This aspect promoted several studies on 5D BIM related to Quantity surveying practices. Therefore, this paper aims to provide a detailed investigation of 5D BIM-based quantity calculation in the Sri Lankan context. Following the aim of this study the objectives were set as overview of conventional Quantity calculation and its problems, identifying the key features of 5D-BIM-based quantity calculation and method of solving the problems of the conventional method. and identifying the problems related to conventional quantity calculation and methods of solving them using 5D-BIM features in the Sri Lankan context. First two objectives were addressed through literature synthesis and the third objective was addressed through the data collection section. Moreover, collected data were analysed using manual content analysis.

2. OVERVIEW OF CONVENTIONAL QUANTITY CALCULATION

Cost estimation is a cost forecasting process employed to ascertain the prospective cost of a construction project (Akcay et al., 2018; Kurasova et al., 2021; Washington State Department of Transportation, 2015). Elfaki et al. (2014) identified cost estimation as a prominent preliminary process of any construction project. An estimator primarily concentrates on estimating the cost of a construction project and provides a basic idea regarding the cost before the commencement of work (Varma et al., 2016). Estimation is a core aspect of the construction project; the accuracy of estimates ranging from early cost estimates to tendering stage estimates can influence the success of a construction project. Proper quantity calculation is of vital importance in the cost estimation process as inaccurate quantity calculation could result in erroneous cost estimates (Bettemir, 2018). Currently, quantity calculation is mostly done using 2D estimation software including Planswift, Timberline, and Onscreen Takeoff (Wahab & Wang, 2022). The authors further mentioned that manual taking-off based on hardcopy drawings also prevails in the industry.

2.1 PROBLEMS IN CONVENTIONAL QUANTIFICATION

As traditional-based quantity calculation relies on the human element, errors associated with the human element could result and more complicated structures could not be effectively quantified (Monteiro & Martins, 2013). Higher time consumption (Hasan & Rasheed, 2019; Mayouf et al., 2019; Shen & Issa, 2010; Smith, 2016), lesser accuracy (Hasan & Rasheed, 2019; Shen & Issa, 2010), and minimal collaboration (Hasan & Rasheed, 2019; Mayouf et al., 2019) are some of the major drawbacks associated with manual and 2D-software based quantity calculation methods. Similar to Hasan and Rasheed (2019) and Lee et al. (2005) expressed that traditional quantification entails a time-consuming quantification process since the detailed assessment of measurements is associated with this process. This aspect becomes more problematic on large-scale projects where a significant amount of drawing details needs to be handled, more importantly, when frequent design changes are experienced, inaccurate estimates could ultimately result (Royal Institution of Chartered Surveyors [RICS], 2014). In several circumstances, human errors can occur during manual take-off. Moreover, even after the correction of identified errors, assurance cannot be provided for the prepared estimate (Monteiro & Martins, 2013); nevertheless, 2D software takeoff is identified as one of the commonly used estimating methods in the present construction industry (Matejka & Vitasek, 2018).

In addition, manual or 2D software-based takeoff methods are inefficient for estimating purposes that are required during the preliminary stages of a project (Harrison & Thurnell, 2015; Stanley & Thurnell, 2014). During the design stage, as per the requirements of designers or clients, QS may be required to deliver cost advice on various design options. Moreover, the designers may require ensuring that a cost-effective design is maintained (Wahab & Wang, 2022). In addition, Wahab and Wang (2022) mentioned that through the conventional 2D-based quantity take-off methods, it is difficult to make an effective decision instantly. The reason behind this difficulty is that manual or 2D software-based takeoff methods require significantly more time to prepare takeoffs for various design options to enable comparison (Abanda et al., 2017).

Manual and 2D software-based takeoff methods are reported to be less appropriate for cost planning purposes (Harrison & Thurnell, 2015; Stanley & Thurnell, 2014). When considering 2D software-based quantification for cost planning, it would consume a considerable amount of time and may not be effective in managing the complexities of conducting comparative analysis within the designated time frame for the design development process (Smith, 2014). Table 1 summarises the problems of conventional quantification methods.

Table 1: Problems of conventional quantification methods

Problems	Authors
High time consuming	Wahab & Wang (2022); Lee et al. (2005); Smith (2016); Hasan & Rasheed (2019); Shen & Issa (2010); Mayouf et al. (2019)
Lesser accuracy	Wahab & Wang (2022); RICS (2014); Monteiro & Martins (2013); Hasan & Rasheed (2019); Shen & Issa (2010)
Minimal collaboration	Wahab & Wang (2022); Hasan & Rasheed (2019); Mayouf et al. (2019)
Inefficient for preliminary stage estimating	Abanda et al. (2017); Stanley & Thurnell (2014); Harrison & Thurnell (2015)
Inefficient for cost planning	Smith (2014); Stanley & Thurnell (2014); Harrison & Thurnell (2015)

3. BUILDING INFORMATION MODELLING (BIM)

According to Associated General Contractors of America (2005), BIM is the development and use of a computer software model to simulate the construction and operation of a facility.

With its potential and momentum, BIM began to receive more recognition within the construction sector (Mayouf et al., 2019). BIM provides an IT-enabled centralised approach where all disciplines can collaboratively work on a centralised model effectively (Bryde et al., 2013; Grilo & Jardim-Goncalves, 2010). Moreover, BIM as a modern paradigm has an adequate capacity for incorporation during the total life cycle of construction projects (Nagalingam et al., 2013). Various concerns associated with traditional processes in terms of the management of information could be resolved through the adoption of BIM (Smith, 2014). Different subsets of BIM are generally referred to in terms of dimensions (Ds) including 4D (time factor), 5D (cost aspect), 6D (facilities management), 7D (sustainability), and other subsequent dimensions in which each dimension is an outcome of the data/information layer incorporated within the BIM model (Eastman et al., 2010; Smith, 2014). Stanley and Thurnell (2014) mentioned that 5D BIM can be straightly used to price the construction works as model objects contain data related to specification and other relevant properties. 5D BIM encompasses objects and assemblies within the BIM model, which contains a cost dimension incorporated into it either through inserting cost data with the BIM model objects, or that can be linked with estimating software tools (Boon & Prigg, 2012). However, as per the current practice, 5D BIM is used outside the core of the BIM model through live linking with a third-party estimating tool (Stanley & Thurnell, 2014).

3.1 KEY FEATURES OF 5D-BIM-BASED QUANTITY CALCULATION AND METHOD OF SOLVING THE PROBLEMS OF CONVENTIONAL METHOD

According to Thurairajah and Goucher (2013), since BIM model objects contain geometrical properties and objects represent the elements of the building, automatic quantity extraction is enabled through BIM models. Through automation, the duplication work of manually quantifying what designers have already done can be simplified thereby a significant amount of time-saving could be achieved (Hannon, 2007). Further, automatic quantification reduces human error and improper drawing interpretation thereby increasing the accuracy of the estimate (Rundell, 2006). Similar to Hannon (2007) and Wahab and Wang (2022) added that 5D automation assists extensively in accurately quantifying complicated building elements.

3D Visualisation allows the users to obtain a proper understanding of the project design (Goldberg, 2007). 3D visualisation also simplifies the overall estimation process since it provides a better understanding of the orientation and integration of building elements (Aibinu & Venkatesh, 2014; Stanley & Thurnell, 2014; Usman et al., 2019).

The introduction of BIM has encouraged a collaborative work environment with a single central model where changes in design can be updated automatically and coordinated with the project team members (Hasan & Rasheed, 2019; Nawari & Ravindran, 2019). Further to (Nawari & Ravindran, 2019), BIM introduces an ideal way of interconnecting all relevant data into a centralised-shared model including geometrical, temporal, financial, and property management layers.

Incorporating design changes in the estimate is a tedious task in the conventional quantification method (Wahab & Wang, 2022). However, in the 5D-BIM-based method, design changes can be conveniently accommodated (Harrison & Thurnell, 2015; Kamardeen, 2010; Stanley & Thurnell, 2014). Moreover, during design changes, 5D-BIM could assist in rapidly comparing different design alternatives and assessing the consequences of design to the total cost (Lu et al., 2016; Vigneault et al., 2019). Accuracy of the estimate and time requirement can be maintained at a desirable level as design alterations are easily managed in 5D BIM-based quantity calculation (Wahab & Wang, 2022).

4. RESEARCH METHODOLOGY

The research approach refers to the systematic plans and procedures used to conduct research, encompassing the progression from broad hypotheses to specific techniques for collecting, analysing, and interpreting data (Ritchie et al., 2013). For this study, the qualitative research approach has been used because the qualitative research approach is adopted to represent the perceptions, experiences, beliefs, and viewpoints of a particular group of people and this approach is an ideal option for research regarding emerging conceptions investigations (Ritchie et al., 2013). Generalising research findings is not expected in most of the qualitative research (Dawson, 2007). This paper addressed the research problem "What are the advancements of 5D BIM-based quantity calculation that solve the problems of conventional quantity calculation methods in the Sri Lankan context?".

The study required gathering information regarding problems of conventional quantity calculation methods, advancements of 5D BIM-based quantification, and improvements to 5D BIM-based quantification through an in-depth inquiry. The flexibility to adjust the questions during the study was also required. Hence, semi-structured interviews have been selected for this research as a data collection technique. Accordingly, eleven interviews were conducted with experts in 5D BIM-based quantity calculation to explore the problems of conventional quantity calculation methods in the Sri Lankan context, key features of 5D- BIM-based quantity calculation which addresses the problems of conventional quantification approaches with cross-reference to the findings in the literature review.

Sampling is used to select appropriate samples from the established population (Taherdoost, 2016). This study required the notions of experts who have adequate experience in both conventional quantification and 5D BIM-based quantification. Therefore, purposive sampling is initially adopted to identify experts who fulfill the requirements. In addition, snowball sampling is adopted for the instances where it is difficult to identify the potential respondents from the defined population (Etikan & Bala, 2017). In the Sri Lankan context, 5D BIM adoption has occurred recently and it is difficult to identify the respondents who have adequate experience in both 5D BIM-based quantification and conventional quantification. Therefore, followed by purposive sampling, snowball sampling was also adopted to identify respondents for this study. Accordingly, as mentioned above the initial sample was limited to interviews of Eleven (11) respondents who were saturated after the ninth interview. Table 2 summarises the profile of the interviewees.

Table 2: Profiles of interviewees

Code	Designation	Number of projects involved with 5D-BIM-based quantity calculation	Industry Experience
R1	Quantity Surveyor	More than 50	5
R2	Senior Consultant Quantity Surveyor	More than 30	11
R3	Quantity Surveyor	More than 30	4
R4	Senior Quantity Surveyor, BIM leader for QS division	More than 30	9
R5	General manager-Estimation	20	16

Code	Designation	Number of projects involved with 5D-BIM-based quantity calculation	Industry Experience
R6	Quantity Surveyor	12	5
R7	Quantity Surveyor	10	4
R8	Director, Senior Quantity Surveyor	8	17
R9	Senior Quantity Surveyor	8	15
R10	Director, Senior Quantity Surveyor	6	30
R11	Director, Senior Quantity Surveyor	5	18

5. RESEARCH FINDINGS

Based on the generic factors that are identified in the literature review related to problems in conventional quantification key features of 5D-BIM-based quantity calculation for solving these problems were analysed according to the opinions of the experts. The collected data were analysed through manual content analysis. Consequently, findings through the conducted expert interviews have been discussed as follows.

5.1 PROBLEMS RELATED TO CONVENTIONAL QUANTITY CALCULATION AND METHODS OF SOLVING

Problems regarding conventional quantity calculation methods in the Sri Lankan context were gathered through expert interviews. Accordingly, Table 3 indicates the responses of experts regarding problems of the conventional quantity calculation methods. Six additional problems were identified beyond those identified in the literature review.

Table 3: Problems related to conventional quantity calculation methods

Factors	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11
Higher time consumption	√	√	√	√	√	√	√	√	√	√	√
Lower accuracy		√		√	√	√	√	√	√		√
Minimal collaboration	√	√	√	√	√	√	√	√	√	√	√
Inefficient option for preliminary stage estimating	√		√		√		√	√	√		
Inefficient option for cost planning	√		√		√		√	√	√		
Difficulties in understanding the drawing	√	√	√	√	√	√	√	√	√	√	√
Hard to trace back				√			√				√
High cost for estimators	√			√							
Mismatches among drawings		√									
Hard to compile the work of different employees				√							
QSs feel discomfort							√				

5.1.1 Higher Time Consumption

All the respondents criticised that higher time consumption is a prime problem associated with conventional quantification approaches. On this issue, R2 elaborated that conventional quantification is a tedious task and QSs may be required to refer to different parts of the drawings to measure a single item. By agreeing with R1, R7, and R8, R2 mentioned that through 5D-BIM-based quantity calculation, manual works in quantification can be **automated** thereby significant time saving can be achieved. R2 mentioned, *"Various details are integrated into one place. Therefore, together with the automation, information integration assists in achieving a higher level of time-saving"*. R1 added that this **information integration** simplifies the quantity-checking process since it is not required to refer to various drawings to check one element. R7 stated that in most instances, design changes are initiated during the quantity calculation process. R7 further stated that since 5D BIM facilitates accommodating **design changes conveniently**, the total time required for the quantification process is minimised. R1 and R4 commented that the 5D BIM-based method expedites the communication in the quantification process through **increased collaboration**.

5.1.2 Difficulties in Understanding the Drawing

According to the explanation provided by R5, in the 5D-BIM-based quantity calculation method, building elements can be virtually visualised in 3D. Therefore, unlike the conventional method, QS can quickly obtain a proper understanding of what is going to be quantified. It assists in doing the quantity calculation properly.

5.1.3 Lower Accuracy

Eight respondents contended that the **accuracy of the conventional quantification is lower**. R11 mentioned, *"possibility of making errors is quite higher in terms of missing quantities and during quantity calculation. Therefore, the collective accuracy of the quantity estimate is lower"*. This reasoning is aligned with the explanation presented by R4. Moreover, by agreeing with R3, R1 brought a different perspective for the reasoning on lower accuracy. R1 proposed, *"due to the intensive involvement of human element, human-related errors can occur in this process thereby accuracy is lower".* Conversely, R10 believes that the accuracy of the conventional method is reasonable. However, deviating from the above arguments, both R2 and R9 argued that the accuracy of conventional quantity calculation depends on the person who is doing it. R2 stated, *"Knowledge and understanding of the person especially on structural element influences on the accuracy"*. Moreover, R9 added that the interest of the person also affects the accuracy of the output.

R1 stated that 5D BIM **automation** significantly replaces the involvement of the human element in quantity calculation. Therefore, human-related errors are minimised, and accuracy is improved. R8 elaborated, *"For example, when you are measuring an area of a curvy element in the conventional method, you may be required to draw a polyline. When drawing the element, you may make mistakes. Similarly, there are various mistakes. However, the 5D BIM-based method uses advanced calculation algorithms to calculate them with 100% accuracy"*.

5.1.4 Minimal Collaboration

R9 added that the interest of the person also affects the accuracy of the output. All the respondents mentioned that the **collaboration level is lower** among project stakeholders in the conventional project delivery method. According to R1 and R4, minimal collaboration and its consequential adverse impacts are there with the conventional method. Decreased productivity, wastage of resources, communication deficiencies, decreased knowledge sharing and thereby decreased value addition to the project are some of the consequences of minimal collaboration. However, the 5D-BIM-based quantity calculation method minimises those consequences through **increased collaboration**.

5.1.5 Inefficient Option for Preliminary Stage Estimating and Cost Planning

Five respondents expressed that the conventional method is reasonable for the preliminary stage estimating. R2 mentioned that BIM models become more detailed at the design stage. However, six respondents argued that **the conventional method is inefficient for the preliminary stage estimating**. R1 described, *"Basically conventional method is inefficient for the preliminary stage estimating since it involves various manual quantification works. Moreover, the conventional method becomes more inefficient especially when the scale of project and complexity of the project is higher".* This argument is aligned with R3, R7, R8 and R9. According to R7 and R8, **all the six key features** identified above collectively help to improve the preliminary stage estimating. A similar trend of responses was received regarding the concerns associated with conventional cost-planning methods.

5.1.6 Hard to Trace Back

Three respondents stated that **tracing back quantities is a difficult** task in the conventional quantification method. R4 stated, *"When you need to check any quantities that are produced in the conventional method, of course, you can do that. But it is very difficult for you to identify how the quantities have been derived".* By agreeing with R4 and R7, R11 highlighted that the tracing back feature of the 5D BIM-based method including tracing quantity breakdown and tracing model demarcation helps to reduce the difficulties associated with checking the quantities.

5.1.7 High Cost for Estimators

R1 and R4 identified that the **cost for the estimators is higher** in the conventional method. R1 elaborated that in the conventional method, payment for estimators is provided based on the deployed man hours. R1 stated that 5D BIM **automation** significantly reduces the manual work of the estimators. Further to R1, the time requirement for quantity calculation is reduced thereby cost for the estimators can be reduced. Moreover, it should be noted that this cost reduction can be obtained when a project is large or complex.

5.1.8 Mismatches among Drawings

R2 stated that **mismatches among drawings** are also a drawback of the conventional method. R2 mentioned *"During the conventional method of quantity calculation, you will receive different types of drawings and design information such as plans, elevations, sections and specifications, etc. Everything will be in different places. Sometimes the information in one place does not match with the same information that you see in another place".* This aspect could cause problems in quantity calculation. R2 mentioned that **increased collaboration** in BIM helps to reduce the discrepancies between drawings. R2 further elaborated, *"in the conventional method, for example, you will find differences* *between Architectural drawings and structural drawings. This type of problem can be controlled through increased collaboration".*

5.1.9 Hard to Compile the Work of Different Employees

R4 asserted that in conventional quantification methods, quantification works of large projects are distributed among numerous estimators. Therefore, it is **difficult to compile the estimates of different estimators** since they may use different procedures, estimating techniques, tools, and formats. R4 opined that **automation** reduces the number of estimators working on one project and provides output in the same format. Further to R4, subsequently, difficulties in compiling the works are minimised.

5.1.10 QSs Feel Discomfort

R7 stated that compared to the conventional method, QSs' work is simplified in a 5D BIM-based method through **automation, virtual visualisation,** and **convenient accommodation of design changes**.

6. DISCUSSION

Respondents mentioned that the 'automation' and 'convenient accommodation of design change' features of the 5D BIM-based method reduce the time required for quantity calculation. This is consistent with the literature findings by Hannon (2007) and Wahab and Wang (2022) respectively. Further, respondents highlighted that 'information integration' also together with 'automation' facilitates the time reduction. According to Rundell (2006), 'automation' results in increased accuracy of quantity calculation. This aspect is aligned with the data collection findings. One respondent added that 'collaboration' enhances the accuracy of output as design changes can be effectively communicated to the estimator. In addition, respondents argued that the 'increased collaboration' of the 5D-BIM-based method assists in controlling the adverse consequences of minimal collaboration which is a drawback of the conventional method. Moreover, as per the collected data, 'virtual visualisation' reduces the difficulties in understanding the drawings. This is consistent with the literature finding by Goldberg (2007). Fewer research studies are focusing on what key features of 5D BIM help to improve preliminary stage estimating and cost planning. When analysing the responses it can be understood that 'automatic quantity extraction', 'tracing back of quantities', 'virtual visualisation', 'convenient accommodation of design changes', 'information integration', and 'increased collaboration' collectively assists in improving both the preliminary stage estimating and cost planning. The above-discussed problems were primarily identified from the literature as the main problems of the conventional method. The following problems were identified during the data collection process beyond the literature findings. Key features for the problems that were identified during the data collection are discussed below. The 'Tracing back' feature assists in checking the quantities easily. For large-scale or complex projects, 'automation' helps to reduce the expenditure for the estimators. Further, 'automation' controls the difficulties associated with compiling the works of different estimators who are working on a particular project under the conventional method. 'Increased collaboration' reduces the discrepancies between drawings. Moreover, 'automation', 'virtual visualisation', and 'convenient accommodation of design changes' collectively reduce the discomfort level of estimators.

Figure 1 summarises the collected data. On the left-hand side of the diagram, it illustrates the problems related to conventional quantity calculation methods. On the right-hand side of the diagram, it illustrates the 5D-BIM features that address those problems.

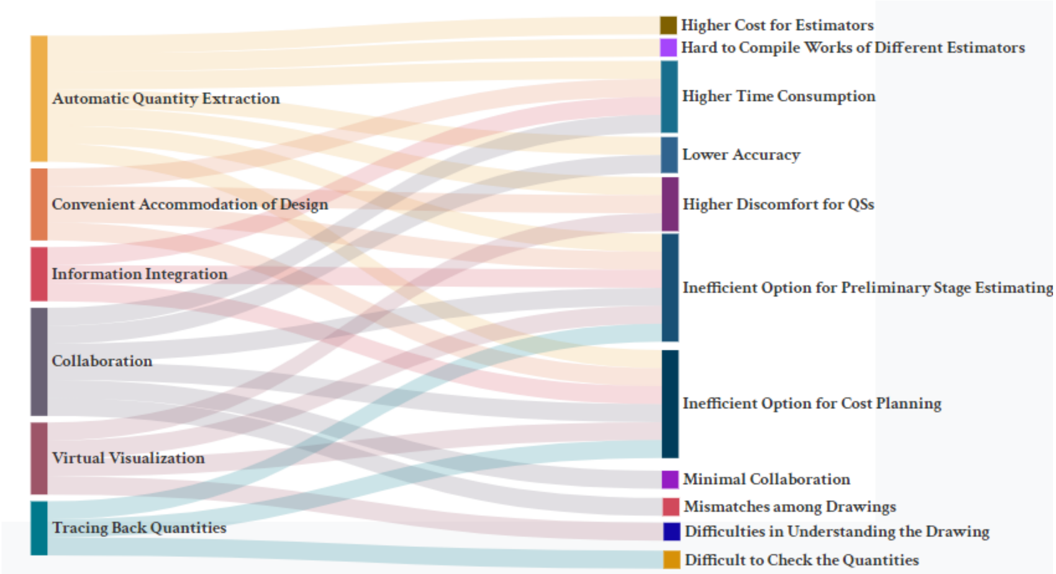


Figure 1: Problems related to conventional quantity calculation and solving 5D-BIM features

7. CONCLUSIONS

Numerous problems are associated with conventional quantity calculation methods. Higher time consumption and lower accuracy are the major drawbacks of conventional methods. Moreover, conventional methods are inefficient in multi-rate methods of preliminary estimating. Further, conventional methods are unproductive for preliminary estimating and cost planning when the project is larger in scope and higher in complexity. Similarly, conventional methods become less suitable for cost planning during the later stages of design development due to the availability of increased design details. From the perspective of the Quantity Surveying profession, 5D BIM is the prominent dimension of BIM technology. 5D BIM-based

quantity calculation entails numerous key features including ‘automatic quantity extraction’, ‘3D-visualisation’, ‘convenient accommodation of design changes’, ‘information integration’, ‘tracing back quantities, and ‘collaboration’. These key features are the pivotal factors that enable the potential of the 5D BIM in quantity calculation. Accordingly, this study assesses how the deficiencies of conventional quantification methods can be overcome through the incorporation of 5D BIM.

This study is limited to the Sri Lankan context, especially with the available 5D BIM-based quantification software used in the Sri Lankan construction industry. Future research should be focused on the “detailed comparison between 5D BIM-based cost estimation and conventional cost estimation can be done in the Sri Lankan context to ascertain whether there are any deviations from the outcomes of this research”. Moreover, the A framework can be developed to implement BIM in the Sri Lankan context in such a way that 5D BIM-based applications are effectively enabled as a future study.

8. REFERENCES

Abanda, F. H., Kamsu-Foguem, B., & Tah, J. H. M. (2017). BIM – New rules of measurement ontology for construction cost estimation. *Engineering Science and Technology, an International Journal*, *20*(2), 443–459. https://doi.org/10.1016/j.jestch.2017.01.007

Aibinu, A., & Venkatesh, S. (2014). Status of BIM adoption and the BIM experience of cost consultants in Australia. *Journal of Professional Issues in Engineering Education and Practice*, *140*(3), 1–10. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000193

Akcay, C., Aslan, S., Sayin, B., & Manisal, E. (2018). Estimating OHS costs of building construction projects based on mathematical methods. *Safety Science*, *109*, 361–367. https://doi.org/10.1016/j.ssci.2018.06.021

Associated General Contractors of America. (2005). *The contractor's guide to BIM* (1st ed.). AGC Research Foundation.

Babatunde, S. O., Perera, S., Ekundayo, D., & Adeleye, T. E. (2020). An investigation into BIM-based detailed cost estimating and drivers to the adoption of BIM in quantity surveying practices. *Journal of Financial Management of Property and Construction*, *25*(1), 61–81. https://doi.org/10.1108/JFMPC-05-2019-0042.

Bettemir, Ö. H. (2018). Development of spreadsheet-based quantity take-off and cost estimation application. *Journal of Construction Engineering, Management & Innovation*, *1*(3), 108–117. https://doi.org/10.31462/jcemi.2018.03108117

Boon, J., & Prigg, C. (2012*). Evolution of quantity surveying practice in the use of BIM – The New Zealand experience*. Joint CIB International Symposium of W055, W065, W089, W118, TG76, TG78, TG81 and G84. https://www.semanticscholar.org/paper/Evolution-of-Quantity-Surveying-Practice-in-the-Use-Boon/c2540a963bda2725f75017b1236853bd9a446ef4

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). *International Journal of Project Management*, *31*(7), 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001

Dawson, C. (2007). *A practical guide to research methods: A user-friendly manual for mastering research techniques and projects* (3rd ed.). How To Books.

Doloi, H. (2012). Cost overruns and failure in project management: Understanding the roles of key stakeholders in construction projects. *Journal of Construction Engineering and Management*, *139*(3), 267–279. http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000621

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2010). *BIM handbook: A guide to building information modelling for owners, managers, designers, Engineers, and contractors* (2nd ed.). John Wiley and Sons.

Elfaki, A. O., Alatawi, S., & Abushandi, E. (2014). Using intelligent techniques in construction project cost estimation: 10-Year survey. *Advances in Civil Engineering*, *2014*(11), 1–11. https://doi.org/10.1155/2014/107926

Etikan, I., & Bala, K. (2017). Sampling and sampling methods. *Biometrics & Biostatistics International Journal*, *5*(6), 215- 217. https://doi.org/10.15406/bbij.2017.05.00149

Fazeli, A., Dashti, M. S., Jalaei, F., & Khanzadi, M. (2021). An integrated BIM-based approach for cost estimation in construction projects. *Engineering, Construction and Architectural Management*, *28*(9), 2828–2854. https://doi.org/10.1108/ECAM-01-2020-0027

Goldberg, E. (2007). Automated estimating and scheduling using BIM. *AEC in Focus*, *24*(9), 1–3. https://rb.gy/y6iovu

Grilo, A., & Jardim-Goncalves, R. (2010). Value proposition on interoperability of BIM and collaborative working environments. *Automation in Construction*, *19*(5), 522–530. https://doi.org/10.1016/j.autcon.2009.11.003

Hannon, J. J. (2007). Estimators' functional role change with BIM. *AACE International Transactions*, 1–8. https://www.proquest.com/docview/208175596

Harrison, C., & Thurnell, D. (2015). BIM implementation in a New Zealand consulting quantity surveying practice. *International Journal of Construction Supply Chain Management*, *5*(1), 1–15. https://doi.org/10.14424/ijcscm501015-01-15

Hasan, A. N., & Rasheed, S. M. (2019). The benefits of and challenges to implement 5D BIM in construction industry. *Civil Engineering Journal*, *5*(2), 412–421. https://doi.org/10.28991/cej-2019-03091255

Ismail, N. A. A., Drogemuller, R., Beazley, S., & Owen, R. (2016). A review of BIM capabilities for quantity surveying practice. In S. N. B. Kamaruzzaman, A. S. B. Ali, N. F. B. Azmi, & S. J. L. Chua (Eds.), *Proceedings of the 4th international building control conference 2016* (pp. 1–7). EPD Sciences. https://doi.org/10.1051/matecconf/20166600042

Kamardeen, I. (2010). 8D BIM modelling tool for accident prevention through design. In C. Egbu (Ed.), *26th annual ARCOM conference*, 6- 8 September (pp. 281–289). Leeds, UK, Association of Researchers in Construction Management.

Kurasova, O., Marcinkevičius, V., Medvedev, V., & Mockevicine, B. (2021). Early cost estimation in customized furniture manufacturing using machine learning. *International Journal of Machine Learning and Computing*, *11*(1), 28–33. https://doi.org/10.18178/ijmlc.2021.11.1.1010

Lee, A., Wu, S., Marshall-Ponting, A. J., Aouad, G., Cooper, R., Tah, J. H. M., Abbott, C., Barrett, P., & S. (2005). *nD modelling road map: A vision for nD-enabled construction*. University of Salford. http://ndmodelling.scpm.salford.ac.uk

Lu, Q., Won, J., & Cheng, J. C. P. (2016). A financial decision-making framework for construction projects based on 5D Building Information Modelling (BIM). *International Journal of Project Management*, *34*(1), 3–21. https://doi.org/10.1016/j.ijproman.2015.09.004

Matejka, P., & Vitasek, S. (2018). Comparison of different cost estimation methods with use of building information modelling (BIM). *Engineering for Rural Development*, *17*, 843–849. DOI: 10.22616/ERDev2018.17.N154

Mayouf, M., Gerges, M., & Cox, S. (2019). 5D BIM: An investigation into the integration of Quantity surveyors within the BIM process. *Journal of Engineering, Design and Technology*, *17*(3), 537–553. https://doi.org/10.1108/JEDT-05-2018-0080

Monteiro, A., & Martins, J. P. (2013). A survey on modelling guidelines for quantity take-off-oriented BIM-based design. *Automation in Construction*, *35*, 238–253. https://doi.org/10.1016/j.autcon.2013.05.005

Nagalingam, G., Jayasena, H. S., & Ranadewa, K. A. T. O. (2013). *Building Information Modelling and future quantity surveyor's practice in Sri Lankan construction industry*. The second world construction symposium: Socio economic sustainability in construction, Colombo, Sri Lanka. (pp. 81–92).

National Institute of Building Sciences (NIBS). (2007). *National building information modelling standard Version 1*. https://buildinginformationmanagement.files.wordpress.com/2011/06/nbimsv1_p1.pdf

Nawari, N. O., & Ravindran, S. (2019). Blockchain technology and BIM process: Review and potential applications. *Journal of Information Technology in Construction*, *24*, 209–238. http://api.semanticscholar.org/CorpusID:181837887

Olatunji, O. A., & Sher, W. (2015). Estimating in geometric 3D CAD. *Journal of Financial Management of Property and Construction*, *20*(1), 24–49. https://doi.org/10.1108/JFMPC-07-2014-0011

Royal Institute of Chartered Surveyors. (2014). *How can building information modelling (BIM) support the new rules of measurement (NRM1)*. https://www.isurv.com/downloads/download/2015/how_can_building_information_modelling_bim_support_the_new_rules_of_measurement_nrm1_rics

Ritchie, J., Lewis, J., Nicholls, C. M., & Ormston, R. (Eds.). (2013). *Qualitative research practice: A guide for social science students and researchers* (2nd ed.). Sage.

Rundell, R. (2006). *1-2-3 Revit: BIM and cost estimating*. Building Design.

Shen, Z., & Issa, R. (2010). Quantitative evaluation of the BIM assisted construction detailed cost estimates. *Journal of Information Technology in Construction (ITcon)*, *15*, 234–257. http://www.itcon.org/2010/18

Smith, P. (2014). BIM & the 5D project cost manager. *Procedia - Social and Behavioural Sciences*, *119*, 475–484. https://doi.org/10.1016/j.sbspro.2014.03.053

Smith, P. (2016). Project cost Management with 5D BIM. *Procedia - Social and Behavioural Sciences*, *226*, 193–200. https://doi.org/10.1016/j.sbspro.2016.06.179

Stanley, R., & Thurnell, D. (2014). The benefits of, and barriers to, implementation of 5D BIM for Quantity Surveying in New Zealand. *Australasian Journal of Construction Economics and Building*, *14*(1), 105–117. http://dx.doi.org/10.5130/ajceb.v14i1.3786

Sylvester, K. E., & Dietrich, C. (2010). Evaluation of Building Information Modelling (BIM) estimating methods in construction education. *Proceedings of 46th ASC annual international conference*, April 2010, (p. 7). http://ascpro0.ascweb.org/archives/cd/2010/paper/CEUE221002010.pdf

Taherdoost, H. (2016). Sampling methods in research methodology; How to choose a sampling technique for research. *SSRN Electronic Journal*, *5*(2), 18–27. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3205035

Thurairajah, N., & Goucher, D. (2013). Advantages and challenges of using BIM: A cost consultant's perspective. *49th ASC annual international conference proceedings*, *California Polytechnic State University (Cal Poly)*, *San Luis Obispo*, *California.* (pp. 10–13).

Usman, O. S., Oaikhena, E. O., & Ojo, L. D. (2019). Benefits of integrating 5D BIM in cost management practices in quantity surveying firms. *4th Research conference of the Nigerian institute of Quantity Surveyors*, (pp. 67–73). https://www.researchgate.net/publication/343064443

Varma, A. K.V., Manideep, T., & Asadi, S. (2016). A critical comparison of quantity estimation for gated community construction project using traditional method vs plan swift software: A case study. *International Journal of Civil Engineering and Technology*, *7*(6), 707–713. https://iaeme.com/Home/article_id/IJCIET_07_06_078

Vigneault, M. A., Boton, C., Chong, H. Y., & Cooper-Cooke, B. (2019). An innovative framework of 5D BIM solutions for construction cost management: A systematic review. *Archives of Computational Methods in Engineering*, *27*(4), 1013–1030. https://doi.org/10.1007/s11831-019-09341-z

Wahab, A., & Wang, J. (2022). Factors-driven comparison between BIM-based and traditional 2D quantity takeoff in construction cost estimation. *Engineering*, *Construction and Architectural Management*, *29*(2), 702–715. https://doi.org/10.1108/ECAM-10-2020-0823

Washington State Department of Transportation. (2015). *Cost estimating manual for projects*. https://www.wsdot.wa.gov/publications/manuals/fulltext/m3034/estimatingguidelines.pdf

Jayakodi, J.A.D.K.S., Mallawaarachchi, B.H. and Yatawatta, Y.J.M., 2024. Internet of things (IoT) enabled carbon emission monitoring in residential buildings: A bibliometric analysis. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 648-660. DOI: https://doi.org/10.31705/WCS.2024.51. Available from: https://ciobwcs.com/papers/

INTERNET OF THINGS (IOT) ENABLED CARBON EMISSION MONITORING IN RESIDENTIAL BUILDINGS: A BIBLIOMETRIC ANALYSIS

J.A.D.K.S. Jayakodi[1], B.H. Mallawaarachchi[2] and Y.J.M. Yatawatta[3]

ABSTRACT

Carbon emissions from residential buildings have drastically increased in the recent past because of lifestyle changes. Hence, there is a critical necessity to implement carbon reduction pathways, and among them, carbon emissions monitoring can be identified as one of the prerequisites for carbon reduction. Many researchers have attempted to deploy various technologies for this purpose, such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), and electricity big data to name a few. This research aims to review the adaptability of IoT for carbon emissions monitoring in residential buildings through a bibliometric analysis of key literature. Accordingly, a Scopus-based systematic review was conducted to analyse the journal articles related to the IoT, carbon emissions monitoring and residential buildings and their intersection. The bibliometrics techniques were used for the analysis of the results of the systematic review. As the primary implication of this research, the bibliometric analysis outcomes significantly contribute to identifying the number of published journals, leading journal authors, and countries active in this field. Accordingly, the outcomes reveal that the number of published articles has consistently increased over the last ten years. Further, the 'Journal of Energies' had published the highest number of articles. Secondly, the proposed framework gives important insights into the intersection of IoT, carbon emissions monitoring and residential buildings including the different types of carbon emission from residential buildings and potential outcomes from IoT-based carbon emission monitoring platforms.

Keywords: *Carbon Emissions Monitoring; Internet of Things (IoT); Residential Buildings***.**

1. INTRODUCTION

The 2023 Global Status Report for Buildings and Construction, which is published by the Global Alliance for Building and Construction hosted by the United Nations Environmental Program claimed that, CO_2 emissions from building construction and

[1] Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, jayakodijadks.19@uom.lk
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, harshinim@uom.lk
[3] Temporary Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, jayaniem@uom.lk

operation have surged to unprecedented levels in 2022 (United Nations Environment Programme, 2024). Further, it mentioned that both direct and indirect emissions from the residential sector hold a 17% share of total global carbon emissions, according to 2022 statistics and it has emerged a critical necessity to implement carbon reduction strategies focused on every sub-sector in the building industry including residential buildings (United Nations Environment Programme, 2024).

When focusing on carbon reduction pathways, carbon emissions monitoring can be identified as one of the key elements because it is beneficial for developing emission reduction plans and policies and post-analysis (Liu, et al., 2020a) IoT, CPS and electricity big data are some technologies can be utilised for carbon emissions monitoring. (Chawla et al., 2023; Devan et al., 2019; Liu, et al., 2020b; Mao et al., 2018; Zhou et al., 2023). Among these technologies, IoT can be recognised as a prominent methodology for carbon emissions monitoring due to its outstanding benefits such as real-time monitoring and the capability of in-depth analysis to determine trends and patterns in carbon emissions (Olatomiwa et al., 2023; Xu et al., 2022). Accordingly, this research paper aimed to review the adoptability of IoT for carbon emissions monitoring of residential buildings through systematic review of key literature as a way forward for future research.

In order to achieve the research aim, two (02) research objectives were formulated:

- To review the evolution of publications, prominent journals, and authors who had made most publications on the intersections of carbon emissions monitoring, IoT, and residential buildings, and
- To propose insights on different intersections between carbon emissions monitoring in residential buildings and IoT as a basis for future research.

2. LITERATURE REVIEW

2.1 CARBON EMISSIONS MONITORING IN RESIDENTIAL BUILDINGS

Carbon emissions from any typical building including residential buildings can be broken down into two main categories as; embodied emissions and operational emissions (Ibn-Mohammed et al., 2013; Izaola et al., 2023). Embodied emissions can be defined as *"the allocation of Green House Gas emissions that arise in the production of construction products of all kinds, their transport to and from the building site, the processes of building construction, maintenance, replacement, and deconstruction, as well as the end of life of building components and the building"* (Lützkendorf & Balouktsi, 2022). Further, Ibn-Mohammed et al., (2013) claim that embodied emissions can be categorised further as initial embodied emissions and recurring embodied emissions. Initial embodied emissions refer to the emissions that occurred due to the initial construction of the building (Ramesh et al., 2010) while recurring embodied emissions refer to the emissions from building repair and replacements (Ibn-Mohammed et al., 2013; Li et al., 2014). Building superstructures and substructures can be identified as the flashpoints of embodied carbon even though they can be varied based on the material usage and building design (Cang et al., 2020; Victoria & Perera, 2017). According to Akbarnezhad and Xiao, (2017), operational carbon emissions can be defined as "the operating carbon comprises of carbon emissions incurred during the service life of a building and includes the carbon emissions incurred in maintaining the indoor environment through processes such as heating, cooling, lighting, and the operation of appliances". Most of the researchers claim that operational emissions are higher than embodied emissions due to the continuous consumption of energy despite the building locations, occupancy patterns and utilising energy sources (Cao et al., 2016; Fenner et al., 2020; Huo et al., 2019). Operational carbon emissions encompass both direct emissions resulting from direct fuel combustion and indirect emissions from producing and distributing required products and services respectively (Hirano et al., 2020; Jiang et al., 2020; Zarco-Periñán et al., 2022; Zhang et al., 2015). According to statistical data, residential buildings are one of the main contributors to total carbon emissions from buildings. For example, residential buildings contribute to 12% of carbon emissions, which is equivalent to over 45 million tonnes of greenhouse gas emissions annually in Australia (Dcceew, 2023). In addition to that, on average, residential buildings emit 2,928 kg of greenhouse gas emissions per m^2 of gross building area throughout their lifecycle, according to Fan and Fang, (2023). Furthermore, according to Li et al., (2022) and Nejat et al., (2015), it is predicted that the energy usage in houses will increase in the future allowing further operational carbon emissions increments. Accordingly, these excessive carbon emissions create a critical necessity to implement carbon reduction projects and policies immediately. In this case, carbon emissions monitoring is the initial layout for implementing carbon emissions reduction plans and policies (Zhou et al., 2023). As reviewed in the literature, many researchers focused on applying different techniques such as IoT, Cyber-physical systems and electricity big data for real-time carbon emissions monitoring with the advancements in information technology (Chawla et al., 2023; Devan et al., 2019; Liu, et al., 2020b; Mao et al., 2018; Zhou et al., 2023). Among these technologies, IoT technology appears to be a promising solution for monitoring carbon emissions because it offers outstanding benefits for real-time carbon emission monitoring (Olatomiwa et al., 2023; Xu et al., 2022).

2.2 IOT-ENABLED CARBON EMISSIONS MONITORING

IoT can be identified as one of the novel paradigms for carbon emissions monitoring in different industries (Xu et al., 2022). IoT can be defined as *"a group of interconnected static and/or mobile objects such as devices equipped with communication, sensors, and actuator modules connected through the internet"* (Sengupta et al., 2020). The main advantage of using IoT for carbon monitoring is their ability for real-time data collection and analysis capabilities. This enables facilities to react promptly to reduce carbon emissions such as energy conservation measures and implement modifications as required (Olatomiwa et al., 2023). Furthermore, the capacity to offer in-depth analysis is another outstanding benefit of IoT-based carbon emissions monitoring (Xu et al., 2022).

However, various research attempts focus on adopting IoT for carbon emissions monitoring in different sectors including the building sector. For example, Mao et al., (2018) developed a real-time carbon emissions monitoring tool for prefabricated construction based on IoT; Tao et al., (2018) introduced an IoT-based carbon emission monitoring system for manufacturing prefabricated components; Zhang et al., (2021) formulated a smart carbon emissions monitoring platform for small cities based on IoT; Devan et al., (2019) established a vehicle emissions monitoring and alert system based on IoT; Martillano et al., (2017) launched an Android-based industrial emissions monitoring system using IoT; and Xu et al., (2023) developed a method for tracking and visualising embodied carbon of prefabricated buildings using IoT and Building Information Modelling to name a few. Despite the widespread use of IoT for carbon emissions monitoring in various industries, there is a scarcity of adopting IoT for monitoring carbon emissions in residential buildings.

3. RESEARCH METHODOLOGY

To complete the present study, a systematic review of literature was used as the methodological basis. Key literature published at the intersection of the fields of Internet of Things (IoT), carbon emission monitoring, and residential building was identified through a systematic review in the Scopus database. This Scopus-based review paper provides initial insights into the adoption of IoT for carbon emission and carbon emission monitoring in residential buildings from 2015 to 2024. Since there were no articles related to the intersection between carbon emission monitoring in residential building and IoT before 2015, the article search was limited to time period from 2015 - 2024. As the initial step of the review, a literature search was conducted in the Scopus database using the keywords 'Internet of Things', 'carbon emission', 'carbon emission monitoring', and 'residential building' to search titles, abstracts, and document keywords published from 2015 to 2024 [TITLE-ABSKEY ("Internet of Things" AND "Carbon Emission" OR "Carbon Emission Monitoring" AND "Residential Building")].

Initially, there were 132 articles that were further refined using the filters available on Scopus's search tool: (i) DOCUMENT TYPES=(Articles) AND (ii) SOURCE TYPE=(Journals) to identify high-quality literature. Accordingly, 95 journal articles were selected as the basis for bibliometric analysis. Bibliometric analysis was used to identify papers relevant to the review. As stated by Donthu et al., (2021) the bibliometric analysis technique has been highly used to evaluate the contributions of research scholars in various fields, patterns of publications, and the relationship between research findings. Hence, the analysis of literature was conducted by adopting two selected bibliometric indicators: the co-occurrence of words and the number of articles showing the intersection of the fields of IoT, carbon emission monitoring, and residential building. According to the Mokhtarpour and Khasseh, (2021), the number of articles reflects scientific output, providing a count of the quantity of works produced by a researcher, while co-occurrence facilitates the recognition of the specific network of a given type of research based on its development over the years.

Hence, the evolution of the number of journal articles published over the years, leading journals, leading authors, and leading countries on the intersection of IoT, carbon emission monitoring, and residential building were identified through the analysis of the evolving trends in the publication of journal articles over time. The literature was chosen based on selected bibliometric indicators to understand the intersection between IoT and carbon emission monitoring concepts in residential buildings.

4. RESULTS AND DISCUSSION

This section presents the key research findings related to two major areas; (i) Outcomes of bibliometric analysis, and (ii) Adopting IOT for carbon emission monitoring in residential buildings.

4.1 OUTCOME OF THE BIBLIOMETRIC ANALYSIS

As the initial step, the data derived through the Scopus-based systematic review were analysed using bibliometric analysis to track the adoption of IoT for carbon emission monitoring in residential buildings. The results, which were analysed for the period from 2015 to 2024, are organised under four key headings: (i) Evolution of the number of journal articles published on adopting IoT for carbon emission monitoring, (ii) Leading journals published on adopting IoT for carbon emission monitoring, (iii) Analysis of the leading authors in the field, and (iv) Analysis of leading countries on adopting IoT for carbon emission monitoring.

4.1.1 Evolution of the Number of Journal Articles Published on Adopting IoT for Carbon Emission Monitoring

In the systematic review, 95 journal articles published between 2015 and the first two months of 2024 were selected for analysis. The evolution of the number of journal articles published on Adopting IoT for carbon emission monitoring in residential buildings in the Scopus database is presented in Figure 1.

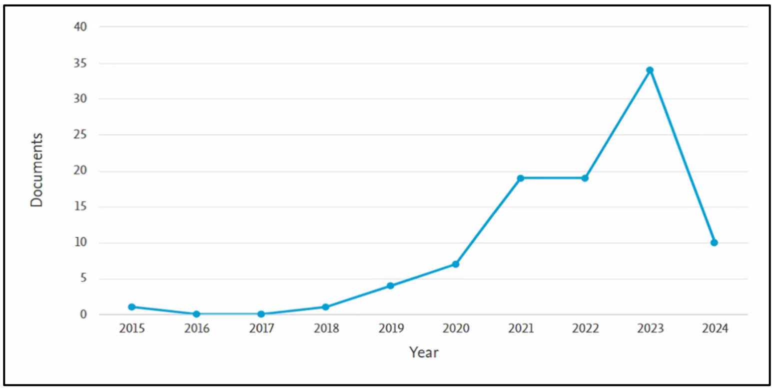


Figure 1: Evolution of number of journal articles

Upon analysis, it was found that the total number of journal articles published on the intersection of IoT, carbon emission monitoring, and residential buildings in Scopus was only 1, which was published in the year 2015. No publications were identified in 2016 and 2017. However, the number increased to 1, 4, and 7 in the years 2018, 2019, and 2020 respectively. Subsequently, there was a significant rise to 19 articles in both 2021 and 2022. The peak occurred in 2023 with 34 articles, while 10 articles were found during the first two months of 2024.

Overall, the graph illustrates a consistent growth in publications on the intersection of IoT, carbon emission monitoring and residential buildings from 2015 (1 article) to 2023 (peak of 34 articles). Many of the published articles focused on analysing the use of IoT for energy usage, energy management, and its adoption in the construction industry. Notably, a study conducted by Azizi et al., (2020) proposed managing energy efficiency and renewable energy in the residential sector through a bibliometric study. Similarly, Ba Nguyen and Cao Nguyen, (2023) explored the design and fabrication of an IoT-based smart electrical meter for residential energy management.

Despite this growing body of research, no articles were found that specifically addressed the intersection of IoT and carbon emission monitoring in residential buildings. Therefore, this study focuses on adopting IoT for carbon emission monitoring in residential buildings.

4.1.2 Leading Journals Published on Adopting IoT for Carbon Emission Monitoring

The leading journals that have published the most articles considering the intersection of IoT, carbon emission monitoring, and residential building from 2015 to 2024 were identified through the review. 'Journal of Energies' was the leading journal that published the highest number of articles (10 articles) on the intersection of IoT, carbon emission monitoring, and residential building during the period from 2015 to 2024. The 'Journal of Cleaner Production' is the second leading journal that published a high number of articles, with 8 articles. 'Building', 'Building Engineering', and 'Sustainability' (Switzerland) are other journals that have given major attention to publishing articles on the intersection of IoT, carbon emission monitoring, and residential building during the period from 2015 to 2024.

The fluctuations in leading journal publications from 2015 to 2024 are shown in Figure 2. In 2019, the leading journal for the intersection of IoT, carbon emission monitoring, and residential building is the 'Journal of Cleaner Production', with 1 publication. This number increases to 2 in 2020 and 2021 respectively. However, by 2023, it stabilises with 1 journal article published. In 2020, the 'Energies' journal begins publishing, with a dramatic increase to 4 journal articles by 2023. The 'Building' journal starts publishing in 2020, but the number of publications slightly decreases until only 1 document is published in 2022. After 2022, there are no journal publications related to the intersection of IoT, carbon emission monitoring, and residential building. Additionally, the 'Building' journal shows a slight increase in publications from 2020, with one publication in 2024 within the first two months.

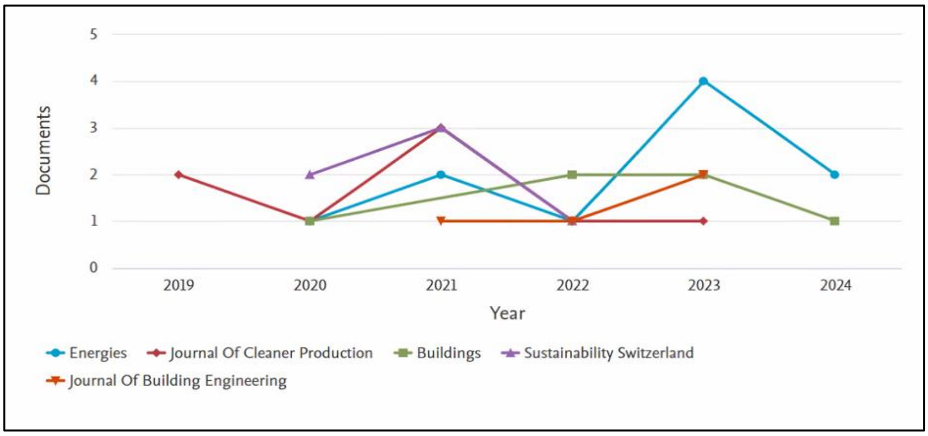


Figure 2: Evolution of leading journals

4.1.3 Leading authors on adopting IoT for carbon emission monitoring

Various scholars have contributed to the adoption of digital technology for carbon emission monitoring, such as BIM and digital twin. Figure 3 presents the leading authors who have published the most papers on IoT, carbon emission, and carbon emission monitoring for residential buildings in Scopus from 2015 to 2024. According to the analysis, the author who has published the most articles during the period from 2015 to 2024 is Oke A.E. with 3 records in Scopus. With the second-highest number of records in Scopus, 2 articles have been published by multiple authors including Aliu J., Chan A.P.C., Deng X., Fan Y.V., Klemes J.J., Lee C.T., Li H., Lu K., and Wu Z. Since there has been less focus on IoT in the context of carbon emission and carbon emission monitoring for residential buildings, the number of articles published by authors is considerably lower.

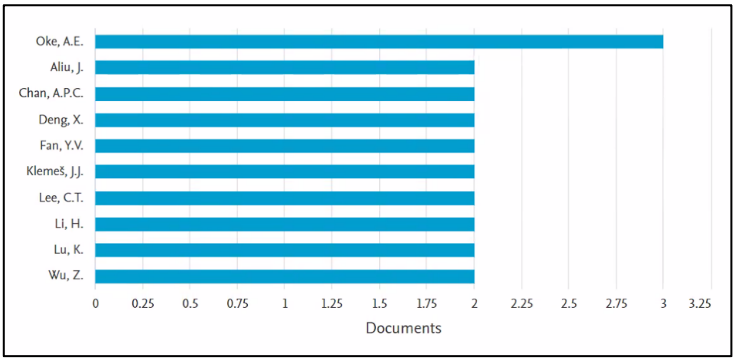


Figure 3: Leading authors analysis

The articles were further reviewed to identify the insights for adopting IoT for carbon emission monitoring of residential buildings as described below.

4.2 ADOPTING IOT FOR CARBON EMISSION AND CARBON EMISSION MONITORING AT RESIDENTIAL FACILITIES

Since IoT provides number of advantages in real-time carbon emission monitoring as mentioned earlier, many researchers have paid their attention on utilising IoT for carbon emissions monitoring in diverse sectors (Olatomiwa et al., 2023). The IoT has the potential to significantly reduce carbon emissions in residential facilities. The concept of IoT represents the energy-efficient procedures adopted by IoT to facilitate reducing energy consumption and carbon emission of existing applications and services (Oke et al., 2023). IoT can be combined with technologies like AI, machine learning, computer vision, cloud computing, nanotechnology, and big data to develop environmentally sustainable solutions (Javaid et al., 2022).

The term IoT describes a network of connected devices that are equipped with software, sensors, and other technologies to gather and share data via the internet (Oke et al., 2023). Further to the authors, IoT devices can be installed to track energy consumption, identify inefficiencies, and make recommendations for improvements in the context of carbon emission monitoring.

In the context of residential buildings, IoT is enabling buildings to reduce energy consumption and emissions. Smart buildings, which leverage IoT, manage assets, resources, and services efficiently, thereby reducing energy consumption and making buildings safer, more productive, and overall, a better place in which to live or work (Lee et al., 2015; Maksimovic, 2017). Accordingly, it appears that the use of IoT for real time carbon emissions monitoring and quantification acquires a considerable attention among researchers even though still there is a dearth in practical context. Further, according to Olatomiwa et al., (2023), IoT technology seems like a promising solution for assessing carbon emissions in houses, despite some potential challenges and ethical restrictions. Furthermore, Sarrab et al., (2020) also declare that IoT enable carbon monitoring platforms allow to determine how day-to-day activities in houses impact on carbon emissions by collect real-time data on household activities such as energy consumption and other environmental data including indoor temperature, and humidity to name a few. This facilitate individuals to identify where high carbon emissions are occurred and how to make changes in their living patterns to mitigate them (Olatomiwa et al., 2023). Further, IoT-based carbon monitoring systems can monitor energy usage, water consumption, heating and cooling patterns, and other pertinent household metrics using a combination of sensors, smart meters, and other connected devices which has an impact on total carbon emissions from houses (Lukyanov et al., 2021). Moreover, Real-time tracking of energy consumption is one of the main uses of IoT in residential carbon emission monitoring (Ming et al., 2019). Residential building equipped with smart meters are able to measure water, gas and electricity usage very precisely (Mudumbe & Abu-Mahfouz, 2015). These meters send data to a central system, where it is examined to find trends and patterns in the usage of energy (Adams et al., 2021).

Additionally, the use of IoT sensors is possible to monitor specific sources of carbon emissions in buildings (Rokonuzzaman et al., 2021). For instance, sensors can be added to HVAC systems (heating, ventilation, and air conditioning) to monitor energy use and identify problems or inefficiencies (Rashid et al., 2019). In order to monitor energy usage and carbon emissions, sensors can also be installed in appliances like dishwashers, washing machines, and refrigerators (Bansal et al., 2011). IoT devices have the potential to reduce carbon emissions by encouraging residents to make changes in their behaviour by giving them instant feedback on their energy consumption (Nižetić et al., 2020). For instance, to further reduce energy waste, IoT-enabled lighting systems and thermostats can also automatically adjust settings based on occupancy patterns (Natarajan et al., 2022). Moreover, utilise IOT as a data analytics tool to examine the gathered information and identify trends, deviations and patterns in emissions and energy use (Mohindru et al., 2020). Data visualisation tools like dashboards, graphs, and charts make it easier for building managers and residents to understand the information (Lavalle et al., 2020). When establishing IoT in residential buildings, several challenges will be encountered, such as high capital costs, a limited number of IoT experts, data accuracy and reliability issues, network connectivity problems, cyber security threats, IoT adoption and engagement, and ongoing maintenance and operation costs (Zhang et al., 2021).

4.3 A FRAMEWORK FOR IOT ENABLED CARBON EMISSION MONITORING OF RESIDENTIAL BUILDINGS

Based on the different intersections reviewed on the adopting IoT for carbon emission monitoring, a framework was developed providing important insights for future researchers in the field. The framework clearly illustrates the types of carbon emissions of residential buildings, data gathering, processing and visualising tools of IoT in a carbon emission monitoring system and potential outcomes that can be derived through the utilisation of IoT technology for carbon emissions monitoring in residential buildings. Accordingly, embodied, and operational are the main types of carbon emissions from a residential building. These emission sources can be integrated with an IoT-based carbon emission monitoring system which include data gathering, processing and visualisation tools. Subsequently, the end users can monitor the residential carbon emissions that lead to initiate carbon reduction strategies. Additionally, it facilitates several benefits as visualised in the proposed framework in Figure 4.

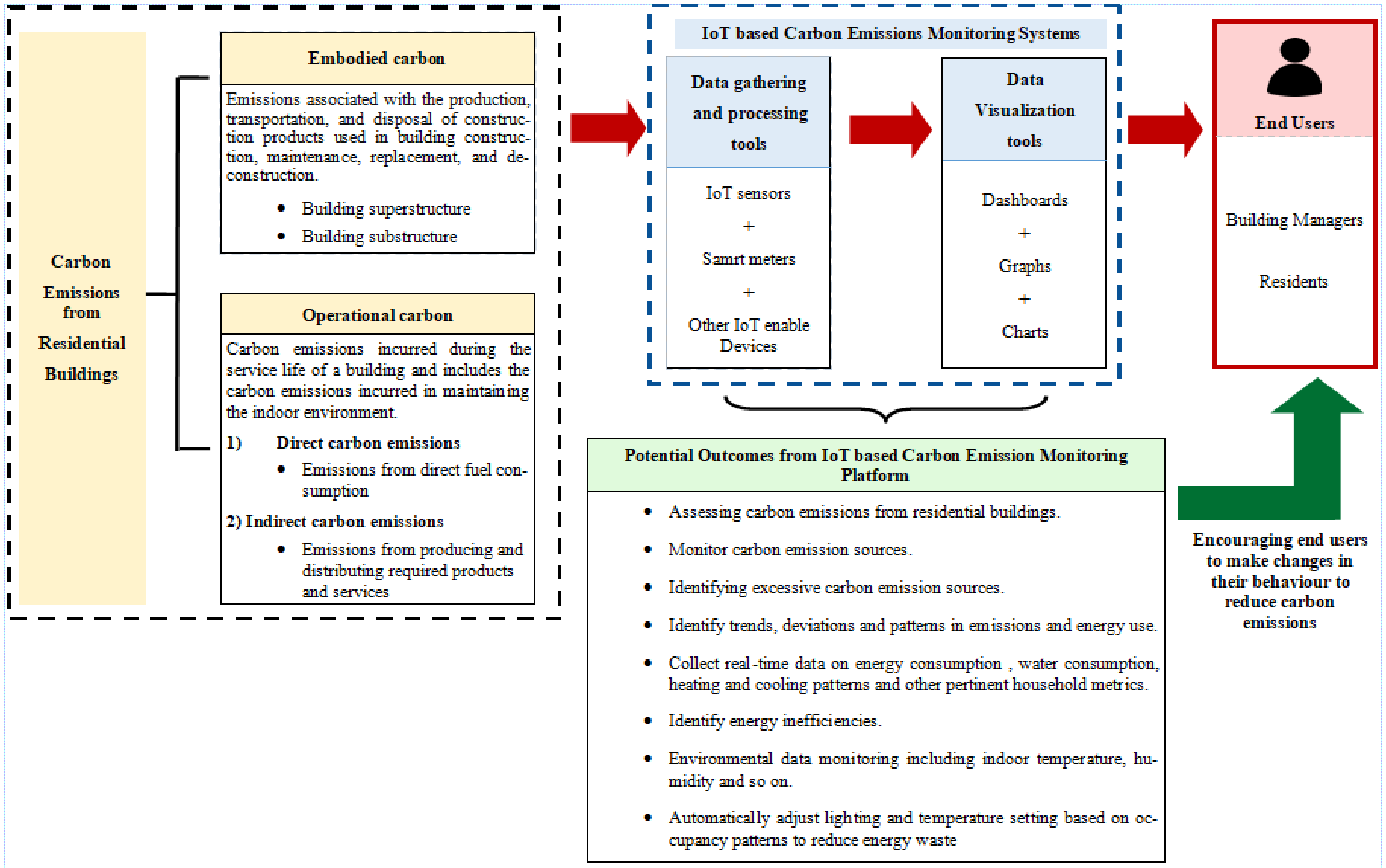


Figure 4: Framework for IoT enabled carbon emissions monitoring of residential buildings

5. CONCLUSIONS AND A WAY FORWARD

Monitoring carbon emissions at residential facilities is crucial for achieving sustainability goals. IoT solutions can be used to understand user behaviour of inhabitants through monitoring of comfort parameters in residential buildings. The use of IoT in monitoring carbon footprints has the potential to save billions of metric tons of carbon emissions. This can be achieved by automating monitoring and repetitive maintenance tasks, which can also reduce the costs of delivering service. Hence, the adoption of IoT in residential facilities can play a significant role in reducing carbon emissions and monitoring them effectively. However, it's important to note that the successful implementation of these technologies requires careful planning and consideration of various factors such as cost, privacy, and security. With such importance, this study conducted a systematic review of key literature published in the Scopus database between 2015 and 2024 to explore the adoption of carbon emission monitoring in residential buildings. The bibliometric analysis outcomes significantly contribute to identifying the number of published journals, leading journal authors, and countries active in this field. It is evident from the analysis that this is an evolving and growing area of study worldwide, with a particular focus on carbon emission monitoring. Through the analysis of existing literature, several key findings have emerged regarding the adoption of carbon emission monitoring in residential buildings. considering the intersections between IoT and carbon emissions monitoring in residential buildings, IoT enabled carbon emissions monitoring and accounting model will be developed as a way forward of this research, which may pave an important pathway for reducing carbon emissions from residential buildings while enhancing knowledge on the application of IoT for carbon emission monitoring.

6. REFERENCES

Adams, J. N., Bélafi, Z. D., Horváth, M., Kocsis, J. B., & Csoknyai, T. (2021). How smart meter data analysis can support understanding the impact of occupant behaviour on building energy performance: a comprehensive review. *Energies*, *14*(9), 2502. Retrieved from https://doi.org/10.3390/en14092502

Akbarnezhad, A., & Xiao, J. (2017). Estimation and minimization of embodied carbon of buildings: A review. In *Buildings 7*(1), 5. MDPI AG. Retrieved from https://doi.org/10.3390/buildings7010005

Azizi, S., Nair, G., Rabiee, R., & Olofsson, T. (2020). Application of Internet of Things in academic buildings for space use efficiency using occupancy and booking data. *Building and Environment*, *186*, 107355. Retrieved from https://doi.org/10.1016/j.buildenv.2020.107355

Ba Nguyen, T., & Cao Nguyen, T. (2023). Design and fabrication of an IoT-based smart electrical meter for residential energy management. *Indonesian Journal of Electrical Engineering and Computer Science*, *30*(3), 1259. Retrieved from https://doi.org/10.11591/ijeecs.v30.i3.pp1259-1268

Bansal, P., Vineyard, E., & Abdelaziz, O. (2011). Advances in household appliances- A review. *Applied Thermal Engineering*, *31*(17–18), 3748–3760. Retrieved from https://doi.org/10.1016/j.applthermaleng.2011.07.023

Cang, Y., Yang, L., Luo, Z., & Zhang, N. (2020). Prediction of embodied carbon emissions from residential buildings with different structural forms. *Sustainable Cities and Society*, *54*, 101946. Retrieved from https://doi.org/10.1016/j.scs.2019.101946

Cao, X., Dai, X., & Liu, J. (2016). Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy and Buildings*, *128*, 198–213. Retrieved from https://doi.org/10.1016/j.enbuild.2016.06.089

Chawla, A., Arellano, Y., Johansson, M. V., Darvishi, H., Shaneen, K., Vitali, M., Finotti, F., & Rossi, P. S. (2023). IoT-based monitoring in carbon capture and storage systems. *IEEE Internet of Things Magazine*, *5*(4), 106–111. Retrieved from https://doi.org/10.1109/iotm.001.2200175

Department of Climate Change, Energy, the Environment, and Water (DCCEEW). (2023). National Energy Performance Strategy. Retrieved from https://www.dcceew.gov.au/energy/strategies-and-frameworks/national-energy performance-strategy

Devan, P. A. M., Hussin, F. A., Ibrahim, R., Bingi, K., & Nagarajapandian, M. (2019, October). IoT based vehicle emission monitoring and alerting system. *2019 IEEE Student Conference on Research and Development, Malaysia,* 15-17 October 2019. (pp. 161-165). doi: 10.1109/SCORED.2019.8896289

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

Fan, Y., & Fang, C. (2023). GHG emissions and energy consumption of residential buildings—a systematic review and meta-analysis. *Environmental Monitoring and Assessment*, *195*(7), 885. Retrieved from https://doi.org/10.1007/s10661-023-11515-z

Fenner, A. E., Kibert, C. J., Li, J., Razkenari, M. A., Hakim, H., Lu, X., Kouhirostami, M., & Sam, M. (2020). Embodied, operation, and commuting emissions: A case study comparing the carbon hotspots of an educational building. *Journal of Cleaner Production*, *268*. Retrieved from https://doi.org/10.1016/j.jclepro.2020.122081

Hirano, Y., Ihara, T., Hara, M., & Honjo, K. (2020). Estimation of direct and indirect household CO2 emissions in 49 Japanese cities with consideration of regional conditions. *Sustainability (Switzerland)*, *12*(11). Retrieved from https://doi.org/10.3390/su12114678

Huo, T., Ren, H., & Cai, W. (2019). Estimating urban residential building-related energy consumption and energy intensity in China based on improved building stock turnover model. *Science of the Total Environment*, *650*, 427–437. Retrieved from https://doi.org/10.1016/j.scitotenv.2018.09.008

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

Izaola, B., Akizu-Gardoki, O., & Oregi, X. (2023). Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building. *Sustainable Production and Consumption*, *40*, 252–264. Retrieved from https://doi.org/10.1016/j.spc.2023.07.001

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustainable Operations and Computers*, *3*, 203–217. Retrieved from https://doi.org/https://doi.org/10.1016/j.susoc.2022.01.008

Jiang, Y., Long, Y., Liu, Q., Dowaki, K., & Ihara, T. (2020). Carbon emission quantification and decarbonization policy exploration for the household sector - Evidence from 51 Japanese cities. *Energy Policy*, *140*. Retrieved from https://doi.org/10.1016/j.enpol.2020.111438

Lavalle, A., Teruel, M. A., Maté, A., & Trujillo, J. (2020). Improving sustainability of smart cities through visualization techniques for big data from IoT devices. *Sustainability*, *12*(14), 5595. Retrieved from https://doi.org/10.3390/su12145595

Lee, C. K. M., Na, C. M., & Kit, N. C. (2015). IoT-based asset management system for healthcare-related industries. *International Journal of Engineering Business Management*, *7*. Retrieved from https://doi.org/10.5772/61821

Li, K., Ma, M., Xiang, X., Feng, W., Ma, Z., Cai, W., & Ma, X. (2022a). Carbon reduction in commercial building operations: A provincial retrospection in China. *Applied Energy*, *306*. https://doi.org/10.1016/j.apenergy.2021.118098

Li, X., Yang, F., Zhu, Y., & Gao, Y. (2014). An assessment framework for analyzing the embodied carbon impacts of residential buildings in China. *Energy and Buildings*, *85*, 400–409. https://doi.org/10.1016/j.enbuild.2014.09.051

Liu, G., Chen, R., Xu, P., Fu, Y., Mao, C., & Hong, J. (2020a). Real-time carbon emission monitoring in prefabricated construction. *Automation in Construction*, *110*. Retrieved from https://doi.org/10.1016/j.autcon.2019.102945

Liu, G., Yang, H., Fu, Y., Mao, C., Xu, P., Hong, J., & Li, R. (2020b). Cyber-physical system-based real-time monitoring and visualization of greenhouse gas emissions of prefabricated construction.

Journal of Cleaner Production, *246*, 119059. Retrieved from https://doi.org/https://doi.org/10.1016/j.jclepro.2019.119059

Lukyanov, A., Donskoy, D., Vernezi, M., & Karev, D. (2021). Estimation of the carbon footprint of IoT devices based on ESP8266 microcontrollers. *E3S Web of Conferences*, *279*. Retrieved from https://doi.org/10.1051/e3sconf/202127901002

Lützkendorf, T., & Balouktsi, M. (2022). Embodied carbon emissions in buildings: explanations, interpretations, recommendations. *Buildings and Cities*, *3*(1), 964–973. Retrieved from https://doi.org/10.5334/bc.257

Maksimovic, M. (2017). The role of green internet of things (G-IoT) and big data in making cities smarter, safer and more sustainable. *International Journal of Computing and Digital Systems*, *6*(4), 175–184. Retrieved from https://doi.org/10.12785/IJCDS/060403

Mao, C., Tao, X., Yang, H., Chen, R., & Liu, G. (2018). Real-time carbon emissions monitoring tool for prefabricated construction: An IoT-based system framework. *ICCREM 2018: Sustainable Construction and Prefabrication - Proceedings of the International Conference on Construction and Real Estate Management 2018*, (pp.121–127). American Society of Civil Engineers. doi: 10.1061/9780784481738.015

Martillano, D. A., Dita, J. M. R., Cruz, C. G., & Sadhra, K. S. (2017). Android based real-time industrial emission monitoring system using IoT technology. *Journal of Communications*, *12*(11), 623–629. Retrieved from https://doi.org/10.12720/jcm.12.11.623-629

Ming, F. X., Habeeb, R. A. A., Md Nasaruddin, F. H. B., & Gani, A. Bin. (2019). Real-time carbon dioxide monitoring based on IoT and Cloud Technologies. *Proceedings of the 2019 8th International conference on software and computer applications*, 517–521. Retrieved from https://doi.org/10.1145/3316615.3316622

Mohindru, G., Mondal, K., & Banka, H. (2020). Internet of Things and data analytics: A current review. *WIREs Data Mining and Knowledge Discovery*, *10*(3). Retrieved from https://doi.org/10.1002/widm.1341

Mokhtarpour, R., & Khasseh, A. A. (2021). Twenty-six years of LIS research focus and hot spots, 1990–2016: A co-word analysis. *Journal of Information Science*, *47*(6), 794–808. Retrieved from https://doi.org/10.1177/0165551520932119

Mudumbe, M. J., & Abu-Mahfouz, A. M. (2015). Smart water meter system for user-centric consumption measurement. *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, 993–998. IEEE. https://doi.org/10.1109/INDIN.2015.7281870

Natarajan, A., Krishnasamy, V., & Singh, M. (2022). Occupancy detection and localization strategies for demand modulated appliance control in Internet of Things enabled home energy management system. *Renewable and Sustainable Energy Reviews*, *167*, 112731. https://doi.org/10.1016/j.rser.2022.112731

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., & Muhd, M. Z. (2015). A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). *Renewable and Sustainable Energy Reviews*, *43*, 843–862. Retrieved from https://doi.org/10.1016/j.rser.2014.11.066

Nižetić, S., Šolić, P., López-de-Ipiña González-de-Artaza, D., & Patrono, L. (2020). Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future. *Journal of Cleaner Production*, *274*, 122877. Retrieved from https://doi.org/10.1016/j.jclepro.2020.122877

Oke, A. E., Aliu, J., Agbaje, D. H., Jamir Singh, P. S., Alade, K. T., & Samsurijan, M. S. (2023). Effective measures to bolster the deployment of indoor environmental quality (IEQ) principles in building design: a focus on quantity surveying (QS) firms in Nigeria. *Management of Environmental Quality: An International Journal, 35*(4), 818-838. Retrieved from https://doi.org/10.1108/MEQ-05-2023-0138

Olatomiwa, L., Ambafi, J. G., Dauda, U. S., Longe, O. M., Jack, K. E., Ayoade, I. A., Abubakar, I. N., & Sanusi, A. K. (2023). A review of Internet of Things-based visualisation platforms for tracking household carbon footprints. *Sustainability*, *15*(20), 15016. Retrieved from https://doi.org/10.3390/su152015016

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings 42*(10), 1592–1600. Retrieved from https://doi.org/10.1016/j.enbuild.2010.05.007

Rashid, S. A., Haider, Z., Chapal Hossain, S. M., Memon, K., Panhwar, F., Mbogba, M. K., Hu, P., & Zhao, G. (2019). Retrofitting low-cost heating ventilation and air-conditioning systems for energy management in buildings. *Applied Energy*, *236*, 648–661. Retrieved from https://doi.org/10.1016/j.apenergy.2018.12.020

Rokonuzzaman, Md., Mishu, M. K., Amin, N., Nadarajah, M., Roy, R. B., Rahman, K. S., Buhari, A. M., Binzaid, S., Shakeri, M., & Pasupuleti, J. (2021). Self-sustained autonomous wireless sensor network with integrated solar photovoltaic system for Internet of Smart Home-Building (IOSHB) applications. *Micromachines*, *12*(6), 653. Retrieved from https://doi.org/10.3390/mi12060653

Sarrab, M., Pulparambil, S., & Awadalla, M. (2020). Development of an IoT based real-time traffic monitoring system for city governance. *Global Transitions*, *2*, 230–245. Retrieved from https://doi.org/10.1016/j.glt.2020.09.004

Sengupta, J., Ruj, S., & Das Bit, S. (2020). A comprehensive survey on attacks, security issues and blockchain solutions for IoT and IIoT. *Journal of Network and Computer Applications*, *149*, 102481. Retrieved from https://doi.org/10.1016/j.jnca.2019.102481

Tao, X., Mao, C., Xie, F., Liu, G., & Xu, P. (2018). Greenhouse gas emission monitoring system for manufacturing prefabricated components. *Automation in Construction*, *93*, 361–374. Retrieved from https://doi.org/https://doi.org/10.1016/j.autcon.2018.05.015

United Nations Environment Programme. (2024). *2023 Global status report for buildings and construction: Beyond foundations - mainstreaming sustainable solutions to cut emissions from the buildings sector*. https://doi.org/10.59117/20.500.11822/45095

Victoria, M., & Perera, S. (2017). An elemental approach for predicting embodied carbon of office buildings. *World Sustainable Built Environment Conference 2017, Hong Kong*. 5-7 June 2017. (pp. 522-527). Retrieved from http://wsbe17hongkong.hk/download/WSBE17%20Hong%20Kong%20-%20Conference%20Proceedings.pdf

Xu, J., Pan, W., Teng, Y., Zhang, Y., & Zhang, Q. (2022). Internet of Things (IoT)-integrated embodied carbon assessment and monitoring of prefabricated buildings. *IOP Conference Series: Earth and Environmental Science*, *1101*(2). IOP Publishing Ltd. Retrieved from https://doi.org/10.1088/1755-1315/1101/2/022031

Xu, J., Zhang, Q., Teng, Y., & Pan, W. (2023). Integrating IoT and BIM for tracking and visualising embodied carbon of prefabricated buildings. *Building and Environment*, *242*, 110492. Retrieved from https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110492

Zarco-Periñán, P. J., Zarco-Soto, F. J., Zarco-Soto, I. M., Martínez-Ramos, J. L., & Sánchez-Durán, R. (2022). CO2 emissions in buildings: A synopsis of current studies. In *Energies 15*(18), 6635. MDPI. Retrieved from https://doi.org/10.3390/en15186635

Zhang, H., Zhang, J., Wang, R., Huang, Y., Zhang, M., Shang, X., & Gao, C. (2021). Smart carbon monitoring platform under IoT-Cloud architecture for small cities in B5G. *Wireless Networks*. Retrieved from https://doi.org/10.1007/s11276-021-02756-2

Zhang, X., Luo, L., & Skitmore, M. (2015). Household carbon emission research: An analytical review of measurement, influencing factors and mitigation prospects. *Journal of Cleaner Production*, *103*, 873–883. Retrieved from https://doi.org/10.1016/j.jclepro.2015.04.024

Zhou, C., Lin, X., Wang, R., & Song, B. (2023). Real-time carbon emissions monitoring of high-energy-consumption enterprises in Guangxi based on electricity big data. *Energies*, *16*(13). Retrieved from https://doi.org/10.3390/en16135124

Fernando, S.M.H., Fernando, Y.I.R. and Kulatunga, U., 2024. Investigating community-based participatory design approaches in planning and constructing public community facilities: A scoping review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 661-672. DOI: https://doi.org/10.31705/WCS.2024.52. Available from: https://ciobwcs.com/papers/

INVESTIGATING COMMUNITY-BASED PARTICIPATORY DESIGN APPROACHES IN PLANNING AND CONSTRUCTING PUBLIC COMMUNITY FACILITIES: A SCOPING REVIEW

S. Malintha H. Fernando[1], Y. Inodee Fernando[2] and U. Kulatunga[3]

ABSTRACT

The construction industry is witnessing a paradigm shift towards Community-Based Participatory Design (CBPD) approaches, deviating from traditional top-down methodologies. CBPD prioritises local knowledge and perspectives, encouraging inclusive collaboration among stakeholders. With the aim of investigating different CBPD approaches in planning and constructing public community facilities, focusing on their applicability, benefits, and limitations, this study employed a Scoping Review Methodology. Scopus and Web of Science databases were used to identify the papers with the use of predefined keywords. Following the screening process, 30 relevant research studies were analysed. Findings revealed that CBPD approaches offer several benefits, including promoting democratic decision-making, sustainable development, and community empowerment, ultimately enhancing the inclusivity and effectiveness of infrastructure projects. Simultaneously, limitations were identified, including navigating power dynamics, reconciling stakeholder interests, addressing scalability concerns, and overcoming resource constraints. Real-life examples and case studies were thoroughly analysed to identify the applicability of CBPD approaches and the importance of implementing such approaches in public community facilities. Based on the findings as well as the identification of gaps, future research areas were proposed.

Keywords: *CBPD Approaches; Community-based Participatory Design Approaches; Construction; Public Places; Sustainability.*

1. INTRODUCTION

In recent years, the approaches to planning and constructing public community facilities have evolved significantly, with an emphasis on community-based participatory design (CBPD) approaches (Valladares, 2017). In traditional practice, construction planners, engineers, and architects held significant authority in shaping the vision of the project and its outcomes, often based on technical expertise and organisational hierarchies

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, fernandosmh.20@uom.lk

[2] Undergraduate, Department of Town and Country Planning, University of Moratuwa, Sri Lanka, fernandoyir.20@uom.lk

[3] Professor in Building Economics, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

(McAnany, 2012). This top-down approach has been efficient in some respects including providing clear direction from leadership, enabling streamlined decision-making, and ensuring efficient implementation of strategies aligned with organisational goals (Semeraro et al., 2020). However, when it comes to the construction of public community facilities, this traditional approach often overlooks the specific requirements and desires of the communities that these projects were intended to benefit, which are frequently ignored or not fully considered (Schutte, 2016). CBPD challenges this approach by recognising the local expertise and perspectives that community members bring to the process (Galamba & Nielsen, 2016).

Participatory development strategies aimed at enhancing the effectiveness and sustainability of development projects, in the context of promoting inclusive growth. In general, the project outcomes developed adopting the participatory development and construction strategies have been termed “democratic innovations” (Björgvinsson et al., 2010). Further, CBPD is not just a design methodology; it represents a paradigm shift in the way projects are conceptualised and executed. It is argued that the involvement of all stakeholders and planners in the construction process would be the most suitable strategy for sustainable development (Mueller et al., 2018).

On the other hand, the traditional top-down development model has faced criticisms for its limited effectiveness in meeting the diverse needs of communities, not being sustainable and neglecting the perspectives and aspirations of local stakeholders (Dias et al., 2014). A construction project to address a certain problem may succeed in one community, and it may encounter obstacles and fail to meet expectations in another community for the same problem. This highlights the importance of adopting context-specific and participatory approaches that address community-specific needs and priorities (Schutte, 2016).

Major public community development projects around the world include various infrastructure such as roads, railways, waterways, and pipelines, alongside community-centric establishments such as community centres, recreational spaces, and health facilities, and their success is assessed by how the community members in the society benefited from the project (Baporikar, 2016). Community-based development has been identified as a missing component in most community infrastructure projects, leading to the failure of the majority of them (Hussein & Kisimbii, 2019; Baporikar, 2016). Recognising these limitations, practitioners have increasingly adopted CBPD approaches to promote a sense of ownership, and sustainability in infrastructure projects (Meetiyagoda et al., 2024).

This review paper aims to investigate the applicability, benefits, and limitations of CBPD approaches in the planning and construction of public community facilities. By analysing diverse case studies and existing literature, the research seeks to identify how CBPD can facilitate inclusive and sustainable development, promote community empowerment, and enhance cultural preservation.

This paper comprises sections discussing the employed scoping review methodology, followed by the presentation of analysis and findings. It concludes by discussing the results and their future implications.

2. METHODOLOGY

This study adopts a Scoping Review Methodology, to comprehensively examine CBPD approaches in planning and constructing public community facilities. This research approach was chosen due to its suitability for exploring emerging evidence and providing insights as the research area requires clarification and refinement (Arksey & O'Malley, 2005). Unlike systematic reviews, which focus on specific research questions, scoping reviews are instrumental in mapping the breadth and depth of existing literature, making them ideal for synthesising diverse perspectives and methodologies related to CBPD in community facility development (Schultz et al., 2017). Extensive research has been conducted on participatory post-disaster construction, with significant community participation (Harahap, 2020; Hosseini & Izadkhah, 2020). Thus, a scoping review was identified as the most suitable research approach to investigate the study under consideration. The process followed for the scoping study is given in Figure 1.

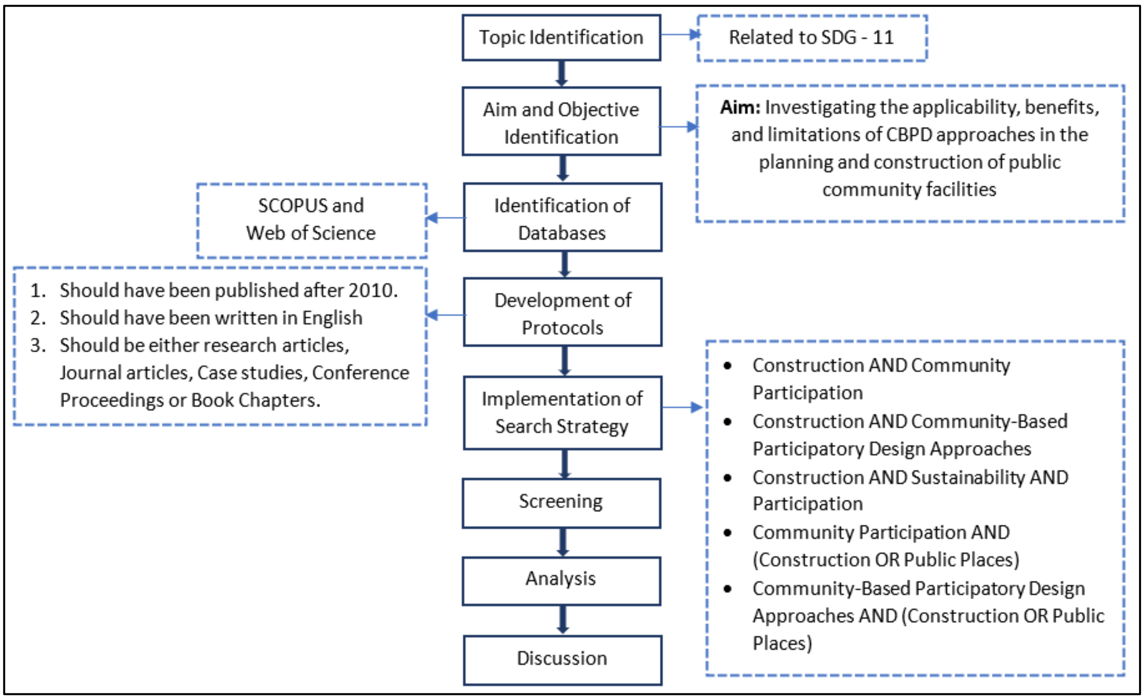


Figure 1: Methodology flowchart

The process of reviewing the papers involved a multi-stage process in alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, yet customised., as outlined in Figure 2.

Figure 2: Multi-stage paper reviewing process

First, a protocol is developed to outline eligibility criteria, search strategies, and data extraction methods. This protocol serves as a guiding tool, allowing flexibility to adapt to the evolving needs of the study while maintaining consistency and transparency. The following are the main criteria for the selection of papers.

1. Should have been published after 2010. This ensures maximum validity and currency.
2. Should have been written in English.
3. Should be either research articles, journal articles, case studies, conference proceedings or book chapters.

A comprehensive search strategy is implemented, utilising predefined keywords and search strings to identify relevant literature from diverse sources such as academic databases, industry reports, and relevant journals (Refer to Figure 1). The search is focused on recent publications to ensure the inclusion of up-to-date evidence. Screening procedures are rigorously applied to select publications based on predefined eligibility criteria, ensuring the inclusion of high-quality sources relevant to CBPD in community facility development. Scopus and Web of Science databases will be implemented.

Then, data extraction is conducted systematically, capturing key information related to CBPD approaches, methodologies, outcomes, and implications for practice and policy. Data charting tools are utilised to organise and analyse the extracted data, facilitating a structured approach to synthesis and interpretation.

Finally, the analysis of findings employs a descriptive and standardised classification approach, allowing for the identification of patterns, trends, and key insights across the literature. This synthesis aims to contribute to a comprehensive understanding of CBPD approaches in planning and constructing public community facilities, identifying gaps in knowledge, and informing future research and practice in community development.

3. FINDINGS AND DISCUSSION

3.1 SELECTION OF THE SOURCES

Only papers published after 2010 were chosen for the scoping review to ensure maximum validity and timeliness. The majority of the papers are from 2017 and 2018, each constituting 16.67%. Initially, a criterion was established that the selected papers should fall under specific categories such as research articles, journal articles, case studies, conference proceedings, or book chapters (refer to Figure 1). However, after the screening process, only journal articles and conference proceedings remained within the scope, as other types of papers did not meet the predefined criteria (refer to Figure 4). Among these, the majority of the selected papers were journal articles. The demographic data regarding publication type and publication year are outlined in Figure 3.

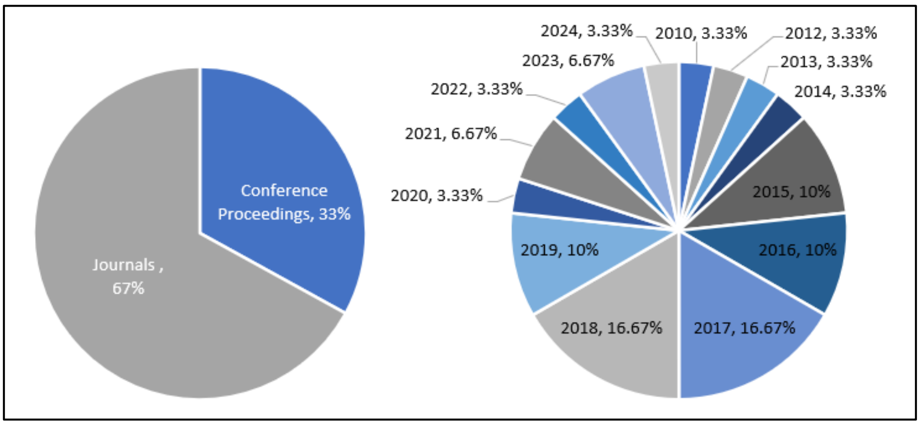


Figure 3: Demographic data: publication type and publication year, respectively

Throughout the selection process, a methodical filtration process was executed, considering predefined criteria as stated above. Initially, 116 papers were identified based on the specified keywords. Afterwards, filtration was applied, resulting in the selection of 30 papers for inclusion in the scoping review. The papers were filtered to ensure that the outcomes of the scoping review were of good standard. A significant number of papers, totalling 86, were excluded during the process due to reasons, including language issues, lack of relevance to the construction topic, discrepancies in abstracts, published years, and duplication of published data. These exclusions are shown in Figure 4.

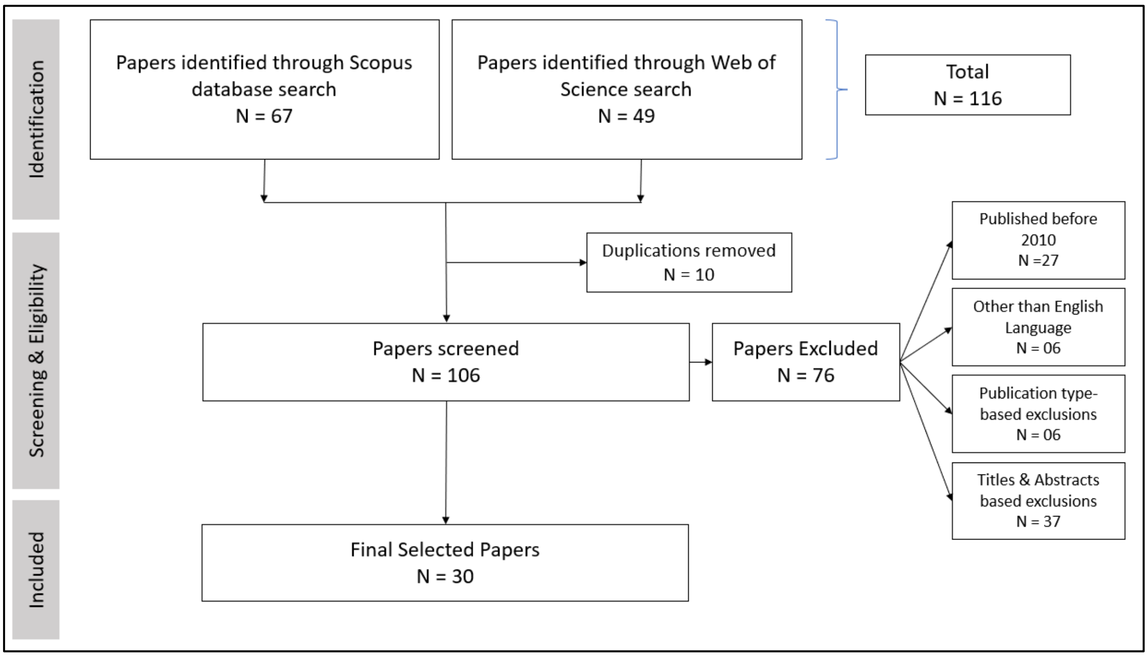


Figure 4: Screening process

3.2 CBPD APPROACHES IN PLANNING AND CONSTRUCTING PUBLIC COMMUNITY FACILITIES

CBPD approaches have gained significant popularity in recent years for planning and constructing public community facilities. This section examines various case studies and research articles that explore the benefits, applicability, and limitations of CBPD approaches in this context.

3.2.1 Applicability of CBPD Approaches in Planning and Constructing Public Community Facilities

CBPD approaches have been used in post-disaster housing projects as illustrated by Hussain (2017) and Shafique & Warren (2015). These approaches are also commonly used in road infrastructure projects in several countries including Indian and Kenya (Ahuja & Priyadarshini, 2017; Hussein & Kisimbii, 2019). For infrastructure projects CBPD have been effective bringing forth optimistic outcomes (Baumann et al., 2017; Ahuja & Priyadarshini, 2017; Meetiyagoda et al., 2024). They help communities define preferable futures, preserve cultural norms, facilitate meaningful encounters, and bridge gaps between groups. The Sankofa City and Leimert Phone Company projects involved African American communities in defining their future, and community-led reconstruction initiatives in Kathmandu, Nepal, emphasised traditional heritage conservation (Baumann et al., 2017; Joshi et al., 2021). CBPD also aids in inclusive decision-making, as seen in the Bengaluru Transportation Projects Impacted Communities Network in India, the Construction Logistics Stakeholder Framework in Brussels, and post-disaster reconstruction in Pakistan (Ahuja & Priyadarshini, 2017; Brusselaers et al., 2021; Hussain, 2017). Furthermore, CBPD approaches adapt design processes to participants' specific needs, as demonstrated in the case study of Care+ building for Older Adults in Oslo, Norway (Joshi & Bratteteig, 2016; Bratteteig & Wagner, 2016). Furthermore, several studies emphasise the importance of CBPD in encouraging effective communication, empowering communities and building their capacity to participate effectively (Marín & Roelofs, 2018; Shafique & Warren, 2015; Hussain, 2017). In line with these cases studies, development of tools like Qua-kit aimed to bridge the gap between expert designers and local knowledge through crowd-creative participation in urban design (Mueller et al., 2018).

Table 1 summarises the case studies focusing on the applicability, benefits and limitations.

Table 1: Summary of the case studies

#	Case Study	Type of Applicability	CBPD Approaches Used	Outcomes	Citations
1	Sankofa City Project - USA (Los Angeles)	City Infrastructure Project	Collaborative workshops, prototyping, design fictions	Preserved cultural norms; beneficial urban infrastructure	(Baumann et al., 2017)
2	Cultural heritage reconstruction - Traditional public rest house, Kasthamandap, Nepal	Heritage Site Reconstruction	Community involvement, local labour and materials, community committees	Heritage preservation, resilient infrastructure, increased community ownership	(Joshi et al., 2021)
3	Bengaluru road widening and other urban transport projects, India	Road Infrastructure Project	Formation of Bengaluru Transportation Projects Impacted Communities (BATPIC) network	Advocacy for community rights, minimal displacement, promotion of sustainable transportation	(Ahuja & Priyadarshini, 2017)
4	Sardar Patel Ring Road project in Ahmedabad, India	Road Infrastructure Project	Public consultations by Urban Development Authority, Consultation meetings	Faster land acquisition, voluntary land handover, greater local support	(Ahuja & Priyadarshini, 2017)
5	Pakistan's Housing Reconstruction Programme in Azad Jammu & Kashmir	Post-Disaster Housing Project	Owner-driven reconstruction	Seismic-resistant construction, cultural acceptance	(Hussain, 2017; Shafique & Warren, 2015)
6	Road construction projects in Garissa County, Kenya	Road Infrastructure Project	Decision-making forums (barazas)	Improved implementation efficiency, effective projects for	(Hussein & Kisimbii, 2019)

#	Case Study	Type of Applicability	CBPD Approaches Used	Outcomes	Citations
				arid/semi-arid regions	
7	Care+ building for Older Adults in Oslo, Norway	Infrastructure for Elderly	Project SmartWalker - Interviews, home visits, workshops, usability testing	Alternative indoor navigation systems using Bluetooth and sensors	(Joshi & Bratteteig, 2016)
8	Crow Island Beach Park, Sri Lanka	Public Infrastructure Project	Community initiated the idea, actively involved throughout the entire process from the start.	Sense of Place among the community, Sustainable maintenance	(Meetiyagoda et al., 2024)
9	Kandalama Resort, Sri Lanka	Commercial Infrastructure Project	Making the community partners of the project, transparency and accountability	Acceptance from the Community	(Gayanika, 2017)

3.2.2 Benefits of CBPD Approaches in Planning and Constructing Public Community Facilities

CBPD approaches offer numerous benefits and are applicable in various contexts. They incorporate local knowledge, cultural practices, and social beliefs into the design process, ensuring that the resulting facilities are relevant and meaningful to the community (Baumann et al., 2017). These approaches foster democratic decision-making processes and promote the empowerment of marginalised or underrepresented groups (Baumann et al., 2017; Björgvinsson et al., 2010; Racadio et al., 2014; Ahuja & Priyadarshini, 2017). Furthermore, they facilitate capacity building and the transfer of ownership to the community, contributing to sustainable and long-term solutions (Racadio et al., 2014).

CBPD approaches promote mutual learning and knowledge exchange between designers, researchers, and community members (Baumann et al., 2017; Bødker et al., 2022). They increase the appropriateness, effectiveness, and adoption of interventions or solutions by deeply understanding the users' experiences and contexts (Chen et al., 2019). Additionally, these approaches facilitate the identification and resolution of potential conflicts or controversies early in the process, contributing to more sustainable and inclusive urban planning and infrastructure development (Ahuja & Priyadarshini, 2017; Baumann et al., 2017; Brusselaers et al., 2021).

Hussein and Kisimbii (2019) investigated the role of community participation in the implementation of county road development projects in Kenya. The study highlighted the vital contributions of community members in decision-making processes, human resource mobilisation, conflict resolution, and providing capital resources such as land and raw materials. The researchers recommend involving local communities at all levels of project implementation to prevent conflicts, ensure effective utilisation of resources, and foster a sense of ownership among community members.

Corbett and Le Dantec (2018) stated that municipal agencies often employ practices such as raising awareness, building relationships, setting the table, and finding opportunities to involve community members in city-scale projects. These practices not only foster a sense of ownership and belonging but also ensure that the community's needs and preferences are accurately reflected in the outcome. Furthermore, by giving communities a voice and enabling them to shape their built environment, CBPD approaches can promote inclusivity and address the spatial manifestations of social inequalities (Corbett & Loukissas, 2019).

Furthermore, Forst et al. (2013) demonstrate the effectiveness of a participatory health and safety program for Hispanic immigrant construction workers in the US, showing that engaging workers in program design improves safety knowledge and empowers them to advocate for safer conditions. Gayanika (2017) highlights the significance of assessing residents' empowerment perceptions, indicating that understanding psychological, social, and political empowerment influences community support for sustainable initiatives, aiding in fostering well-being and sustainable development over time. Summary of benefits and limitations of CBPD approaches are shown in Figure 5.

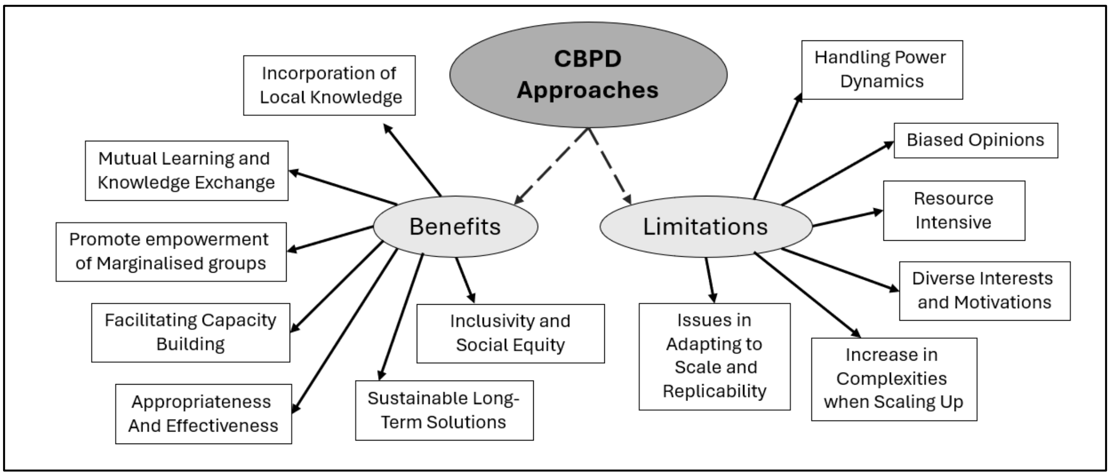


Figure 5: Summary of benefits and limitations of CBPD approaches

3.2.3 Limitations and Challenges of CBPD Approaches in Planning and Constructing Public Community Facilities

While CBPD approaches offer significant advantages, they also present several limitations and challenges. Ensuring genuine participation and addressing power imbalances between researchers/designers and community members can be challenging (Baumann et al., 2017; Joshi & Bratteteig, 2016; Peralta & Murphy, 2016). The inherent complexity and ambiguity of the sense of place concept, as well as the diverse interests and motivations of stakeholders, can complicate the design process and decision-making (Meetiyagoda et al., 2024; Brusselaers et al., 2021).

Facilitating meaningful community engagement and participatory processes can be resource-intensive and time-consuming (Joshi & Bratteteig, 2016; Brusselaers et al., 2021). Reconciling conflicting views, interests, and priorities among stakeholders may require extensive negotiation (Baumann et al., 2017; Joshi & Bratteteig, 2016; Peralta & Murphy, 2016; Brusselaers et al., 2021). Addressing the complexities and uncertainties of real-life contexts and ensuring that the designed solutions are feasible and sustainable can be challenging (Baumann et al., 2017; Brusselaers et al., 2021).

Furthermore, while some case studies demonstrate the applicability of CBPD approaches in specific contexts, scaling up or replicating these approaches across different settings may require further adaptation and validation (Brusselaers et al., 2021). Additionally, the limited capacity and resources of community members, such as low knowledge, poverty, and lack of education, can hinder their effective participation in the design and construction processes, necessitating capacity-building initiatives and sensitisation programs (Wedam et al., 2015; Stewart et al., 2023; Shafique and Warren, 2015; Roosli et al., 2018).

Another challenge lies in the complex power dynamics and potential conflicts that may arise when involving diverse stakeholders with varying interests and agendas. Effective conflict resolution mechanisms and equitable power-sharing arrangements are crucial for ensuring inclusive and productive collaboration (Tremblay et al., 2017; Hussein and Kisimbii, 2019). Furthermore, the scalability and replicability of CBPD approaches may be constrained by context-specific factors, such as the availability of supportive legal frameworks, access to financing, and the willingness of public institutions and private sector entities to embrace alternative housing models and community-driven initiatives (Cabré and Andrés, 2017; Kazemidemneh and Lashgari, 2023; Wedam et al., 2015).

3.3 WAY FORWARD

Based on these findings, several future implications can be proposed. By embracing these approaches and addressing the identified limitations through further research, capacity building, and the development of inclusive and adaptive frameworks, the construction industry can play a pivotal role in creating sustainable, resilient, and community-driven public facilities and infrastructure, aligning with the goals of Sustainable Development Goal 11 (SDG 11). Furthermore, future research should aim to establish robust conflict resolution mechanisms to foster inclusive collaboration among diverse stakeholders. Also, it is recommended to conduct research to develop and evaluate practical strategies for addressing specific challenges, such as power imbalances, reconciling conflicting interests, and managing the complexities and uncertainties of real-life contexts. Such endeavours are essential for promoting sustainable development and equitable outcomes in community-driven initiatives.

4. CONCLUSIONS

The findings of this scoping review emphasise the growing significance and potential of community-based participatory design approaches in the planning and construction of public community facilities. By actively engaging community members and incorporating their local knowledge, cultural practices, and social beliefs, these approaches promote inclusive and sustainable solutions.

The scoping review highlights the diverse applications of CBPD across various contexts such as urban planning, infrastructure development, post-disaster reconstruction, affordable housing initiatives, and heritage preservation. Key findings demonstrate that CBPD is instrumental in defining futures tied to local cultural norms, facilitating meaningful encounters, promoting inclusive decision-making, addressing immediate community needs, and fostering community ownership and empowerment. Despite its numerous benefits, CBPD faces challenges like ensuring genuine participation, reconciling conflicting stakeholder interests, and addressing real-life complexities, which are resource-intensive and time-consuming. Additionally, limited community capacity and resources necessitate capacity-building initiatives. Nevertheless, the review underscores CBPD's potential in creating sustainable, inclusive, and community-driven public facilities and infrastructure, emphasising the need for further research, capacity building, and the development of inclusive frameworks to overcome its limitations.

Furthermore, the case studies illustrate the importance of adapting CBPD processes to the specific needs and abilities of participants, bridging the gap between expert designers and local knowledge, and fostering effective communication and community ownership throughout project lifecycles. While some case studies demonstrate the applicability of CBPD approaches in specific contexts, scaling up or replicating these approaches across different settings may require further adaptation and validation. Addressing power imbalances between designers/researchers and community members, reconciling conflicting views and priorities among stakeholders, and navigating the complexities and uncertainties of real-life contexts remain ongoing challenges.

This review contributes to the ongoing discussions on public participatory development strategies in the construction industry, providing a theoretical background for practitioners, researchers, and community stakeholders. It advocates for inclusive and sustainable infrastructure development that incorporates local knowledge, preserves cultural values, and promotes community empowerment. By fostering collaborative and participatory approaches, the construction industry can play a crucial role in creating resilient, equitable, and community-driven public facilities and infrastructure that meet the diverse needs and aspirations of local communities.

5. REFERENCES

Ahuja, V., & Priyadarshini, S. (2017). Community participation in urban road infrastructure redevelopment: Indian scenario. *Journal of Urban Regeneration and Renewal, 11*(1), 16-29. https://www.researchgate.net/publication/320615215_Community_participation_in_urban_road_infrastructure_redevelopment_Indian_scenario

Arksey, H., & O’Malley, L. (2005). Scoping studies: towards a methodological framework. *International Journal of Social Research Methodology, 8*(1), 19–32. https://doi.org/10.1080/1364557032000119616

Baporikar, N. (2016). Infrastructure development as a catalyst for Social-Economic advancement. *International Journal of System Dynamics Applications, 5*(4), 101–113. https://doi.org/10.4018/ijsda.2016100106

Baumann, K., Stokes, B., Bar, F., & Caldwell, B. (2017). Infrastructures of the imagination: Community design for speculative urban technologies. In *Proceedings of the 8th International Conference on Communities and Technologies* (pp.266-269). ACM International Conference Proceeding Series, Part F128532. https://doi.org/10.1145/3083671.3083700

Björgvinsson, E., Ehn, P., & Hillgren, P. (2010). Participatory design and democratizing innovation. In *Proceedings of the 11th Biennial Participatory Design Conference* (pp.41-50). ACM International Conference Proceeding Series. http://dx.doi.org/10.1145/1900441.1900448

Bødker, S., Dindler, C., Iversen, O. S., & Smith, R. C. (2022). What are the results of participatory design? In *Synthesis lectures on human-centered informatics* (pp. 95–102). Springer, Cham. https://doi.org/10.1007/978-3-031-02235-7_9

Bratteteig, T., & Wagner, I. (2016). What is a participatory design result? In *Proceedings of the 14th Participatory Design Conference: Full papers - Volume 1* (pp. 141–150). Association for Computing Machinery. https://doi.org/10.1145/2940299.2940316

Brusselaers, N., Mommens, K. M., & Macharis, C. (2021). Building bridges: A participatory stakeholder framework for sustainable urban construction logistics. *Sustainability, 13*(5), 2678. https://doi.org/10.3390/su13052678

Cabré Romans, E., & Andrés, A. (2017). La Borda: A case study on the implementation of cooperative housing in Catalonia. *International Journal of Housing Policy, 18*(1), 1-21. https://doi.org/10.1080/19491247.2017.1331591

Chen, E., Leos, C., Kowitt, S. D., & Moracco, K. E. (2019). Enhancing community-based participatory research through human-centered design strategies. *Health Promotion Practice, 21*(1), 37–48. https://doi.org/10.1177/1524839919850557

Corbett, E., & Le Dantec, C. A. (2018). The problem of community engagement: Disentangling the practices of municipal government. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (pp. 1–13). Association for Computing Machinery. https://doi.org/10.1145/3173574.3174148

Corbett, E., & Loukissas, Y. (2019). Engaging gentrification as a social justice issue in HCI. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI 2019) (pp. 1–16). Association for Computing Machinery. https://doi.org/10.1145/3290605.3300510

Dias, N., Curwell, S., & Bichard, E. (2014). The current approach of urban design, its implications for sustainable urban development. *Procedia Economics and Finance, 18,* 497–504. https://doi.org/10.1016/s2212-5671(14)00968-x

Forst, L., Ahonen, E., Zanoni, J., Holloway-Beth, A., Oschner, M., Kimmel, L., Martino, C., Rodriguez, E., Kader, A., Ringholm, E., & Sokas, R. (2013). More than training: Community-based participatory research to reduce injuries among Hispanic construction workers. *American Journal of Industrial Medicine, 56*(8), 827-837. https://doi.org/10.1002/ajim.22187

Galamba, K. R., & Nielsen, S. B. (2016). Towards sustainable public FM: collective building of capabilities. *Facilities, 34*(3/4), 177–195. https://doi.org/10.1108/f-05-2013-0039

Gayanika, D. (2017). The role of community empowerment on sustainable Eco-Friendly Resort Development: A case study of Kandalama residents in Sri Lanka. *NSBM Journal of Management, 3*(1), 73. https://doi.org/10.4038/nsbmjm.v3i1.41

Harahap, G. Y. (2020). Instilling participatory planning in disaster resilience measures: Recovery of tsunami-affected communities in Banda Aceh, Indonesia. *Budapest International Research in Exact Sciences, 2*(3), 394–404. https://doi.org/10.33258/birex.v2i3.1085

Hosseini, K. A., & Izadkhah, Y. O. (2020). From "Earthquake and safety" school drills to "safe school-resilient communities": A continuous attempt for promoting community-based disaster risk management in Iran. *International Journal of Disaster Risk Reduction, 45,* 101512. https://doi.org/10.1016/j.ijdrr.2020.101512

Hussain, L. (2017). *Post-disaster housing reconstruction: A study of the Government of Pakistan's housing reconstruction programme in Azad Jammu & Kashmir after October 2005 earthquake* (Doctoral dissertation, Durham University). Durham E-Theses Online. http://etheses.dur.ac.uk/12285/

Hussein, H. I., & Kisimbii, J. (2019). Influence of community participation on projects implementation in Arid and Semi-Arid regions: A case of road construction projects in Garissa County, Kenya. *International Journal of Current Aspects, 3*(V), 12–27. https://doi.org/10.35942/ijcab.v3iv.58

Joshi, R., Tamrakar, A., & Magaiya, B. (2021). Community-based participatory approach in cultural heritage reconstruction: A case study of Kasthamandap. *Progress in Disaster Science, 10,* 100153. https://doi.org/10.1016/j.pdisas.2021.100153

Joshi, S. G., & Bratteteig, T. (2016). Designing for prolonged mastery: On involving old people in participatory design. *Scandinavian Journal of Information Systems, 28*(1), https://aisel.aisnet.org/sjis/vol28/iss1/1

Kazemidemneh, M., & Lashgari, A. (2023). Sustainable urban development in Venezuela: A management and economic perspective. *European Journal of Development Studies, 3*(5), 32–38. https://doi.org/10.24018/ejdevelop.2023.3.5.292

Marín, L.S., & Roelofs, C. (2018). Engaging small residential construction contractors in community-Based participatory research to promote safety. *Annals of Work Exposures and Health, 62 (S1),* S72-S80. https://doi.org/10.1093/annweh/wxy040

McAnany, E. G. (2012). *Saving the World: A Brief History of Communication for Development and Social Change.* University of Illinois Press. http://www.jstor.org/stable/10.5406/j.ctt2ttb3k

Meetiyagoda, L., Mahanama, P., Ley, A., & Amarawickrama, S. (2024). A ladder of sense of place: Case study of Crow Island Beach Park, Sri Lanka. *Cities*, *145*, 104695. https://doi.org/10.1016/j.cities.2023.104695

Mueller, J., Lu, H., Chirkin, A., Klein, B., & Schmitt, G. (2018). Citizen design science: A strategy for crowd-creative urban design. *Cities*, 72, 181–188. https://doi.org/10.1016/j.cities.2017.08.018

Peralta, K. J., & Murphy, J. W. (2016). Community-based participatory research and the co-construction of community knowledge. *Qualitative Report, 21*(9). 1713-1726. https://doi.org/10.46743/2160-3715/2016.2526

Racadio, R., Rose, E. J., & Kolko, B. E. (2014). Research at the margin: Participatory design and community-based participatory research. In *Proceedings of the 13th Participatory Design Conference: Short Papers, Industry Cases, Workshop Descriptions, Doctoral Consortium Papers, and Keynote Abstracts - Volume 2* (pp. 49–52). Association for Computing Machinery. https://doi.org/10.1145/2662155.2662188

Roosli, R., Nordin, J., & O'Brien, G. (2018). The evaluation of community participation in post-disaster housing reconstruction projects in Malaysia. *Procedia Engineering, 212*, 667-674. https://doi.org/10.1016/j.proeng.2018.01.086

Semeraro, T., Nicola, Z., Lara, A., Cucinelli, F. S., & Aretano, R. (2020). A bottom-up and top-down participatory approach to planning and designing local urban development: Evidence from an urban university center. *Land*, *9*(4), 98. https://doi.org/10.3390/land9040098

Schultz, A., Goertzen, L., Rothney, J., Wener, P., Enns, J., Halas, G., & Katz, A. (2017). A scoping approach to systematically review published reviews: Adaptations and recommendations. *Research Synthesis Methods*, *9*(1), 116–123. https://doi.org/10.1002/jrsm.1272

Schutte, D. W. (2016). *Community development and community participation: A conceptual revisit.* Cape Peninsula University of Technology. https://doi.org/10.13140/RG.2.2.22723.81443

Shafique, K., & Warren, C. M. J. (2015). Significance of community participation in success of post natural disaster reconstruction project - Evidence from developing country. In S. Perera, T. Gajendran, & A. Revez (Eds.), *Proceedings of the 5th International Conference on Building Resilience* (pp. 1-12). University of Southern Queensland. https://www.preventionweb.net/files/45623_45623androiddoctoralschoolproceedin.pdf

Stewart, J. H., Phillipo, F., & Pesha, J. (2023). Challenges facing community participation in construction projects of ward secondary schools in Kibaha Town Council, Tanzania. *Asian Research Journal of Arts & Social Sciences, 21*(4), 22–31. https://doi.org/10.9734/arjass/2023/v21i4489

Tremblay, M., Martin, D. H., Macaulay, A. C., & Pluye, P. (2017). Can we build on social movement theories to develop and improve community-based participatory research? A framework synthesis review. *American Journal of Community Psychology, 59*(3–4), 333–362. https://doi.org/10.1002/ajcp.12142

Valladares, A. (2017). Successes and failures of participation-in-design: Cases from Old Havana, Cuba. *Frontiers of Architectural Research, 6*(3), 401–411. https://doi.org/10.1016/j.foar.2017.06.001

Wedam, E., Quansah, J. Y. D., & Debrah, I. A. (2015). Community participation in educational infrastructure development and management in Ghana. *Education, 5*(5), 129-141. https://doi.org/10.5923/j.edu.20150505.02

Thiruna, J., Kulatunga, U., AL-Dahash, H.F.K. and Fernando, M.L.S.S., 2024. Investigating the challenges of implementing COVID-19 preventive practices in the construction industry in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 673-686. DOI: https://doi.org/10.31705/WCS.2024.53. Available from: https://ciobwcs.com/papers/

INVESTIGATING THE CHALLENGES OF IMPLEMENTING COVID-19 PREVENTIVE PRACTICES IN THE CONSTRUCTION INDUSTRY IN SRI LANKA

J. Thiruna[1], U. Kulatunga[2], H.F.K. AL-Dahash[3], and M.L.S.S. Fernando[4]

ABSTRACT

The COVID-19 pandemic has had a significant impact on various industries worldwide, including the construction industry. The construction industry in Sri Lanka has faced numerous challenges due to the COVID-19 pandemic. The COVID-19 preventive measures were followed and resumed the work to mitigate the impacts of COVID-19. However, there were challenges when implementing the COVID-19 safety measures. Thus, the study aimed at investigating the challenges of implementing COVID-19 preventive practices. The research adopted a qualitative approach, including twelve structured expert interviews within four case studies from different graded contractor organisations. According to the findings of expert interviews, the background of the research problem was validated. Besides, the challenges of adopting COVID-19 preventive measures were identified in the literature. Data collection was conducted to validate the literature review findings. The findings of this study reveal that the safety measures followed by the highest-graded organisations are different from the other organisations. Hence, the challenges were changed according to the grade of companies. ignorance, contradiction and conflicts when someone near does not follow guidelines, additional time, limited resources, contractors having financial difficulties and difficulties in adapting preventive measures are common challenges of implementing COVID-19 preventive practices in the Sri Lankan construction industry. Hence, this provides insights into the effective implementation of COVID-19 preventive measures in construction sites to overcome the challenges posed by the pandemic.

Keywords: *Challenges; Construction Industry; COVID-19; Preventive Practices; Sri Lanka.*

1. INTRODUCTION

Global pandemics of diseases are not a new phenomenon (Vithana et al., 2020). Several regional and global pandemics of diseases have emerged at different scales throughout history. During the last century, the world experienced Spanish Flu in 1918, Asian Flu in 1957, Hong Kong Flu in 1968, and more recently, SARS in 2002, swine flu in 2009, and

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, E-mail
[2] Professor in Quantity Surveying, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Lecturer, Civil Engineering Department, University of Babylon, Iraq, eng.hajer.fack@uobabylon.ac.iq
[4] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, shamalfernando96@gmail.com

Ebola in 2014 (Wickramaarachchi et al., 2020). Sri Lanka periodically faces epidemics of infections that cause morbidity and mortality, such as leptospirosis and dengue (Wickramaarachchi et al., 2020). Accordingly, Sri Lanka faced COVID-19. The SARS-CoV-2 virus, which causes the respiratory condition coronavirus disease 2019 (COVID-19), was first identified in December 2019 (Rath, 2022). Strict precautions were to be implemented globally to combat the pandemic (Umar, 2022).

The COVID-19 pandemic changed the ordinary practices of the entire world, and the construction industry is not an exception (Pamidimukkala & Kermanshachi, 2021). As a result of the pandemic, there were travel warnings, border and store closures, regional lockdowns, and social distancing measures that led to uncertainty in economic and social performances (Vithana et al., 2020) Considering the effects of the lockdown, many construction projects had been closed (Faithful Cloud, 2020). Measures such as screening, site access and handling of material and equipment deliveries on-site are some measures that were adopted to manage COVID-19 on the sites (Amoah & Simpeh, 2021). Further, the construction workforce had many safety and health concerns due to the pandemic. However, conducting and updating the risk assessment regularly for work-related exposure to COVID-19, developing action plans to prevent COVID-19, maintaining flexible sick leave policies, installing temporary and possible barriers between work areas and ensuring employees reduce the sharing office stationaries, tools, and equipment are some of the safety practices among construction organisations (Alara, 2021). Even though the COVID-19 pandemic is a nonexistent issue there is a possibility of occurrence of any type of pandemic in future. Hence it is essential to assess the COVID-19 pandemic and review it as a learning platform to identify weaknesses and propose strong suggestions to overcome the pandemic situations. Therefore, this research aims to investigate the challenges of implementing COVID-19 preventive practices in the construction industry in Sri Lanka, as COVID-19 was a new and unexpected pandemic.

2. LITERATURE REVIEW

2.1 IMPACT OF COVID-19 ON THE CONSTRUCTION INDUSTRY

COVID-19 caused severe respiratory illness, including pneumonia and led to hospitalisation, long-term health complications and death. According to WHO (2024), there had been 775,293,630 confirmed cases of COVID-19, including 7,044,637 deaths, reported to WHO (2024) until April 07 2024. The total cases and deaths that occurred all over the world until April 07, 2024, are shown in Figure 1. Based on this number, COVID-19 has caused numerous fatalities continuously. As a result, numerous countries implemented precautionary measures to minimise the implications of COVID-19 (Gamil & Alhagar, 2020; Khankeh et al., 2021; Sierra, 2022). According to Alsharef et al. (2021) and Bou Hatoum et al. (2021), the COVID-19 epidemic has ignited a global health crisis that has severely disrupted and impacted nations and all sectors of the economy, including restaurants, retail, and airlines. The COVID-19 pandemic has several effects that have been reported in the construction industry, including delays (time and cost overruns), payment delays, material shortage and delivery delays, labour shortages, price variations at the market, inadequate site management and supervision, inadequate communication between parties, supply chain disruptions, decreased productivity and workflow, and effects on revenue and cash flow (Parameswaran & Ranadewa, 2021).

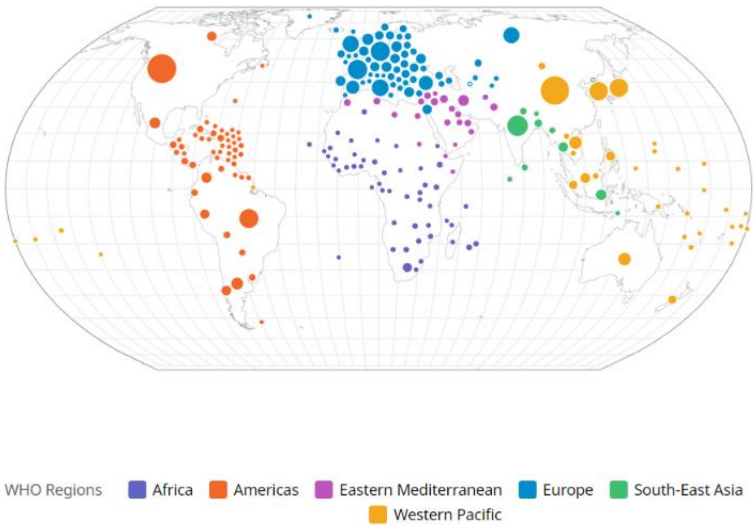


Figure 1: COVID-19 cases reported to WHO until April 2024 (source: WHO, 2024)

According to King and Lamontagne (2021), the construction industry is regarded as one of the key economic pillars of the societies in which it operates all over the world. It is vital to identify the COVID-19 impacts that have a significant influence on the construction sector to recognise a solution to the pandemic. The construction industry could not be shut down indefinitely during COVID-19 due to its significant contribution to the country's economy (Amoah & Simpeh, 2021). Hence, preventive measures were adopted to curb the spread of positive cases and minimise the impacts of COVID-19 on the construction industry and workforce (Stiles et al., 2020). The goal of these measures is to ensure the safety of construction workers. However, there were mixed feelings among industry professionals about their feasibility and effectiveness (Nnaji et al., 2022). Therefore, to improve COVID-19 risk mitigation in the construction industry, it was necessary to understand how field workers perceive the effectiveness of safety measures and solutions during a pandemic, as these perceptions directly impact their behaviour and performance (Jiang et al., 2017).

2.2 CHALLENGES OF IMPLEMENTING COVID-19 PREVENTIVE MEASURES AT CONSTRUCTION SITES

Different challenges facing implementing COVID-19 safety measures in the construction industry have been extracted from the literature review. One of the major challenges is the lack of awareness among workers about the seriousness of the virus and the importance of following safety guidelines (Amoah & Simpeh, 2021). Another challenge is the difficulty of maintaining social distancing at construction sites, which are often crowded and require close interaction between workers (Goh et al., 2022). The non-availability of Personal Protective Equipment (PPE) was a challenge, as the demand for PPE has increased significantly during the pandemic (Khankeh et al., 2021). This has led to shortages and increased costs, making it difficult for contractors to provide adequate PPE to all workers (Burnett et al., 2022). It is important to prioritise the use of PPE based on the level of risk and to ensure that PPE is properly maintained and replaced when necessary (Burnett et al., 2022). Table 1 summarises the previous studies that have elaborated on the challenges of implementing safety measures at construction sites due to the COVID-19 pandemic.

Table 1: Challenges of implementing safety measures at construction sites due to the COVID-19 pandemic

Challenge	References
Compliance and enforcement challenges	(Almohassen et al., 2023; Padidar et al., 2021; Kukoyi et al., 2022; Amoah & Simpeh, 2021)
Training and Awareness issues	(Almohassen et al., 2023; Boti Sidamo et al., 2021; Kukoyi et al., 2022)
Difficulty in accessing personal protective equipment	(Almohassen et al., 2023; Amoah & Simpeh, 2021)
Communication and coordination challenges	(Boti Sidamo et al., 2021; Khankeh et al., 2021;
Physical and logistical challenges	(Sierra, 2022)
Financial difficulties	(Ly et al., 2022; Sierra, 2022; Boti Sidamo et al., 2021; Khankeh et al., 2021)
Limited resources	(Sierra, 2022; Boti Sidamo et al., 2021; Khankeh et al., 2021;
Decrease in productivity	(Kukoyi et al., 2022)
Mental and physical health problems	(Khankeh et al., 2021)
Poor supportive supervision	(Boti Sidamo et al., 2021; Khankeh et al., 2021)
Shortages in PPE	(Khankeh et al., 2021; Kukoyi et al., 2022)
Lack of standardization	(Pamidimukkala et al., 2021)
Adaption of preventive measures	(Singh et al., 2021)
Rapid changing guidelines	(Singh et al., 2021; Kukoyi et al., 2022)
Negligence	(Boti Sidamo et al., 2021; Padidar et al., 2021; Kukoyi et al., 2022)
Resistance to change	(Boti Sidamo et al., 2021)
Unpredictable nature of construction work	(Almohassen et al., 2023)

According to the outcome of Table 1 compliance and enforcement challenges, financial difficulties, negligence, limited resources, and training and awareness issues were identified as mostly reviewed challenges. The results and discussion section validates and further discusses these challenges with the primary data collection.

3. METHODOLOGY

Multiple case studies have been selected to investigate the phenomena of COVID-19 preventive practices in the construction industry in greater detail. This enhances the validity and reliability of the research. Moreover, because the authors focus on studying the phenomena itself, not the case, multi-case studies can be discussed, presented and analysed as one set based on Yin (2014). To get a fuller picture of the studied phenomenon, four cases, which were contracting organisations of Construction Industry Development Authority (CIDA) grades C9, C8, CS1 and CS2, are selected and explored. Those were selected since those are the highest-graded and lowest-graded companies. Three interviews were conducted for each case study with professionals who have experience more than five years in construction site supervision and site safety. This research explores the subjective matter. Therefore, the qualitative approach is more appropriate for this study. Expert semi-structured interviews, working in the highest and lowest-graded contracting organisations in Sri Lanka, were targeted during the primary data collection process. Based on Saunders et al. (2019), face-to-face interviews allow researchers to interact with the interviewees to get a full understanding of a specific issue. Therefore, twelve face-to-face structured interviews are carried out to extract relevant information from the experts to collect data. Table 2 shows the overview of the interviews based on their type of organisation and relevant case study.

Table 2: Overview of the Interviewees

Case Identification	Grade of the company	Interview code	Designation	Years of experience
A	**C9**	AR1	Technical Officer	7 years
		AR2	Engineer	7 years
		AR3	Engineering Assistant	5 years
B	**C8**	BR1	Technical Officer	5 years
		BR2	Engineering Assistant	6 years
		BR3	Engineering Assistant	10 years
C	**CS1**	CR1	Quantity Surveyor	10 years
		CR2	Site Engineer	8 years
		CR3	Engineering Assistant	6 years
D	**CS2**	DR1	Safety Officer	6 years
		DR2	Project Manager	10 years
		DR3	Construction Manager	10 years

4. RESULTS AND DISCUSSION

There were challenges in implementing COVID-19 preventive measures faced by the management team at construction sites. Most of the challenges mentioned by interviewees were similar between the organisations. The similarities between responses and challenges identified in the literature review were provided in the following sections.

4.1 PERSONAL PROTECTIVE EQUIPMENT (PPE)

It is widely known that social distancing and PPE-related issues were major challenges found hindering COVID-19 safety measures (Kukoyi et al., 2022). Interviewees agreed with this view and stated that maintaining social distancing, washing hands often, being clean and wearing gloves and masks are most of the difficulties faced by labourers in every stage of construction work. CR3 mentioned that "*wearing masks continuously was difficult for labourers while working with sweat and hot weather*". Further, CR3 mentioned that "*some labourers felt uncomfortable working while wearing gloves*". Hence, labourers tried to avoid COVID-19 preventive measures often. Kukoyi et al. (2022) agree with this view stating that individual performance can be negatively affected as the use of PPE was considered uncomfortable and not practicable. AR1 mentioned that "*washing hands often was difficult to labourers; however, using hand sanitisers was easier than washing hands often*". Further, AR1 mentioned that some of the highest-graded organisations provided separate hand sanitisers for all the labourers. DR1 mentioned that "*most of the labourers forgot to bring gloves, and hand sanitisers even if it provided for free*". Further, DR1 stated that "*being clean while construction works was a burden for labourers and that it is impractical*". Kukoyi et al. (2022) agreed with the aforementioned views and added there is inadequate use of PPE. Further, some construction practitioners used COVID-19 personal protective equipment incorrectly.

4.2 SOCIAL DISTANCING MEASURES AND PRODUCTIVITY LOSSES

According to Niroshana et al. (2022), the low levels of health and safety in the Sri Lankan construction sites have affected their productivity even before the COVID-19 pandemic. However, during it, the situation becomes worse. CR2 stated that "*Social distancing measures led to a decrease in productivity*". Kukoyi et al. (2022) and Nnaji et al. (2022) agreed with this view stating that because the construction industry is labour-intensive, applying the practice of social distancing can negatively affect productivity on site besides its cost implications on contractors, contractors' employees and clients. Amoah and Simpeh (2021) explained that workers might not always follow these preventive measures due to perceived productivity losses. Further, DR3 mentioned that "*it required changes to the work schedule, additional cleaning procedures, and changes to the workflow to maintain distance between workers*". Construction, by its nature, is an extremely labour-intensive industry and most of the work requires carrying out the work closely (Hossain et al., 2020; Kukoyi et al., 2022; Sui Pheng et al., 2019). Further, remote work arrangements and the need for virtual meetings and communication affected productivity as it may take additional time for workers to adjust to new technology and communication methods. Maintaining social distance was another difficulty faced during every stage of construction work. If labourers are concerned about maintaining social distancing, labourers could not work properly. Similar to the primary findings, Goh et al. (2022), Parameswaran and Ranadewa (2021) and Shibani et al. (2020) also agreed that maintaining social distancing was difficult to implement. The primary difficulty faced by labourers was fear of virus infection. Some labourers fought with other labourers for not wearing masks and not maintaining social distancing. In agreement Kukoyi et al. (2022) assured that the prescribed social distancing is considered one of the most challenging measures to abide by on construction sites.

4.3 DIFFICULTIES IN ADOPTING THE NEW NORMAL

Workers and labourers had difficulty adjusting to new safety protocols such as social distancing, mask-wearing, and increased sanitisation measures. This challenge has been identified through the primary data collection as an addition to the literature findings. Additionally, CR3 mentioned that "*some workers may be resistant to change or lack awareness of the importance of these measures*". Boti Sidamo et al. (2021) agree with this view stating that resistance to change is one of the different barriers facing the effective implementation of public health measures. It might be due to a lack of experience and difficulties in adopting the measures. These difficulties in adopting the "new normal" pose a challenge in effectively implementing and maintaining COVID-19 safety measures at construction sites. In agreement, Kukoyi et al. (2022) stated that some workers do not comply with the COVID-19 safety regulations and ignore the dangers of the virus. Amoah and Simpeh (2021) noted that some companies failed to comply with preventive measures due to productivity losses perceived by workers.

4.4 CONTINUOUS CHANGES IN PROJECT SCHEDULING AND PLANNING

The continuous changes in project scheduling and planning due to COVID-19 present a significant challenge for implementing safety practices in the construction industry. The pandemic caused disruptions to the supply chain and availability of materials, as well as labour shortages and reduced demand, resulting in changes to project timelines and scheduling. CR3 mentioned that "*This uncertainty and fluctuation in project timelines* *made it challenging to plan and implement safety measures effectively"*. It also created a need for constant re-evaluation and adaptation of safety protocols to accommodate changes in project schedules and timelines. This led to increased costs and delays in completing projects. Singh et al. (2021) agreed with this view and stated that rapidly changing guidelines are one of the different challenges in implementing COVID-19 pandemic measures.

4.5 MENTAL AND PHYSICAL HEALTH DIFFICULTIES

It is widely known that the COVID-19 pandemic is one of countless stressors. These tensions were excessive with no adequate government support, particularly in low-income economies. These stressors can cause mental health problems. During the pandemic period, the most common disorders that can be seen are depressive and anxiety disorders (Khankeh et al., 2021). DR1 mentioned that "*During masonry work, one labour got tired of using a mask continuously. Hence, he fainted due to breathing problems*". Other interviewees agreed and mentioned many labourers felt dizzy due to using masks continuously while working. Hence, most of the labourers removed masks to avoid getting tired. Breathing was difficult for labourers while wearing masks. Kukoyi et al. (2022) reported that fatigue can be caused by wearing a face mask as it contributes to the increase of sweat which can cause goggles to fog.

4.6 CONSTRUCTION ACCIDENTS

BR3 stated that "*some accidents occurred when labourers tried to maintain distance between labourers*". Hence, it was a burden for labourers. Moreover, DR3 and DR2 mentioned that "Fear about infection was the primary difficulty faced by labourers in construction site". Since there were fights between labourers about not following preventive measures. Labourers with normal flu and fever were treated badly due to this fear.

DR2 mentioned that "after all, COVID-19 preventive measures were strictly followed and supervised but general safety measures were not prioritized" Further, DR2 claimed that "most of the labourers failed to wear safety jackets and safety helmets while wearing masks". Supervisors were also frightened about virus infection and maintained social distance than expected. Hence, supervisors failed to guide labourers in taking care of safety. Additionally, DR3 mentioned that "most of the labourers worried about family and children". Therefore, those labourers could not concentrate on their work. Those labourers worked with multiple thoughts and failed to concentrate on their work. Hence, accidents have occurred in sites including slips and cutting body parts unconsciously. Further, DR3 mentioned that "labourers need to be more careful while using electrical equipment and sharp-end tools".

DR1 mentioned that "*During masonry work, one labour got tired of using a mask continuously. Hence, he fainted due to breathing problems*." AR2, BR3, BR1, AR1, and DR1 agreed and mentioned many labourers felt dizzy due to using masks continuously while working. Hence, most of the labourers removed masks to avoid getting tired.

According to AR2's answer, while carpentry work going on, one labour coughed. Another labour who worked near that labour got frightened and moved a bit back unconsciously to maintain distance from that labour. At the time labour was standing on scaffolding. Hence, that labour slipped from the scaffolding.

DR2 mentioned an accident similar to this, while soffit plastering works were going on labour slipped from scaffolding. However, that labour did not fall. That labour managed to catch scaffolding while slipping. Hence labour could escape from a big accident.

Further, DR2 mentioned another accident that happened during excavation similar to the above accidents. However, this time engineering assistant while supervising. The supervisor fell into the excavated pit. At the time there were some tools used for excavation. Since the supervisor got an injury. That injury bled and the supervisor was taken to the hospital.

4.7 FREQUENT CLEANING

"*Cleaning hands often was mentioned as a difficulty*" according to BR2. Washing hands while working reduces effective working hours and interest. However, using sanitiser was an easy way to clean hands. However, labourers do not have the financial facilities to use sanitisers on their own. DR2 mentioned that "*some highest-graded organisations provided private sanitisers to each labourer*". Most of the labourers forgot to bring and use sanitiser during work even though sanitisers were provided for free. Additionally, being clean was another difficulty, since construction works are involved with dust, debris and waste.

4.8 LIMITED RESOURCES

When the COVID-19 outbreak is destroying the world, resource availability will have particular importance in construction organisations (Kukoyi et al., 2022). According to primary data, there was limited availability of PPE and sanitisation resources. This is because the demand for PPE has increased significantly during the pandemic (Khankeh et al., 2021). This has led to shortages and increased costs, making it difficult for contractors to provide adequate PPE to all workers (Burnett et al., 2022). AR3 mentioned that "*face masks, gloves, and hand sanitisers are required for workers to maintain their safety while carrying out their duties"*. Further, DR3 stated that "*insufficient staffing to enforce and monitor safety measures which led to non-compliance among workers*". The Sri Lankan construction industry did not have the resources to carry out frequent testing and screening of workers to detect COVID-19 infections. Hence, there were challenges in implementing safety measures due to limited resources. Not only that, based on Khankeh et al. (2021), even though the use of PPE will prevent the spread of infection at the community level, sometimes disruption in the supply chain of such equipment has led to the spread of the disease. Improper management of resources and equipment such as lack of access to resources and resource scarcity are the most effective shortcomings in preventive measures of COVID-19. Kukoyi et al. (2022) agree with the aforementioned view stating that the Adequacy and durability of PPE were found as a challenge to implementing COVID-19 safety measures.

4.9 FINANCIAL DIFFICULTIES

It is widely acknowledged by AR2, BR1, and CR3 stating applying different health and safety measures can cause significant financial difficulties to contractors (Nnaji et al., 2022; Sierra, 2022) in different territories such as England, Wales Scotland and Northern Ireland due to COVID (Sierra, 2022). According to DR2, CR3 and AR1 contractors, based on might be discouraged from imbibing risk assessment measures due to financial implications on construction costs (Kukoyi et al. 2022). In fact, without sufficient financial resources, it is difficult to comply with preventive measures (Khankeh et al., 2021; Ly et al., 2022).

4.10 VISITOR SAFETY MEASURES

DR1 mentioned that "*While workers at construction sites took possible COVID-19 safety measures to protect themselves and their colleagues, visitors who came to the sites did not always follow these same safety protocols*". This posed a challenge for site managers and workers, as they had to ensure that everyone on the site followed the necessary safety procedures to prevent the spread of the virus.

4.11 LOW LEVEL OF COVID-19 AWARENESS

It is widely believed that low levels of COVID-19 awareness might cause misconceptions and a lack of adequate information about the virus among some construction practitioners. Therefore, awareness and education were found to a major challenges hindering COVID-19 safety measures (Amoah & Simpeh, 2021; Kukoyi et al., 2022). Primary data agreed with this view: DR2 mentioned that "*Construction workers did not have the necessary knowledge or training to follow safety protocols properly, which led to non-compliance and increased risk of infection*". This occurred due to a lack of education and training resources, language barriers, or a lack of awareness of the importance of following safety protocols. In agreement, Pamidimukkala et al. (2021) reported that construction workers are often not trained in public health and may not be familiar with the latest information about COVID-19. Accordingly, workers' adherence to COVID-19 standard precautions can be improved by education. Further, retraining of construction workers on safety and health is vital.

Kukoyi et al. (2022); and Almohassen et al. (2023) agreed with this view stating that adequate safety awareness levels can be ensured by training of the employees to maintain safety performance and safety of the workers in construction projects. Therefore, it is crucial to provide regular training and awareness programs to ensure that workers understand the risks and the steps they can take to stay safe (Pamidimukkala et al., 2021).

4.12 COMMUNICATION AND COORDINATION

Based on Khankeh et al. (2021), one of the shortcomings facing preventive measures for COVID-19 is a weakness in risk communication. The authors found that the lack of a plan for risk communication negatively affected the management of the disease in terms of the high number of deaths and hospitalised people. Primary data also highlighted the lack of communication between management and workers. This might lead to a lack of information about the safety measures to be followed. Parameswaran and Ranadewa (2021) assert the inadequacy of communication between parties in the construction industry due to the COVID-19 pandemic.

4.13 POOR SUPPORTIVE SUPERVISION

Both primary data and secondary data agreed that poor supportive supervision is one of the different barriers facing the effective implementation of public health measures (Boti Sidamo et al., 2021; Khankeh et al., 2021). Boti Sidamo et al. (2021) mentioned that poor supportive supervision might affect the ultimate goal of implementing public health measures. In the construction industry, based on Parameswaran and Ranadewa (2021) inadequate site management and supervision are caused by the COVID-19 pandemic.

4.14 NEGLIGENCE

It is widely agreed that negligent, reluctant and careless in implementing public health interventions are found in community members in different countries and Sri Lanka one of them as mentioned by primary data. Boti Sidamo et al. (2021) stated that, at the late stage of the COVID-19 pandemic, most community members become like that. In agreement, Kukoyi et al. (2022) stated that some workers have acquired the habit of removing their face masks, whilst some refuse to wear them.

Figure 2 demonstrates that the challenges identified through the literature and primary data for implementing the COVID-19 pandemic are significant according to the size of the organisations. According to the research findings, large organisations mostly confront issues related to management and supervision while small organisations are challenged with primary-level construction activities. Hence, based on the size of the organisation different approaches are required to overcome the challenges of implementing the COVID-19 pandemic in the construction sector.

Figure 2: Categorisation of challenges for implementing COVID-19 preventive measures according to the size of the organisations

Figure 3 summarises the challenges of implementing COVID-19 preventive practices in the Sri Lankan context. The preventive practices were identified through literature review and the challenges were identified via primary data collection and secondary data-related discussion. The mind map illustrated in Figure 3 emphasises that ignorance, contradiction and conflicts when someone near does not follow guidelines, additional time, limited resources, contractors having financial difficulties and difficulties in adapting preventive measures are the common challenges of implementing COVID-19 preventive practices in Sri Lankan construction industry.

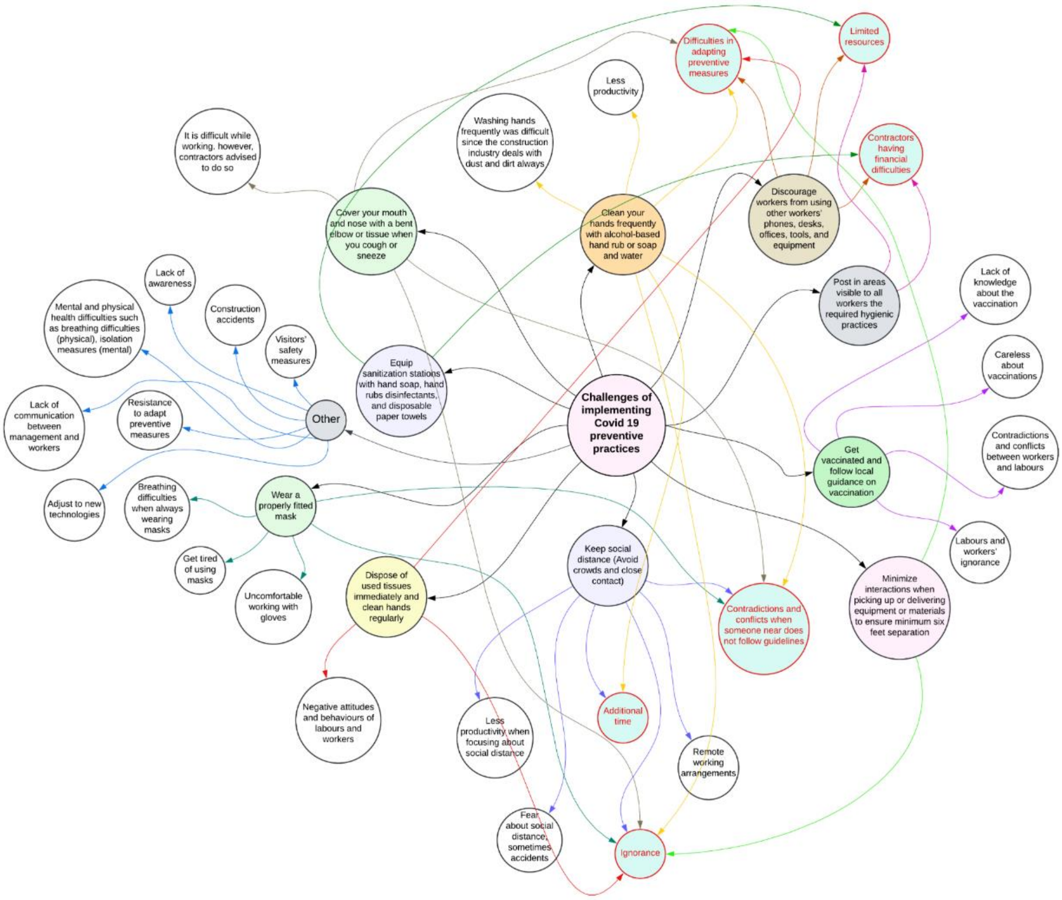


Figure 3: Challenges of implementing COVID-19 preventive practices in the construction industry

Furthermore, Kukoyi et al. (2022); Amoah and Simpeh (2021); Burnett et al. (2022); Boti Sidamo et al. (2021); and Sierra (2022) confirmed that the above-identified common challenges of implementing COVID-19 preventive practices in Sri Lanka has the similar level of impact on global construction sector. Hence, the findings of the study are equally important and applicable to the global context. It embarks on the criticality of the study in the Sri Lankan and global context.

5. CONCLUSIONS

In conclusion, the construction industry faces several challenges in implementing preventive measures, including the difficulty in maintaining social distancing, high implementation costs, lack of awareness among workers, and limited availability of personal protective equipment and sanitisation resources. However, it is essential to consider that there were differences in the challenges faced by organisations involved in small projects versus those involved in large projects. For instance, small organisations face difficulty implementing safety measures due to limited resources and financial constraints, while large organisations encounter challenges coordinating and monitoring safety measures across multiple sites and teams.

The summary of this research provides important insights into the challenges faced by the construction industry in implementing COVID-19 safety measures. By identifying these challenges, solutions can be developed to overcome these obstacles and enhance the implementation of safety measures at construction sites in the future. Further, exploring such challenges can help effectively manage the construction site in similar situations and reduce the burden on site managers inside and abroad. Therefore, other countries in similar situations could be helped.

The scope of the research is mainly focused on COVID-19 preventive measures and the challenges in adopting them at construction sites. The research has a limitation as it was conducted during a specific period and does not reflect the current situation or changes that have occurred since then. Nevertheless, the outcome of the research applies to any future similar pandemics, and it is adaptable to the Sri Lankan and global construction sectors.

6. REFERENCES

Alara, S. A. (2021). Organizational characteristics and COVID-19 safety practices among small and medium construction enterprises (SMEs) in Nigeria. *Frontiers in Engineering and Built Environment, 1*(1), 41-54. doi: https://doi.org/10.1108/FEBE-02-2021-0006

Almohassen, A. S., Alkhaldi, M. S., & Shaawat, M. E. (2023). The effects of COVID-19 on safety practices in construction projects. *Ain Shams Engineering Journal, 14*(1), 101834. doi: https://doi.org/10.1016/j.asej.2022.101834

Alsharef, A., Banerjee, S., Uddin, S. J., Albert, A., & Jaselskis, E. (2021). Early impacts of the COVID-19 pandemic on the United States construction industry. *International Journal of Environmental Research and Public Health, 18*(4), 1559. doi: https://doi.org/10.3390/ijerph18041559

Amoah, C., & Simpeh, F. (2021). Implementation challenges of COVID-19 safety measures at construction sites in South Africa. *Journal of Facilities Management, 19*(1), 111-128. doi: https://doi.org/10.1108/JFM-08-2020-0061

Boti Sidamo, N., Hussen, S., Shibiru, T., Girma, M., Shegaze, M., Mersha, A., Fikadu, T., Gebru, Z., Andarge,E., Glagn, M., Gebeyehu, S., Oumer, B., Temesgen, G. (2021). Exploring barriers to effective implementation of public health measures for prevention and control of COVID-19 pandemic in Gamo Zone of Southern Ethiopia: using a modified Tanahashi model. *Risk Management and Healthcare Policy, 14,* 1219-1232. doi: https://doi.org/10.2147/RMHP.S297114

Bou Hatoum, M., Faisal, A., Nassereddine, H., & Sarvari, H. (2021). Analysis of COVID-19 concerns raised by the construction workforce and development of mitigation practices. *Frontiers in Built Environment, 7,* 688495. doi: doi: 10.3389/fbuil.2021.688495

Burnett, K., Martin, S., Goudy, C., Barron, J., O'Hare, L., Wilson, P., Fleming, G., Scott, M. (2022). Ensuring the quality and quantity of personal protective equipment (PPE) by enhancing the procurement process in Northern Ireland during the coronavirus disease 2019 pandemic: Challenges in the procurement process for PPE in NI. *Journal of Patient Safety and Risk Management, 27*(1), 42-49. doi: https://doi.org/10.1177/25160435211057385

Faithful Cloud. (May, 2020). The impact of lockdown on your construction projects. Retrieved 28 September, 2023, from https://www.fgould.com/uk-europe/articles/the-impact-of-lockdown-on-your-construction-pro/

Gamil, Y., & Alhagar, A. (2020). The impact of pandemic crisis on the survival of construction industry: A case of COVID-19. *Mediterranean Journal of Social Sciences, 11*(4), 122-128. doi: https://doi.org/10.36941/mjss-2020-0047

Goh, Y. M., Tian, J., & Chian, E. Y. T. (2022). Management of safe distancing on construction sites during COVID-19: A smart real-time monitoring system. *Computers & Industrial Engineering, 163,* 107847. doi: https://doi.org/10.1016/j.cie.2021.107847

Hossain, M. A., Zhumabekova, A., Paul, S. C., & Kim, J. R. (2020). A review of 3D printing in construction and its impact on the labor market. *Sustainability, 12*(20), 8492. doi: https://doi.org/10.3390/su12208492

Jiang, K., Hu, J., Liu, S., & Lepak, D. P. (2017). Understanding employees' perceptions of human resource practices: Effects of demographic dissimilarity to managers and coworkers. *Human Resource Management, 56*(1), 69-91. doi: https://doi.org/10.1002/hrm.21771

Khankeh, H., Farrokhi, M., Roudini, J., Pourvakhshoori, N., Ahmadi, S., Abbasabadi-Arab, M., Bajerge, N. M., Farzinnia, B., Kolivand, P., Khanjani, M. S., Ahmadi-Mazhin, S., Sadeghi-Moghaddam, A., Bahrampouri, S., Sack, U., Stueck, M., Domres, B., Delshad, V. (2021). Challenges to manage pandemic of coronavirus disease (COVID-19) in Iran with a special situation: A qualitative multi-method study. *BMC Public Health, 21*, 1-9. doi: https://doi.org/10.1186/s12889-021-11973-5

King, T. L., & Lamontagne, A. D. (2021). COVID-19 and suicide risk in the construction sector: preparing for a perfect storm. *Scandinavian Journal of Public Health, 49*(7), 774-778. doi: https://doi.org/10.1177/1403494821993707

Kukoyi, P. O., Simpeh, F., Adebowale, O. J., & Agumba, J. N. (2022). Managing the risk and challenges of COVID-19 on construction sites in Lagos, Nigeria. *Journal of Engineering, Design and Technology, 20*(1), 99-144. doi: 10.1108/JEDT-01-2021-0058

Ly, B. A., Ahmed, M. A. A., Traore, F. B., Diarra, N. H., Dembele, M., Diarra, D., Kande, I. F., Sangho, H., Doumbia, S. (2022). Challenges and difficulties in implementing and adopting isolation and quarantine measures among internally displaced people during the COVID-19 pandemic in Mali (161/250). *Journal of Migration and Health, 5*, 100104. doi: https://doi.org/10.1016/j.jmh.2022.100104

Niroshana, N., Siriwardana, C., & Jayasekara, R. (2022). The impact of COVID-19 on the construction industry and lessons learned: a case of Sri Lanka. *International Journal of Construction Management*, 23(15), 2521-2538. doi: https://doi.org/10.1080/15623599.2022.2076016

Nnaji, C., Jin, Z., & Karakhan, A. (2022). Safety and health management response to COVID-19 in the construction industry: A perspective of fieldworkers. *Process Safety and Environmental Protection, 159*, 477-488. doi: https://doi.org/10.1016/j.psep.2022.01.002

Padidar, S., Liao, S.-M., Magagula, S., Mahlaba, T. a. A., Nhlabatsi, N. M., & Lukas, S. (2021). Assessment of early COVID-19 compliance to and challenges with public health and social prevention measures in the Kingdom of Eswatini, using an online survey. *Plos One, 16*(6), e0253954. doi: https://doi.org/10.1371/journal.pone.0253954

Pamidimukkala, A., & Kermanshachi, S. (2021). Impact of COVID-19 on field and office workforce in construction industry. *Project Leadership and Society, 2*, 100018. https://doi.org/10.1016/j.plas.2021.100018

Pamidimukkala, A., Kermanshachi, S., & Jahan Nipa, T. (2021). *Impacts of COVID-19 on health and safety of workforce in construction industry. In Proceedings of the International Conference on Transportation and Development*, June 8–10. (pp. 418-430). Austin, TX, United States.

Parameswaran, A., & Ranadewa, K. (2021). Resilience to COVID-19 through lean construction. *Faru Journal, 8*(1), 35-45.

Rath, L. (2022). Coronavirus History: How did coronavirus start?. Retrieved 20 June, 2024, from https://www.webmd.com/covid/coronavirus-history

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students* (8th ed.). New York: Pearson education.

Shibani, A., Hassan, D. H., & Shakir, N. S. (2020). The effects of pandemic on construction industry in the UK. *Mediterranean Journal of Social Sciences, 11*(6), 48-60. doi: https://doi.org/10.36941/mjss-2020-0063

Sierra, F. (2022). COVID-19: Main challenges during construction stage. *Engineering, Construction and Architectural Management, 29*(4), 1817-1834. doi: https://doi.org/10.1108/ECAM-09-2020-0719

Singh, M. J., Verma, D., Banerjee, T. B., Singh, A., & Bhatt, K. (2021). Overcoming challenges in implementing measures across multiple centers of a chain of hospitals to combat Covid-19 pandemic. *Indian Journal of Ophthalmology, 69*(5), 1289-1291. doi: 10.4103/ijo.IJO_2806_20

Stiles, S., Golightly, D., & Ryan, B. (2020). Impact of COVID-19 on health and safety in the construction sector. *Human Factors and Ergonomics in Manufacturing & Service Industries, 31*(4), 425-437. doi: 10.1002/hfm.20882

Sui Pheng, L., & Jia Zheng, S. (2019). Nature of the construction industry. *Construction Productivity in the Multilayer Subcontracting System: The Case of Singapore*, 9-19. Singapore: Springer.

Umar, T. (2022). The impact of COVID-19 on the GCC construction industry. *International Journal of Service Science, Management, Engineering, and Technology (IJSSMET), 13*(2), 1-17. doi: 10.4018/IJSSMET.20220301.oa1

Vithana, N., Bandara, K., & Jayasooriya, S. (2020). *Impact of COVID-19 pandemic to construction industry in Sri Lanka.* In Proceedings of the 13th International Research Conference, Built Environment and Spatial Sciences, General Sir John Kotelawala Defence University, Colombo.

WHO. (June, 2024). *WHO COVID-19 dashboard*. Retrieved June 10, 2024, from https://data.who.int/dashboards/covid19/cases?n=o

Wickramaarachchi, W., Perera, S., & Jayasinghe, S. (2020). COVID-19 epidemic in Sri Lanka: A Mathematical and computational modelling approach to control. *Computational and Mathematical Methods in Medicine, 2020*(1), 4045064. doi: https://doi.org/10.1155/2020/4045064

Yin, R. K. (2014). *Case study research: Design and methods*. London: Sage.

Sanmargaraja, S., Bandirau, J. R., Olanrewaju, A., Ponniah, V., Mathalamuthu, A.D. and Kanniyapan, G., 2024. Issues on foreign labourer's productivity on green buildings in Selangor, Malaysia. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 687-697. DOI: https://doi.org/10.31705/WCS.2024.54. Available from: https://ciobwcs.com/papers/

ISSUES ON FOREIGN LABOURERS PRODUCTIVITY ON GREEN BUILDINGS IN SELANGOR, MALAYSIA

Shalini Sanmargaraja[1], Jagadish Rau Bandirau[2], AbdulLateef Olanrewaju[3], Vignes Ponniah[4], Anselm Dass Mathalamuthu[5], and Gunavathy Kanniyapan[6]

ABSTRACT

Malaysia is Asia's largest net labour importer, suggesting that the construction sector is significantly reliant on foreign labour, primarily from Nepal, Indonesia, Vietnam, and Bangladesh. Foreign labourers are needed to fill labour shortages caused by locals' reluctance to seek jobs in the construction sector. The demand for green buildings escalates the demand for foreign labour. However, there are criticisms of the performance of green buildings on account of accidents on sites, poor workmanship, and project delays. Hence, this research investigates the nature of foreign labourers in the construction of green buildings. In 2021, a total of 100 surveys were administered during the construction of the green building in Selangor, yet only 80 were returned, resulting in an 80% response rate. Based on the results, it is found that the industry's reliance on foreign immigrants arose because of its labour-intensive and dirty, hazardous, and difficult nature, which discourages the locals. The results of the test of goodness of fit for the impact of foreign labourers on the construction of green buildings. The results revealed that all the constructs were statistically significant. Results also found that poor communication leads to accidents, language barriers, a lack of understanding, and poor workmanship badly impacting the projects. Furthermore, a lack of knowledge and education reduces the green building's productivity. Not all foreign labourers are very well experienced in green building construction due to the new concept that they never heard of before in their countries.

Keywords: *Construction; Efficiency; Immigrants; Site Operatives; Sustainability Development.*

[1] Assistant Professor, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, shalinis@utar.edu.my
[2] Postgraduate Student, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, Jagadish0128@1utar.my
[3] Associate Professor, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, olanrewaju@utar.edu.my
[4] Lecturer, Department Building Services Engineering, Trafford and Stockport College Group, United Kingdom ,, Vignes.Ponniah@tcg.ac.uk
[5] Lecturer,School of Architecture ,, Tunku Abdul Rahman University of Management and Technology Malaysia, anselmdass@tarc.edu.my
[6] Assistant Professor, Department of Real Estate, University of Management and Technology or Company, Malaysia, gunavathyk@tarc.edu.my

1. INTRODUCTION

Several studies have proven the benefits of green construction. Reduced Greenhouse Gasses (GHG) emissions, enhanced occupant health, and increased labour productivity are only a handful of the benefits of green buildings (Wong, 2021). Green buildings are designed and operated in such a way that the overall environmental effect of the built environment is as minimal as possible. However, despite this impressive performance of the green building, the productivity of the green building construction is low. Furthermore, a lack of knowledge of green technologies and technical challenges might not only delay the project yet result in higher prices through rework. Mahat et al., (2019), Hwang et al., (2017), Pan (2018), and Shinde and Hedaoo (2017) discovered the essential elements affecting the productivity of green buildings by comparing the likelihood, impact, and criticality of the parameters to traditional projects. The government of Malaysia encourages the supply and demand of green buildings to achieve sustainable development goals (Shafiei, et al., 2017). The primary obstacles to producing green buildings include inadequate knowledge and skills, inadequate precise laws and regulations, inadequate awareness and dedication, and inadequate sustainability components (Ministry of Energy, Green Technology and Water (KeTTHA), 2017).

The future of the construction sector depends on the systemic integration of digitisation, sustainability, and workforce, as Olanrewaju et al. (2023) explained. However, the construction and maintenance of green buildings often require specialised skills and knowledge, which may not be readily available in the local labour market. As a result, many construction companies in Malaysia have turned to foreign labour to fill these skill gaps. However, there is a lack of research on how productive foreign labourers are in the context of green building construction and maintenance. Factors such as language barriers, cultural differences, and unfamiliarity with local building codes and practices may impact their productivity and overall effectiveness on the job.

Foreign labourers employed as construction workers are currently considered a trend, owing to a labour shortage, their eligibility to work, and the availability of cheap foreign labour from neighbouring countries. Therefore, this research aims to investigate productivity and foreign labour engagement in the construction of green buildings. According to the Green Building Index 2020, Selangor has the greenest building projects registered in Malaysia, with 340 compared to the other states. Research on the productivity of foreign labour in the context of green buildings is needed to understand the potential benefits and challenges of using foreign labour and to identify strategies for optimising productivity and ensuring the long-term sustainability of green buildings. In this research, foreign labourers and foreign workers mean the same and are used interchangeably.

2. LITERATURE REVIEW

The demand for sustainable buildings is anticipated to rise in Malaysia. This calls for a workforce that is skilled and knowledgeable which might not always be obtainable locally. The nation has therefore been depending on immigrant employees. However, language difficulties, cultural differences, lack of skill, and a lack of training and certification could all have an impact on how productive and effective they are at work. To ensure that sustainable building practices are implemented, it is imperative to investigate the proficiency of foreign labourers in green building construction in

Malaysia. In the following sections, the impacts of the productivity of foreign labourers in the delivery of green building projects have been discussed.

2.1 IMPACTS OF FOREIGN LABOUR ON THE PRODUCTIVITY IN THE GREEN BUILDING PROJECT

There are some negative effects of foreign labour on the productivity of green construction projects.

2.1.1 Increase in the Number of Accidents on the Job Site

One of the most ignored aspects of a building project is construction site safety. Because of inadequate communication between site supervisors and foreign labourers, the number of accidents at the site is increasing. The significant obstacle between contractors and foreign labourers is the language barrier, which can be a major challenge. Foreign labourers often face challenges in comprehending discussions during toolbox meetings, especially regarding PPE, site laws, and regulations. As a result, when foreign labourers fail to recognise the necessity of safety, they risk catastrophic harm or permanent disability. According to the DOSH report, there were a total of 222 construction incidents in Malaysia in the year 2020. A lack of safety management resulted in the death of 58 workers and the permanent disability of four others (Salleh et al., 2020). Because the labourers worry about being fired or sent back home, migrant workers are less likely to complain about unsafe working conditions. They also frequently fail to report injuries out of fear of retaliation and because they cannot afford to take time off. Furthermore, migrant workers are often assigned more hazardous responsibilities compared to local workers. They also face growing pressure to complete tasks quickly and efficiently, leading to the use of shortcuts due to work fatigue (Shepherd et al., 2021).

2.1.2 Language Barrier among Foreign Labourers

Language barriers are a common problem in Malaysia among construction site operatives. Over 80% of these workers are foreigners from countries such as Indonesia, Bangladesh, Pakistan, Myanmar, Thailand, and India. However, the official language on construction sites is Malay, the national language, which most workers are not fluent in. This often leads to communication barriers between foreign operatives and local supervisors or senior site officers. The consequences of these language barriers include mistakes, errors, reduced productivity, and psychological issues among the workers. These psychological issues, such as fear of making mistakes, shyness, anxiety, lack of confidence, and lack of motivation, further impede the ability of foreign labourers to communicate effectively (Ne'Matullah et al., 2021). The impact of this on green construction is huge. For example, green construction often involves the use of advanced technologies and sustainable practices that require precise implementation. Miscommunication due to language barriers can lead to improper installation or use of these technologies, reducing their effectiveness and potentially causing project failures.

2.1.3 Lack of Knowledge, Training, and Inexperience of Unskilled Foreign Labourers Leading to Poor Productivity

According to Abdul-Rahman et al. (2012), excessive reliance on foreign labour will cause the economy and social equilibrium to be upset, as well as a reduction in productivity. According to Jamalulil et al. (2022), a rise in labour productivity is advantageous to the country, the labourers, employers, and consumers. Regrettably, the productivity of foreign workers is a major problem for the Malaysian construction industry. This occurs because of the inexperience and incompetence of foreign labourers, which could affect the general productivity of green building projects. In addition, a few of them lack sufficient training in their respective trades and are incapable of completing the work as specified. Moreover, the contractor's use of inexpensive, unskilled foreign labourers to address the labour shortage.

2.1.4 Decrease in the Quality of the Work

The quality of the work is determined by the experience and skills of the workers on the job site, not by the presence of foreign or local labour. One of the most serious issues facing the construction industry in green building projects is the influx of unskilled immigrant workers, as skilled labour is critical to project success. As a result, inadequate labour productivity is a primary factor influencing project quality in every construction business (Rahim et al. 2011; Jamadi, 2012). In the Malaysian construction industry, however, unskilled immigrant labour is one of the most inefficient labour types, negatively hurting project quality. Because of their lack of education, foreign employees can have an impact on the quality of work because they are inexperienced or lack an understanding of sustainable or green building methods and criteria. Most of them have rudimentary construction knowledge only (Fateh et al., 2022). As a result, it may have an impact on the outcomes of projects, and this will influence Malaysia's economic and long-term growth (Anderson, 2020). Foreign labourers need to work extended hours which is about 14 to 16 hours for low-income compared to the local labourers also affects their workmanship in green construction (Priya & Kumar, 2018).

2.1.5 Delay in the Project or Work

Due to their limited education, foreign employees may contribute to a decline in work quality by virtue of their inexperience and lack of familiarity with sustainable building methods or green building methods and criteria. As a result, it may have an impact on the outcomes of projects that result in significant losses or problems for the sector because of their inappropriate work methods. As a result, it may have an impact on the outcomes of projects that result in significant losses or problems for the sector because of their inappropriate work methods, thereby, this will influence Malaysia's economic and long-term growth (Yee et al., 2017).

2.1.6 Lack of Importance towards Safety in the Construction Industry

The main concern about safety culture issues at construction sites would be the negative attitudes and poor behaviour of the foreign labourers. Most construction workers did not follow safety procedures at work because of their irresponsibility, attitude, and ignorance of safety issues. Because they are accustomed to surviving in a strange land, most foreign labourers working in construction have low knowledge of safety. Most foreign labourers believe that following safety procedures is a burden that will limit their range of motion. Due to their laziness and bad safety mentality, workers may not always avoid risks even though they are trained (Zulkeflee et al., 2022).

3. METHODOLOGY

The purpose of this research is to investigate productivity and labour engagement in the construction of green buildings. The project managers, safety officers, staff, site operatives, and others at the construction projects in Selangor are the targeted respondents. Approximately 100 questionnaires were sent out via email and WhatsApp, yet only 80 were returned, resulting in an 80% response rate. Google Forms were used due to this research being conducted around July to September 2021 during the Covid-19 pandemic. The information contained in this report was collected in an online survey, comprised of quantitative questions. This research used a literature review and a survey questionnaire to achieve its aim. Primary data were collected through survey questionnaires. The respondents were selected based on convenience sampling. As Olanrewaju and Idrus (2020) explained, convenience sampling is appropriate for research with a limited timeframe and cost. There are three sections in the questionnaire. Section A is for the respondent's demography, Section B is for the factors of hiring a higher number of migrant workers to the industry, and Section C is for the impacts of the foreign labourers on the productivity in the green building projects. The constructs were measured on a five-point Likert scale, where 1= strongly disagreed, 2 = disagreed, 3= Not sure, 4 = strongly agree, and 5 = strongly agreed. The level of agreement or disagreement was estimated by means and the standard deviation. Therefore, the factors that have the highest mean score were considered as the most influential factors. The survey instrument was designed based on a literature review (Abdul-Aziz et al., 2018; Gaur, 2019; Abdul-Aziz, 2001; Olanrewaju et al., 2019; Abdul-Rahman et al., 2012; Pan et al., 2019; Olanrewaju et al., 2017), and input from site operatives and the authors' experiences. A pilot study was conducted involving three stakeholders that have experience with foreign labourers in the Malaysian construction industry. The analyses involved descriptive and diagnostic analyses. The computed statistical tests were the one-way test, reliability tests, and mode. All collected data were analysed using IBM SPSS 25. The t-test was conducted to examine whether each of the factors affects hiring foreign labour or not and whether the factor impacts the productivity of foreign labourers.

4. RESULTS AND DISCUSSION

A total of 100 forms were administered. However, only 80 responses were received. Although the research data were collected in 2021, however, they are still relevant for current practice because of stakeholder confirmation, practice consistency, the longevity of industry norms, the absence of exogenous factors, the ongoing relevance of the issues, the short time elapsed since data collection, and expert opinion have all indicated that no significant changes can be justified. The questionnaires were prepared in dual language, English and Malay language to ease the understanding of the foreign labourers. The administration of questionnaires in both English and Malay to foreign labourers engaged in green building construction projects in Malaysia is justified based on various factors such as language accessibility, inclusivity, improved communication, adherence to ethical standards, response accuracy facilitation, cultural sensitivity, legal and regulatory compliance, and pragmatic concerns.

4.1 RESPONDENTS PROFILE

A total of 80 respondents, comprising 53 males, and 23 females were respondents to the survey. The selection of the respondents consists of professionals and site operatives who are working on green building construction projects due to their first-hand experience, varied viewpoints, thorough understanding, real-world relevance, stakeholder engagement, knowledge transfer, practical implications, and increased credibility. The respondents comprised 23 civil engineers, 17 site operatives, 14 quantity surveyors, seven contractors, six M&E engineers, five developers., four architects, three project managers, and a sub-contractor participated in this research. Most of the respondents have one to five years of experience at the site. A 79% of the respondents have a master's degree as their highest qualification. In total, the data were collected from 20 ongoing green building projects.

4.1.1 Impacts of Foreign Labourers on Productivity

Table 1 shows the results of the test of goodness of fit for the impacts of foreign workers on the construction of green buildings. The Kaiser's Measure of Sampling Adequacy for the expectations was significant $\chi 2$ (36) = 836.445, p<0.001), N = 0.949). To interpret, the data were collected from those with near similar experiences or in the same population. The validity of the data ranges from 0.658 to 0.879. The reliability for the constructs is 0.968. The critical level was set at 3.5. The df for ranges is either 78 or 79. The results revealed that all the constructs were statistically significant.

Table 1: Results of t-test and standard error mean on the impacts of foreign workers on green building construction

Factors	Test Value = 3.5					
	T	DF	Sig. (2-Tailed)	95% Confidence Interval of the Difference		Std. Error Mean
				Lower	Upper	
Accidents increase at the site due to poor communication between the site supervisors and foreign workers	3.34	79.0	0.00	0.19	0.76	0.14
The biggest barrier between the contractors and foreign workers is the language.	2.25	79.0	0.03	0.04	0.61	0.14
The foreign workers fail to understand the safety importance which leads to serious injuries such as permanent disability.	2.63	78.0	0.01	0.08	0.61	0.13
Unskilled foreign labour is one of the unproductive labour types in the Malaysian construction industry which impacts the quality of the project.	7.43	79.0	0.00	0.50	0.87	0.09
Foreign workers can impact the quality of work due to their unskilled or lack of knowledge about green building methods and the requirements because of lack of education.	2.66	79.0	0.01	0.10	0.68	0.15
Lack of knowledge by foreign workers about the industry and improper work skills affect the outcome of the project.	2.90	79.0	0.01	0.13	0.72	0.15

Factors	T	DF	Sig. (2-Tailed)	95% Confidence Interval of the Difference		Std. Error Mean
	Test Value = 3.5					
				Lower	Upper	
A lack of experienced foreign workers with specific skills will cause the project delayed.	3.07	79.00	0.00	0.15	0.70	0.14
Poor labour productivity is the major significant part influencing delay in projects in the construction industry	6.54	79.00	0.00	0.42	0.78	0.09

Figure 1 displays the summary of the measurement of the negative impacts of foreign labour on the construction of green buildings.

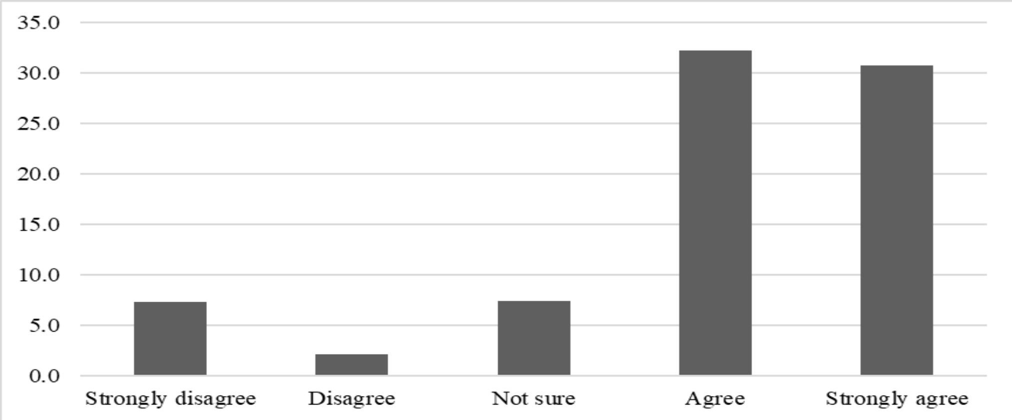


Figure 1: Summary of measurements of the negative impact of foreign workers on green building sites

Approximately 13% of the respondents disagreed or strongly disagreed that foreign workers have an impact on the construction of green buildings. However, while 9% are not sure, about 80% agreed that foreign workers have an impact on the productivity of the construction of green buildings. Table 2 presents the descriptive analysis of the impact of foreign workers on green building construction. As would be expected, if the labour lacks the needed competency, it will lower the site productivity and will ultimately affect the quality and cost of the projects. Considering the distinctive nature of the green building and the absence of prior experiential knowledge, it is anticipated that the costs will be even higher. This is regardless of the less of mechanisation. There may be language and cultural barriers for foreign workers in Malaysia's construction sector from nearby nations such as Indonesia and Bangladesh, as opposed to local labour. This may make it difficult to comprehend the requirements of green building construction and to communicate effectively. This will impact the dynamic between supervisors, construction managers, project managers, and site operatives.

The specifications and design requirements are largely in English, Russian, and Chinese, which dominate the supply of green materials and components. The Malaysian construction sector has yet to translate information into the local languages. The health and safety requirements and compliance of green building construction are high. Deductively, the foreign workers have not been able to meet the safety requirements which results in accidents. This may not be surprising because green buildings emphasise prefabrication (i.e. IBS), the materials and components to be large and possibly also heaving. The foreign workers fail to understand the safety importance which can lead them to serious injury such as or permanent disability obtained the first rank with 3.848 mean and 1.788 standard deviations followed by the outcome of projects that caused the industry a huge loss or problems because of their incorrect method of works obtained the second rank with 4.000 mean and 1.322 standard deviations. Some of them do not even have a valid green card to work at the site, this card will be obtained once the labourers successfully attend the safety training conducted by the Construction Industry Development Board (CIDB). As the labourers are brought to the different sites daily, they feel attending safety training is not worth their time as they will face different situations at different sites.

Some of the labourers do not even have valid papers such as work permits and passports to work in Malaysia. If the contractor, consultant, and client are not satisfied with the workmanship of the final output they need to hack back the completed structure and re-do it. This will increase the time and eventually will delay the completion of the project. Lack of knowledge by foreign workers about the industry and improper work skills which can have to affect the outcome of the project obtained the third rank with 3.923 mean and 1.301 standard deviations. Most of the workers do not get formal training or education in their origin country on the technology used in green buildings. Poor labour productivity is one of the major significant parts influencing delay in the project in every construction industry obtaining the last rank with 4.100 means and 0.821 standard deviations.

Table 2 shows that not all foreigners are very well experienced in green building construction due to the new concept that they never heard of before in their countries.

Table 2: Descriptive analysis of impacts of foreign labourers on productivity

Descriptions	Standard Deviation	Mean	Rank
Unskilled foreign labour is one of the most unproductive labour types in the Malaysian construction industry which impacts the quality of the project.	0.828	4.188	8
Poor labour productivity is one of the major significant parts influencing delays in the project in every construction industry.	0.821	4.100	9
The outcome of projects that cause the industry a huge loss or problems because of their incorrect method of work.	1.322	4.000	2
The number of accidents increases at the site because of poor communication between the site supervisors and foreign workers.	1.273	3.975	6
A lack of experienced foreign workers or a lack of workers with specific skills will cause the project behind or be delayed.	1.240	3.925	7
Lack of knowledge by foreign workers about the industry and improper work skills can affect the outcome of the project.	1.301	3.923	3
Foreign workers can impact the quality of work due to their unskilled or lack of knowledge about sustainable or green building methods and the requirements because of their lack of education.	1.302	3.888	4
The foreign workers fail to understand the safety importance which can lead them to serious injuries such as permanent disability.	1.778	3.848	1
The biggest barrier between contractors and foreign workers is the language.	1.290	3.825	5

Emphasis on the green features in building construction is still very low, therefore, the idea of the green concept is still very new for many contractors. Most of the workers do not get formal training or education on the technology used in green buildings. Unskilled labourers need to be well trained before they can produce a good quality of work. Most of the time, the on-the-job training is not sufficient to get the required skills before they can work on the actual projects. If the contractor, consultant, and client are not satisfied with the workmanship of the final output they need to hack back the completed structure and re-do it. This will increase the time and eventually will delay the completion of the project. Poor communication occurs at times due to the different cultures and different local dialects used in Malaysia such as Mandarin, Cantonese, Malay, and others. Foreign labourers will take some time to get used to the local dialect. The Malay language is the formal language in Malaysia hence if the foreign labourers cannot converse in this language, they will have difficulty in reading and understanding the safety rules and regulations. Foreign labourers do not wear their Personnel Protective Equipment (PPE) on site which can protect themselves and reduce the severity of the injuries if an accident occurs. Generally, labourers on-site will only use their PPE when there is an inspection or site visit by authorities. If there is an accident on-site, it will also delay a project because work on-site cannot be started immediately due to the investigation process on the accident will be carried out to identify the root cause of the accident.

5. CONCLUSIONS AND RECOMMENDATION

This study delves into the crucial labour factors involved in the construction of green buildings. The use of foreign workers in green building projects has raised worries about Malaysian construction businesses' efficiency. Due to the lack of experience and language barriers, foreign labourers are contributing to an increase in site accidents, jeopardising the safety and quality of green building construction. Furthermore, poor labour productivity is one of the most significant factors influencing project delays in every construction business, which can result in large losses or problems due to the wrong work methods. To improve the quality of green building construction, the government must tighten the rules on recruiting foreign labourers in the construction industry. Even though the government has begun to impose different restrictions on the hiring of foreign labours in recent years for a variety of reasons, including prioritising local workers and legalising certain groups of undocumented workers in the country, the number of foreign labourers is still excessive. The implications of this research highlight how crucial it is to address labour issues while developing green buildings to improve output in terms of quality, safety, and productivity. The government must devise strategies to limit foreign labour recruitment while also balancing the labour shortfall, particularly in the construction industry. The government might also make green building principles and safety rules mandatory for new and existing foreign workers. To minimise language hurdles, construction firms can engage a translator or train senior international labourers.

It is important to investigate how the productivity of foreign labourers negatively affects green buildings in Malaysia, for several reasons. It assists in highlighting issues and potential areas of development, guaranteeing that green construction initiatives fulfil their sustainability objectives. Additionally, it influences practice and policy, which improves the management of the foreign workforce and produces better results for green buildings. In the end, this research has the potential to further sustainable building techniques generally and to realise the financial and environmental advantages of green buildings.

The results of this research may be used to create focused training initiatives, better management techniques, and practical regulations that will raise the standard, sustainability, and output of green construction projects. However, due to the COVID-19 pandemic and some restrictions on physical meetings, the data collection process was constrained, resulting in a sample size of only 80 respondents for this project. Additionally, because this research was only conducted in Selangor, the results may be not generalisable to the entire Malaysian construction industry. Further research should survey foreign labourers considering the same or an extension of the survey, hence, more studies with larger samples are needed to be conducted in the other states.

6. ACKNOWLEDGEMENTS

Sincere appreciation and thanks to Universiti Tunku Abdul Rahman (UTAR) for providing the funding and support for this research.

7. REFERENCES

Abdul-Aziz, A.-R. (2001). Foreign workers and labour segmentation in Malaysia's construction sector. *Construction Management and Economics*, *19*(8), 789–798. doi:10.1080/01446190110072022.

Abdul-Aziz, A.-R., Umar, A. A. & Olanrewaju, A. L. (2018). South Asian migrants and the construction sector of the Gulf. In M. Chowdhury and S. I. Rajan (Eds.), *South Asian Migration in the Gulf*, (pp.165-189). https://doi.org/10.1007/97833197182179.

Abdul-Rahman, H., Wang, C., Wang, C., Wood, L. C., & Low, S. F. (2012). Negative impact induced by foreign workers: evidence in Malaysian construction sector. *Habitat International*, *36* (4), 433–443. doi:10.1016/j.habitatint.2012. 03.002.

Anderson, J.T. (2020). Managing labour migration in Malaysia: foreign workers and the challenges of "control" beyond liberal democracies. *Third World Quarterly, 42*(1), 86-104, https://doi.org/10.1080/01436597.2020.1784003.

Department of Statistics of Malaysia (2020). Population and Demography. Retrieved from https://www.dosm.gov.my/v1/index.php?r=column/ctwoByCat&parent_id=115&menu_id=L0pheU43NWJwRWVSZklWdzQ4TlhUUT09 on February 2, 2022.

Fateh, M. A. M., Mohamed, M. R., & Omar, S. A. (2022). The involvement of local skilled labour in Malaysia's construction industry. *Frontiers in Built Environment*, *8*, 1-13. https://doi.org/10.3389/fbuil.2022.861018.

Gaur, M.P. (2019). Assessment of socioeconomic status among different state level male team game players of Lucknow. *International Journal of Economic Perspectives,13*(1), 17–23. https://ijeponline.org/index.php/journal/article.

Jamadi, M.A. (2012). *Foreign Labour Employment in Construction Project*. [Masters Thesis]. Universiti Teknologi Malaysia. http://eprints.utm.my/29838/5/

Hwang, B., Zhu, L., & Ming, J. T. T. (2017). Factors affecting productivity in green building construction projects: The case of Singapore. *Journal of Management in Engineering, 33*(3), 04016052. doi: 10.1061/(ASCE)ME.1943-5479.0000499.

Mahat, N.A.A., Adnan, H. Yusuwan, N.M. & Maisham, M. (2019). Productivity improvement strategies in green construction project: Formulation of a theoretical framework. *IOP Conf. Series: Earth and Environmental Science*, 385, 012067, (pp. 1-8). DOI: 10.1088/1755-1315/385/1/012067.

Ministry of Energy, Green Technology and Water (KeTTHA) (2017). Green Technology Master Plan Malaysia 2017-2030 (GTMP), Ministry of Energy, Green Technology and Water (KeTTHA), Putrajaya, Malaysia.

Jamalulil, S. N. N. S., Hussin, S. N., Salleh, N. M., Kamar, I. F. M., & Rizam, K. N. (2022). High dependency on foreign workforce in Malaysian construction industry. *International Journal of Academic Research in Business and Social Sciences, 12*(9), 412 – 418. doi: 10.6007/IJARBSS /v12-i9/14488.

Ne'Matullah, K, F., Lim, S.P. and Roslan, S.A. (2021). Investigating communicative barriers on construction industry productivity in Malaysia: An overview. *International Journal of Evaluation and Research in Education (IJERE), 10* (22), 476-482. doi: 10.11591/ijere.v10i2. 21163.

Olanrewaju, A., Tan, S. Y., & Kwan, L. F. (2017). Roles of communication on performance of the construction sector. *Procedia engineering, 196*, 763-770. doi: 10.1016/j.proeng.2017.08.005.

Olanrewaju, A., Tan, S.Y., Lee, J.E. & Mine, N. (2019). Identification and establishment of weightage for critical success factors in sustainable affordable housing: An interactive approach. In Olanrewaju, A., Shari, Z. and Gou, Z. (Eds.), *Greening Affordable Housing*. (2nd ed. pp. 1-34). Taylor & Francis Group. doi: 10.1201/b22317-14.

Olanrewaju, A. & Idrus, A. (2020). What is determining affordable housing shortages in the greater Kuala Lumpur, Malaysia?, *Property Management*, *38*(1), 52-81. doi: 10.1108/PM-05-2019-0025.

Olanrewaju, A., Anavhe, P.J. & Chen, H.C. (2023). Disputes and claim management during the COVID-19 crisis: The lessons learned. *Journal of Legal Affairs and Disputes Resolution in Engineering and Construction. 15*(1). 1-11. doi: 10.1061/JLADAH.LADR-843.

Pan, W., Chen, L. & Zhan, W. (2019). PESTEL analysis of construction producvity enhancement strategies: A case study of three economies. *Journal of Management in Engineering*, *35*(1), 05018013. https://www.researchgate.net /publication/328063709.

Pan, W. (2018). Rethinking construction productivity theory and practice. *Built Environment and Project Assest Management*, *8*(3), 234-238. https://doi.org/10.1108/BEPAM-07-2018-125.

Hamid, A.R.A., Singh, B., Yusof, A.M. & Abdullah, N.A.M. (2011). *The employment of workers at construction sites*. 2nd International Conference on Construction and Project Management (IPEDR). Singapore. https://www.researchgate.net/publ ication/264623080_The_Employment _of_Foreign_Workers_at_Construction_Sites.

Salleh, N.M., Lop, N.S., Mamter, S.&Abidin, Z.Z. (2020). Preliminary survey on availability of local skilled construction workers at construction sites. *International Journal of Academic Research in Business & Social Sciences. 10*(3), 618-632. doi: 10.6007/IJARBSS/v10-i3/7077.

Salleh, N.M., Mamter, S., Lop, N.S. Kamar, I.F.M. & Hamdan, N. A.M. (2014). *The escalating of numbers of foreign workers in construction site*. MATEC Web of Conferences 15 (01026), 1-6. DOI: 10.1051/matecconf/20141501026.

Shafiei, M.W.M., Abadi, H. & Osman, W.N. (2017). The indicators of green buildings for Malaysian property development industry. *International Journal of Applied Engineering Research, 12*(10), 2182-2189. http://www.ripublication.com.

Shinde, V.J, & Hedaoo, M.N. (2017). A review on productivity improvement in construction industry. *International Journal of Engineering Technology Science and Research (IRJET), 4*(11), 210-215. https://www.irjet.net/archives/V4/i11 /IRJET-V4I1136.pdf.

Shepherd, R., Lorente, L., Vignoli, M., Nielsen, K. & Peiro, J.M. (2021). Challenges influencing the safety of migrant workers in the construction industry: A qualitative study in Italy, Spain and the UK. *Safety Science*, *142*, 1-15. https://doi.org/10.1016/j.ssci.2021.105388.

Wong, S.Y., Low, W.W., Wong, K.S. & Tai, Y.H. (2021). Barriers for green building implementation in Malaysian construction industry. *IOP Conferences Series: Materials Sciences and Engineering*, *1101*, 1-7. doi: 10.1088/1757-899X/1101/1/012029.

Yee, K.C.W.H., Rahim, A. & Zahari, H.Z.A. (2017). Foreign worker's composition at construction site. *Journal of Advanced Research Design*. 30(1). 12-21.

Zulkeflee, A.A., Faisol, N., Ismail, F. & Ismail, N.A.A. (2022). Safety compliances enhancement: foreign labours behaviour in the Malaysian construction site. *Journal of Construction in Developing Countries*, 27(1), 153–171. doi: 10.21315/jcdc2022.27.1.9.

Ekanayake, J., Allis, C., Jayasinghe, S. and Lokuge, A., 2024. Issues with supply chain management documents that contribute to project delays. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 698-711. DOI: https://doi.org/10.31705/WCS.2024.55. Available from: https://ciobwcs.com/papers/

ISSUES WITH SUPPLY CHAIN MANAGEMENT DOCUMENTS THAT CONTRIBUTE TO PROJECT DELAYS

Jananjaya Ekanayake[1], Chamari Allis[2], Sathya Jayasinghe[3] and Angel Lokuge[4]

ABSTRACT

Supply chain management is the process of obtaining the raw materials or components needed to create a product or service for an enterprise and deliver that product or service to customers. In construction, it is vital due to the involvement of a large number of resources and stakeholders. Hence, documentation plays a very important role in such a process. Yet, there are certain issues with supply chain management documents that contribute to the various issues of construction projects, including project delays. Hence, this research aimed to identify the potential factors affecting construction projects due to poor documents in supply chain management. This study was limited to building construction projects in Sri Lanka. Agreement errors of labour suppliers and material suppliers were the main areas of concern. In order to achieve the objectives of the research, semi-structured interviews were conducted among construction professionals such as site engineers, project managers, technical officers, and Quantity Surveyors. The results of the research revealed that the documents were not prepared correctly, which indirectly caused the project to be delayed. This could happen due to various causes, such as documentation errors that take a long time to be corrected, people are not aware of the documentation required in various stages of the supply chain, and the stakeholders are not aware of the procedures correctly for each of the scenarios. Findings further revealed that errors such as delays, arithmetic mistakes, and specification inaccuracies frequently disrupt operations. To address these issues, corrective actions tailored to each document type were detailed, emphasising early negotiation, skilled personnel involvement, and rigorous verification processes. The study contributes significantly to the field by offering practical solutions that enhance document accuracy, improve supply chain efficiency, and reduce project delays. These measures not only address immediate documentation issues but also provide a framework for maintaining high standards of documentation accuracy in the construction industry, ensuring smoother operations and successful project completions.

Keywords: *Construction; Documentation; Errors; Professionals, Supply Chain Management.*

[1] Graduate, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, jananjaya1996@gmail.com
[2] Senior Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, chamari.a@sliit.lk
[3] Academic Instructor, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, sathya.j@sliit.lk
[4] Quantity Surveyor, Construction Cost Information Service (Pvt) Ltd, Sri Lanka, angel.lokuge22@gmail.com

1. INTRODUCTION

The construction industry of Sri Lanka has become a pivotal factor in the economy, and it is necessary to sustain this growth by facilitating sectoral development (Jayasuriya, 2019). This sector has a significant responsibility and energetic relationship with other sectors (Singh, 2019). Following recent trends in the emerging economy of Sri Lanka, although Sri Lanka is a developing country, there is a huge demand for construction. The Sri Lankan construction industry experienced a 21.6% growth, contributing Rs. 894,683 million to the Gross Domestic Product (GDP), which represents 10.3% of the GDP. (Somachandra et al., 2023).

Due to the unique nature of the industry, supply chain management plays a significant role in the competitive construction market (Barber et al., 2000). Today, several developing countries face difficulties with supply chain management documents (Waidyasekara et al., 2016). Hence, over the decade in Sri Lanka, activities related to the construction industry have generated considerable factors that affect supply chain management (Aloini et al., 2012). They further mentioned that among them, one of the big issues is that construction projects also experience delays, leading to increased costs for the project.

Nevertheless, the research aims to identify the effects related to supply chain management, specifically regarding the documents, and then emphasise suggestions to address these weaknesses. Success in construction projects is evaluated using parameters such as quality, price, and the completion time of a project. To fulfil these requirements, the products obtained from suppliers are meant to be transferred to construction industry stakeholders safely and without interruptions. This supply chain includes the movement and storage of raw materials for work in progress, inventory, and fully furnished goods (Barber et al., 2000). The entire process is managed by supply chain management through proper design and planning of the chain (Singh, 2019).

Supply chain management aims to reduce costs and enable every member of the supply chain to generate profits (Hugos, 2024). Members of the supply chain consist of all parties who directly or indirectly meet the needs of the customer (Ruzo-Sanmartín et al., 2023). Due to the nature of the construction industry, selecting suppliers for the construction industry is a time-consuming and daunting task compared to other industries (Van der Vorst, 2004). A template is needed to select the right suppliers to make the purchase process smooth (Clavero, 2018).

Good project management in construction must vigorously pursue the efficient utilisation of labour, materials, and equipment (Ershadi et al., 2021). In building construction, material procurement is a process by which the materials required to construct a building are selected, ordered, invoiced, paid for, and delivered to the site (Donyavi et al., 2024). They further illustrated that materials will typically be ordered from the supply chain, often from external suppliers with whom the team may have had past successful dealings or who may be specified in the contract documents. Procuring materials is a crucial aspect of the construction process as contractors will normally be inundated with requests from suppliers for the provision of goods and services (Pararajasingam et al., 2024). They must, therefore, order materials that align with both the client's and contractor's objectives. In such a situation, various documents might be used, like purchase orders. A purchase order is a document that confirms an order for construction materials sent from a buyer to a material supplier or equipment renter. When a purchase order is accepted, a legal contract forms between the two parties and sets basic terms between the parties – like price, payment terms, and time for performance (Clavero, 2018). A purchase order might be followed up with a written contract that further clarifies the relationship and expectations of the agreement (Benarroche, 2019).

Furthermore, the construction company is following up with a written contract with the labour suppliers. These types of agreements are also a kind of document in the supply chain management in the construction industry. In such a way, various documents can be seen in the construction industry (Norouzi, 2021). If the supply chain management documentation is not done correctly, it can indirectly cause the project to be delayed and various other matters as well (Luo et al., 2020). Hence, this paper aims to identify the potential factors affecting construction projects due to the poor documents in supply chain management. It was achieved by identifying the issues in supply chain management in construction and by analysing the impact on the project due to the matter of documents in supply chain management.

2. LITERATURE REVIEW

2.1 STAKEHOLDERS

A stakeholder is any person, group, or organisation that is impacted in some way by the action or inaction of another (Phillips & Reichart, 2000). When implementing any project, especially in construction projects, different requirements need to be considered. Representatives of these requirements are the so-called project partners. There are two types of stakeholders: direct stakeholders and indirect stakeholders (Nguyen et al., 2019). Direct stakeholders are those directly associated with or involved in the project. These include employers, project managers, architects, structural engineers, quantity surveyors, contractors, labourers, and suppliers (Nguyen et al., 2019). Indirect stakeholders are those indirectly associated with the project. These include local authorities and environmental authorities, to name a few.

2.2 SUPPLY CHAIN MANAGEMENT

Supply Chain Management (SCM) is one of the contemporary themes (Li et al., 2015). The concept of the supply chain was developed between the 1960s and 1970s when companies had to improve their strategies based on the attraction and retention of customers (Ali, 2014). This encompasses a broad range of activities required to plan, control, and execute a product's flow from materials to production to distribution in the most economical way possible (Satyro et al., 2021). The function of SCM is to design and manage the processes, assets, and flows of material and information required to satisfy customers' demands. Efficient SCM allows companies to develop, implement, and sustain supplier management and collaborative strategies (Li et al., 2015).

SCM encompasses the integrated planning and execution of processes required to optimise the flow of materials, information, and capital in functions that broadly include demand planning, sourcing, production, inventory management, and logistics or storage and transportation (Satyro et al., 2021).

SCM is an expansive and complex undertaking that relies on each partner from suppliers to manufacturers and beyond to run well. Since the construction industry is a key social and economic activity in every country, the application of SCM strategies is considered helpful in achieving higher competitiveness for construction firms and the construction sector. The reality in the construction sector is quite different. A myriad of construction supply chains and markets need to be integrated by any construction firm when it delivers a solution to an end customer/client (Butkovic etal., 2016).

The success of a construction project is evaluated through parameters of quality, cost, and time. Construction companies use modern tools and technologies to improve the mentioned parameters in their supply chain. SCM is crucial in different stages of the construction industry including providing materials and tools as well as designing, supervising, and executing stages. The supply chain and its applications can be remarkably effective in each quality stage to reduce time and expenses. Construction companies need new tools and technology to improve the mentioned parameters in their supply chain. Therefore, one of the most important things under the supply chain is SCM.

SCM is a solution that has had acceptable results forconstruction and industrial companies in developed countries. Suppliers need to know market development policies. Suppliers face increasing stresses in terms of flexibility, diversity, time, and value to survive in a market. Organisations should pay great attention to the supply chain to reach their commercial goals and overcome management challenges (Ali, 2014).

The products that are obtained from the suppliers are meant to transfer the goods and services to the customers safely without any interruptions. SCM takes the whole process through the proper design and planning of the chain (Singh, 2019). Large-scale construction companies spend extra time and money due to the overlap of suppliers' activities and the activities of inferior contractors (Ali, 2014).

2.3 COST OVERRUN

Considerable costs are imposed on the company due to a lack of balance between the design and the execution as well as between suppliers, inferior contractors, and public contractors (Ali, 2014). In construction, cost overruns are relatively common, occurring when the costs being incurred are more than the amounts that have been budgeted for (Andrady et al., 2022). One of the most critical reasons is project design errors (Shoar et al., 2023). Even it is allocated proper time and resources for accurate budget and schedule estimates in the pre-construction planning stage. If the design plans are defective, they will inevitably be destined for cost overruns in construction projects. Inaccurate project estimates also result in cost overruns in the construction industry (Amini et al., 2023). Often, in conjunction with design errors, change orders are another very common reason for cost overruns in construction projects. Not hiring the right team can also lead to cost overruns in construction projects (Amini et al., 2023).

2.4 TIME OVERRUN

Not only the cost overrun but also the time overrun in construction projects has become one of the most common problems in the industry causing a multitude of negative effects on the projects and their stakeholders (Gómez-Cabrera, 2024). There are various factors responsible for the time overrun, which require serious attention to understand and address in order to achieve successful completion of projects on time (Memon et al., 2011).

Memon et al. (2011) have depicted some critical factors that lead to time overruns in construction projects. Some of the identified factors are plans and specifications not received by the contractor in time, adequate resources not available on the site, wrong or faulty initial planning, and accidents on site. Delay is the process in which the construction project slows down without stopping it entirely while suppression is the stoppage of the project directed from the clients to the contractor (Clavero, 2018). Procurement issues can be a reason for the overall delay of construction projects (Egwim et al., 2023).

2.5 PROCUREMENT IN THE CONSTRUCTION INDUSTRY

Procurement is a term describing the purchasing process for goods and services. In building construction, material procurement is the process by which the materials required to construct a building are selected, ordered, invoiced, paid for and delivered to the site (Donyavi, 2024). Materials will typically be ordered from the supply chain, often from external suppliers with whom the team may have had past successful dealings or who may be specified in the contract documents (Kollerath, 2019). However, a tendering method is used for imported material (Kar et al., 2021). Procuring materials is a crucial aspect of the construction process, as contractors will normally be inundated with requests from suppliers for the provision of goods and services. They must, therefore, order materials that align with both the client's and contractor's objectives (Benarroche, 2019).

A buyer orders material from the local market or international market. If the buyer orders materials from the local market, there is a simple procedure (Abdel-Galil et al., 2022). It is being done through a purchase order. A purchase order is a document that confirms an order for construction materials sent from a buyer to a material supplier or equipment renter (Nicoletti, 2022). When a purchase order is accepted, a legal contract forms between the two parties and sets basic terms between the parties – like price, payment terms, and time for performance (Benarroche, 2019).

If the buyer orders materials from the international market, materials should be imported using proper procedures. Those who wish to start importing to Sri Lanka should obtain a Tax Identification Number (TIN Number/VAT Number) and be required to enroll at Sri Lanka Customs as a registered importer. The importer is required to make a Customs Declaration through DTI (Direct Trader Input) for the Import of Cargo (Kollerath, 2019).

2.5.1 Material and Labour Procurement

The first step of the import function is to ascertain whether the materials to be imported are banned, restricted, canalised, or free items. In the case of restricted items, the application is to be made to the government by giving proper justifications for import, hence that the government may review the import policies and issue clearance for imports under special circumstances (Shewal, 2018).

Correspondence is then initiated with the foreign suppliers and finally, suppliers are chosen based on price and quality/specification of the items, delivery schedule, terms of payment, and other conditions involved in the transaction (Shewal, 2018). In the order, all the required clauses are to be mentioned such as name and address of the suppliers, reference number of their offer, detailed quantity, quality/specification, testing, unit price and the total price of the items to be imported, delivery period, mode of shipment, terms, and mode of payment, packing and marking specification, transit insurance, documents required for clearance, particulars of foreign exchange sanction (such as the import license/foreign exchange release order) and guarantee and acceptance of the purchase order (Shewal, 2018).

Unless the clauses are clearly stated in the purchase order and properly followed by the foreign suppliers, there may be various complications afterwards, leading to long delays in the clearance of the imported goods. A long delay in the clearance of imported goods means a delay in the project (Shewal, 2018).

On receipt of the acceptance of the supplier, the importer arranges to open a letter of credit in a local bank in favor of the foreign supplier. The latter will receive payment from its bank on the timely shipment of ordered goods to the importer and on submission of the specified shipping documents within a specified period to the bank (strictly as per terms and conditions of the purchase order as laid down in the letter of credit). The foreign bank then forwards the shipping documents to the local bank, which releases the same to the importer to get payment as per the terms of the letter of credit. Payment can also be made to the foreign suppliers against "sight draft" (Shewal, 2018).

Any delay in filing or absence of documents can delay the clearance process and thereby importer is supposed to incur demurrage on the imported cargo. The efficiency of the Customs Clearance process depends on having valid documents, the accuracy of the information provided in the documents as well as the promptness in submitting the documents and filing the necessary applications for the Customs Clearance.

This research is analysing about material supply documents as well as labour supply documents. The labour supplier is the person who supplies the labourers to the construction site when necessary. Most suppliers have several workers permanently attached to them. Participants usually come together through family or friends and form a socially cohesive group, ranging from 5 to 50 members in Sri Lanka. The terms of the contract are usually a fixed price for an item or package of work. Under the first alternative, the supplier mobilises the workers, manages their output, and pays them daily until the work is finished (Winch, 2009). In this situation, the supplier is acting as an entrepreneur, in that he is taking a risk and hoping to make a profit. He tries to maximise his profit by controlling his labour costs and other expenses and getting the best possible price from the subcontractor. In good times the profit can be almost double the wage of a skilled worker, but substantially less in bad times (Wells, 2006).

Under the second alternative, the contractor pays the supplier a monthly income for supplying the labour but retains the responsibility for managing the work. The supplier may be responsible for paying the workers or they may be paid directly by the contractor. The essential difference is that his reward comes in the form of a wage or a fee rather than a profit (Wells, 2006).

In this case, the client would enter into a verbal agreement on the rates for various items of work, so payment would be on a task rate basis. Payments are made by the client to the supplier as each item is completed, minus a retention which is only paid after the completion of the work (Wells, 2006).

2.6 DOCUMENTS IN THE CONSTRUCTION INDUSTRY

In the procurement documents plays a vital role, since they govern the rules and conditions in the process. There are various documents which can be used in the construction industry. These documents are described below:

- Supplier Contracts and Agreements

Supplier contracts are agreements between a company and their suppliers of services or goods. The supplier contract is the legal agreement governing the relationship between the supplier and the company. Wish (2014) has stated that, key elements of a supplier agreement are, the items the supplier must provide, pricing and payments for all goods and/or services, expected time frames for work completion and payments and the responsibilities and terms of the relationship. A clearly written agreement helps you make sure that the services and products ordered reach the client quickly without unnecessary complications (Wish, 2014). The terms and clauses of the agreements are different depending on the industry and products provided. Essentially, the agreement must include everything that governs a business manufacturing (Wish, 2014).

- Letter of Credit (LC)

An import LC is an unconditional undertaking, given by an at the request of their customer (the Applicant or Importer) to pay the supplier against stipulated documents, provided all the terms and conditions in the LC are complied with. The issuing bank can undertake to make payment to or to the order of a third party (the supplier) or to accept and pay bills of exchange drawn by the beneficiary at sight or on a fixed future date and authorise another bank (normally in the exporters' country) to affect such payment or to accept and pay such bills of exchange on a fixed future date (Lowden, 2013)

- Letter of Authority (LoA)

LoA is a legal document that allows customers to authorise someone to act on their behalf within agreed limits. They are often used to create an agreement between three or more parties. LoA gives customers confidence that the person they have appointed knows what they are authorised to act upon, whether it is account information, billing details, or personal information related to their business (Lee, 2017).

- Purchase Orders and Pro Forma Invoice

A purchase order is a kind of commercial document, which is issued by an importer to authorise an import deal (Lowden, 2013). A pro forma invoice is a preliminary bill of sale sent to buyers in advance of a shipment or delivery of goods. Usually, before all details of the sale are known. The invoice will typically describe the purchased items and other important information such as the shipping weight and transport charges (Frazelle, 2020).

- Cargo Clearing Process

At least three bank-stamped invoices, packing lists, goods arrival notices, air way bills, house way bills. Any delay in filing or absence of documents can delay the clearance process and thereby importer is supposed to incur demurrage on the imported cargo. The efficiency of the customs clearance process depends on having valid documents, the accuracy of the information provided in the documents as well as the promptness in submitting the documents and filing the necessary applications for the customs clearance (Kollerath, 2019).

- Agreement with Labour Supplier

Labour supply agreements is the term to describe the supply of workers by a service provider to a receiving company in need of those services (Morgan, 2018). Factors to consider when awarding a labour supply contract are; the date of commencement of service of each employee, the salary/wages and other benefits to which each employee is entitled, details of bonus or profit-sharing schemes, details of current disputes, and whether any are subject to a disciplinary or grievance procedures, details of litigation threatened, pending or ongoing, details of any changes to terms and conditions of any employees introduced in recent past.

2.7 ERRORS IN THE CONSTRUCTION DOCUMENTS

Errors in construction industry-related documents can have significant consequences, leading to conflicts, financial losses, and safety hazards (Dosumu et al., 2017). For example, the absence of a contingency plan can leave a project vulnerable to unexpected challenges and delays. Arithmetic errors, such as inaccurately calculating the number of labourers needed, can result in inefficiencies and additional costs (Ghallab & Hosain, 2020). Furthermore, shortcomings in specifying goods specifications and payment terms can lead to misunderstandings and disputes between contractors and suppliers (Wish, 2014). In addition, the failure to include relevant Harmonised System (HS) codes in contracts and agreements can result in difficulties with customs clearance and import/export processes (Shiberu & Tamene (2021).

Failing to negotiate the terms of a letter of credit during the contract negotiation can expose parties to potential issues that they may be legally bound to, even if these terms are not in their best interest (Noah, 2021). Additionally, allowing someone inexperienced to prepare the documents under the letter of credit and other documents can lead to further complications (Noah, 2021). Hence, there should be a proper mechanism to reduce the errors in documentation of the construction industry.

3. RESEARCH METHODOLOGY

This research aims to identify the issues present in SCM within the construction industry and emphasise the importance of SCM documents. The choice of a qualitative approach in this study is driven by the need to deeply understand the nuanced and context-specific issues related to documentation errors in SCM within the construction industry. Qualitative research is particularly effective in exploring complex phenomena where variables are not easily quantifiable and where understanding participants' perspectives is crucial (Creswell, 2014).

The preliminary study phase involved conducting an extensive literature survey to pinpoint the challenges faced in SCM within the construction sector and highlight the significance of SCM documents. This survey encompassed a thorough examination of articles, websites, books, and relevant sources. Additionally, insights were gathered from similar research studies conducted globally.

Following the literature review, semi-structured interviews were conducted with experienced professionals in the construction industry, including project managers, site engineers, and technical officers with over five years of expertise. Six such professionals were selected using purposive sampling, ensuring a diverse representation of roles and experiences. Their demographic data is presented in Table 1. These interviews were carried out to validate the quality and depth of the literature review findings.

Table 1: Details of the participants for the interviews

Persons	Academic qualification	Construction working experience	Project type (working now)
Response A	Bachelor of Quantity Surveying	6 to 10 years	Building project
Response B	Masters	16 to 20 years	Road Project
Response C	Bachelor of Civil Engineering	11 to 15 years	Building project
Response D	Bachelor of Quantity Surveying	6 to 10 years	Piling
Response E	Bachelor of Quantity Surveying	1 to 5 years	Facilities maintenance and development
Response F	Bachelor of Civil Engineering	11 to 15 years	Road Project

To assess the impact of inadequate SCM documents on construction projects and explore strategies to mitigate these impacts, two construction sites were visited. Semi-structured interviews were conducted during these visits with relevant stakeholders. In the data collection phase, semi-structured interviews with predetermined open-ended questions were employed to gather feedback from industry professionals. Semi-structured interviews were chosen for their flexibility and depth, enabling the researchers to explore specific areas of interest while allowing respondents to elaborate on their experiences and insights (Kallio et al., 2016). This format is especially suitable for understanding the practical challenges and real-world implications of documentation errors as it provides the opportunity to gather detailed narratives and examples from industry experts. These interviews primarily aim to validate the findings from the literature review and provide insights into the local construction industry's ground realities.

Finally, in the data analysis phase, the information obtained from the interviews were precisely evaluated manually. From the collected data, themes were developed that encapsulated the main issues found in the documents. Themes such as inadequate negotiation of terms, errors by inexperienced personnel, and verification and correction processes emerged as central to understanding the documentation errors. This analysis was enabling the presentation of clear and actionable results derived from the combination of literature findings, expert opinions, and on-site observations.

4. RESULTS AND DISCUSSION

4.1 MEASURES TAKEN TO FIX ERRORS IN THE DOCUMENTS

To address the issues in the SCM documents identified during the study, a comprehensive set of measures was implemented based on insights gathered from expert interviews. The measures taken were categorised according to the type of document and the specific errors observed. Table 2 was prepared using the identified errors in the document and their corresponding solutions.

Table 2: Details of the participants for the interviews

Document	Identified Errors	Solutions
Letter of Credit	Unable to send letters of credit on time and is not providing the original date as required	Passing an amendment with the bank to rectify the error of not being able to send letters of credit on time
	Failing to negotiate the terms of a letter of credit during the negotiation of the contract.	Initiate discussions before receiving it. Addressing terms early ensures accuracy and smooth transactions.
	Errors occurred due to inexperienced people handling the documents.	Make sure the person who is preparing the documents under the letter of credit has all the background information and resources available to do this correctly.
Purchase Order	Arithmetic errors	Include revision numbers and error details in the amendment process for correction.
	Goods specifications and payment terms are not mentioned properly	Ensure accurate goods specifications and payment terms by having skilled personnel fill out the purchase order correctly.
	Errors in the HS Code	Rectify the error of missing HS codes by correcting and resending documents through the same email or file to the supplier for proper inclusion.
Supplier Contract and Agreement	Arithmetic errors and spelling mistakes	Both parties must sign a new agreement correcting arithmetic errors and spelling mistakes, ensuring the contract's accuracy and legal validity
Proforma Invoice	Errors in Quantities, Prices, Shipping details, Bank details, measurement units, unit price	Verify all details against the pro forma invoice. Follow local authority ordering processes and obtain BOI approvals if applicable.

The measures implemented to rectify documentation errors have significant implications for improving SCM efficiency and reducing project delays. The proactive steps taken to address these errors ensure that the documentation is precise, thereby minimising misunderstandings and transactional discrepancies. This approach not only streamlines operations but also reinforces the importance of meticulous documentation practices in the construction industry.

The findings indicate that errors in supply chain documents, such as purchase orders and letters of credit, can substantially impact project timelines and costs. The emphasis on early negotiation of terms and ensuring that documentation is handled by experienced personnel highlights the need for thorough training and procedural checks within organisations. Additionally, the standardisation of labour contracts and the rigorous review of critical documents like proforma invoices are essential steps toward mitigating risks associated with documentation errors.

These measures not only address the immediate issues but also contribute to a broader understanding of best practices in SCM within the construction sector. The study underscores the necessity of implementing standardised procedures and continuous training programs to maintain high standards of documentation accuracy, ultimately contributing to the successful completion of construction projects within the stipulated timeframes and budgets which can be applied not only within Sri Lankan context but also in other geographical contexts.

5. CONCLUSIONS AND RECOMMENDATION

The research findings highlight several crucial points regarding documentation errors and procedures in international trade and construction projects. Firstly, minor errors in import or labour agreement documents can disrupt project timelines significantly, underscoring the need for precise documentation to avoid delays. Secondly, there's a lack of awareness among stakeholders in Sri Lanka regarding specific import documents, contrasting with their familiarity with labour contracts. Thirdly, import trade procedures vary across countries, but essential documents like supplier contracts and pro forma invoices remain universally important. Lastly, errors are more common in documents like purchase orders and agreements with labour suppliers, emphasising the importance of meticulousness in handling documentation. Overall, the research emphasises the critical role of accurate documentation in ensuring smooth international trade and construction processes.

Based on the conclusions drawn from the research, it is recommended that standardised labour contracts within SCM be implemented to reduce errors. Additionally, thorough review of documents, such as letters of credit, before signing is advised to avoid costly mistakes and potential project delays. This proactive approach not only ensures accuracy but also helps in saving money by preventing unnecessary corrections and amendments. Therefore the recommendation is to focus on standardising labour contracts and emphasising the importance of meticulous document review to streamline supply chain processes and minimise delays. These findings not only address immediate documentation issues but also contribute to a deeper understanding of effective SCM practices, reinforcing the importance of meticulous documentation and continuous training programs in the industry.

The main limitation of this study lies in its reliance on qualitative data from a relatively small sample of industry experts. While the insights provided are valuable, the findings may not be fully generalisable to all contexts within the construction industry. Future research could address this limitation by incorporating a larger and more diverse sample, including quantitative data to validate and expand upon the qualitative findings. Investigating the role of advanced technologies, such as blockchain or AI, in reducing documentation errors could also provide valuable insights for improving SCM practices.

6. REFERENCES

Abdel-Galil, E., Ibrahim, A. H., & Alborkan, A. (2022). Assessment of transaction costs for construction projects. International Journal of Construction Management, 22(9), 1618-1631. https://doi.org/10.1080/15623599.2020.1738204

Ali, G. (2014). Supply Chain Management in Construction Industry. *Advances in Management*, *7*(8), 17-22. https://www.proquest.com/docview/1550829450?pq-origsite=gscholar&fromopenview=true&sourcetype=Scholarly%20Journals

Aloini, D., Dulmin, R., Mininno, V., & Ponticelli, S. (2012). Supply chain management: a review of implementation risks in the construction industry. *Business process management journal, 18*(5), 735-761. https://doi.org/10.1108/14637151211270135

Amini, S., Rezvani, A., Tabassi, M., & Malek Sadati, S. S. (2023). Causes of cost overruns in building construction projects in Asian countries; Iran as a case study. *Engineering, Construction and Architectural Management, 30(7)*, 2739-2766. https://doi.org/10.1108/ECAM-05-2021-0445

Andrady, W. M. P. T., Allis, C., & Perera, B. K. C. (2022, November). Cost control techniques on the delivery of sustainable construction projects in Sri Lanka. In *International Conference on Sustainable Built Environment* (pp. 205-217). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-3471-3_15

Barber, P., Graves, A., Hall, M., Sheath, D., & Tomkins, C. (2000). Quality failure costs in civil engineering projects. *International Journal of Quality & Reliability Management, 17*(4/5), 479-492. https://doi.org/10.1108/02656710010298544

Benarroche, A. (2019). *Understanding the Construction Purchase Order*. Retrieved 03 02, 2020, from https://www.levelset.com/blog/construction-purchase-order/

Butkovic, L. L., Kauric, A. G., & Mikulic, J. (2016). Supply chain management in the construction industry-a_literature_review. In *International OFEL Conference on Governance, Management and Entrepreneurship* (p. 798). Centar za istrazivanje i razvoj upravljanja doo. https://www.researchgate.net/profile/Alica-Grilec/publication/301566366_Supply_Chain_Management_in_the_Construction_Industry_-_A_Literature_Review/links/571a6d3008ae6eb94d0c7a97/Supply-Chain-Management-in-the-Construction-Industry-A-Literature-Review.pdf

Clavero, J. (2018). *Top Issues Facing the Construction Industry in 2018.* Retrieved 03 01, 2020, from https://esub.com/top-issues-facing-the-construction-industry-in-2018/

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications

Donyavi, S., Flanagan, R., Assadi-Langroudi, A., & Parisi, L. (2024). Understanding the complexity of materials procurement in construction projects to build a conceptual framework influencing supply chain management of MSMEs. *International Journal of Construction Management, 24(2)*, 177-186. https://doi.org/10.1080/15623599.2023.2267862

Dosumu, O., Idoro, G., & Onukwube, H. (2017). Causes of errors in construction contract documents in Southwestern, Nigeria. *Journal of Construction Business and Management, 1*(2), 11-23. https://doi.org/10.15641/jcbm.1.2.59

Egwim, C. N., Alaka, H., Toriola-Coker, L. O., Balogun, H., Ajayi, S., & Oseghale, R. (2023). Extraction of underlying factors causing construction projects delay in Nigeria. *Journal of Engineering, Design and Technology, 21(5)*, 1323-1342. https://doi.org/10.1108/JEDT-04-2021-0211

Ershadi, M., Jefferies, M., Davis, P., & Mojtahedi, M. (2021). Achieving sustainable procurement in construction projects: The pivotal role of a project management office. *Construction Economics and Building, 21*(1), 45-64. https://search.informit.org/doi/abs/10.3316/informit.747647989896066

Frazelle, E. (2020). *Supply chain strategy: the logistics of supply chain management*. McGraw-Hill. http://dspace.vnbrims.org:13000/jspui/bitstream/123456789/4170/1/Supply%20Chain%20Strategy%20The%20Logistics%20of%20Supply%20Chain%20Management.pdf

Ghallab, A. H. O., & Hosain, M. S. (2020). Factors affecting the cost accuracy of construction projects: Arab contractors in Egypt. *International Journal of Construction Project Management, 12*(2).

Gómez-Cabrera, A., Gutierrez-Bucheli, L., & Muñoz, S. (2024). Causes of time and cost overruns in construction projects: a scoping review. *International Journal of Construction Management, 24(10)*, 1107-1125. https://doi.org/10.1080/15623599.2023.2252288

Hugos, M. H. (2024). *Essentials of supply chain management*. John Wiley & Sons.

Jayasuriya, S. (2019, March 24). Construction industry, a key driver of the economy, from https://archives1.sundayobserver.lk/2019/03/24/business/%E2%80%98construction-industry-key-driver-economy%E2%80%99

Kallio, H., Pietilä, A. M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing, 72*(12), 2954-2965. https://doi.org/10.1111/jan.13031

Kar, S., Kothari, C., & Jha, K. N. (2021). Developing an optimum material procurement schedule by integrating construction program and budget using NSGA-II. *Journal of Construction Engineering and Management, 147(4)*, 04021017. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002028

Kollerath, S. (2019, April 22). How to import to Sri Lanka, step by step process. How to export import, from https://howtoexportimport.com/How-to-import-to-Sri-Lanka-step-by-step-process-8707.aspx

Lee, S. (2017). *What is a Letter of Authority or LoA?* Retrieved from https://www.loveenergysavings.com/commercial-electricity/what-is-a-letter-of-authority-or-loa/

Li, G., Fan, H., Lee, P. K., & Cheng, T. C. E. (2015). Joint supply chain risk management: An agency and collaboration perspective. *International Journal of Production Economics, 164*, 83-94. https://doi.org/10.1016/j.ijpe.2015.02.021

Lowden, S. R. (2013). Import transactions and customs compliance. Lulu. com.

Luo, L., Jin, X., Shen, G. Q., Wang, Y., Liang, X., Li, X., & Li, C. Z. (2020). Supply chain management for prefabricated building projects in Hong Kong. *Journal of management in engineering, 36*(2), 05020001. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000739

Memon, A. H., Abdul Rahman, I., & Aziz, A. A. A. (2011). Time overrun in construction projects from the perspective of project management consultant. *Journal of Surveying, Construction and Property, 2*(1). https://doi.org/10.22452/jscp.vol2no1.4

Morgan, B. (2018). *Labour Supply Agreements.* Retrieved April 04, 2024 from https://www.morganmcmanus.com/labour-supply-agreements/

Nguyen, T. H. D., Chileshe, N., Rameezdeen, R., & Wood, A. (2019). Stakeholder influence pathways in construction projects: Multicase study. *Journal of Construction Engineering and Management, 145*(9), 05 019011. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001680

Nicoletti, B. (2022). *Procurement finance*. Palgrave Macmillan.

Noah, D. (2021, March 17). 7 common mistakes when preparing Letters of Credit. Shipping solutions. Retrieved from: https://www.shippingsolutions.com/blog/7-common-mistakes-when-preparing-letters-of-credit

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering, 44*, 102704. https://doi.org/10.1016/j.jobe.2021.102704

Pararajasingam, R., Waidyasekara, A. S., & Victar, H. C. (2024). Exploring causes of ineffective material management and impact on successful project deliverables in civil engineering construction projects in Sri Lanka. *Construction Innovation*. https://doi.org/10.1108/CI-11-2023-0281

Phillips, R. A., & Reichart, J. (2000). The environment as a stakeholder? A fairness-based approach. *Journal of Business Ethics, 23*, 185-197. https://doi.org/10.1023/A:1006041929249

Ruzo-Sanmartín, E., Abousamra, A. A., Otero-Neira, C., & Svensson, G. (2023). The impact of the relationship commitment and customer integration on supply chain performance. *Journal of business & industrial marketing, 38*(4), 943-957. https://doi.org/10.1108/JBIM-07-2021-0349

Satyro, W. C., de Mesquita Spinola, M., de Almeida, C. M., Giannetti, B. F., Sacomano, J. B., Contador, J. C., & Contador, J. L. (2021). Sustainable industries: Production planning and control as an ally to implement strategy. *Journal of Cleaner Production, 281*, 124781. https://doi.org/10.1016/j.jclepro.2020.124781

Shewal, M. (2018, March 25). 5 steps to be followed for importing materials materials management, from http://www.yourarticlelibrary.com/material-management/importing-materials/5-steps-to-be-followed-for-importing-materials-materials-management/69355

Shiberu, B., & Tamene, B. (2021). Effect of Import Customs Procedure on Trade Facilitation the Case of Adama City. *Information Technology in Industry, 9*(3), 01-16. http://it-in-industry.org/index.php/itii/article/view/476/420

Shoar, S., Yiu, T. W., Payan, S., & Parchamijalal, M. (2023). Modeling cost overrun in building construction projects using the interpretive structural modeling approach: a developing country perspective. *Engineering, Construction and Architectural Management, 30(2)*, 365-392. https://doi.org/10.1108/ECAM-08-2021-0732

Singh, H. (2019, October 06). Supply chain management in construction industry. Our heritage, from https://archives.ourheritagejournal.com/index.php/oh/article/view/156

Somachandra, W. D. I. V., Sylva, K. K. K., Bandara, C. S., & Dissanayake, P. B. R. (2022). Corporate social responsibility (CSR) practices in the construction industry of Sri Lanka. *International Journal of Construction Management*, *23(13)*, 2230–2238. https://doi.org/10.1080/15623599.2022.2049489

Van der Vorst, J. G. (2004). Supply Chain Management: theory and practices. In *Bridging Theory and Practice* (pp. 105-128). Reed Business. https://edepot.wur.nl/357992

Waidyasekara, K. G. A. S., De Silva, L., & Rameezdeen, R. (2016). Water use efficiency and conservation during construction: drivers, barriers and practices. *Built environment project and asset management*, *6*(5), 553-566. https://doi.org/10.1108/BEPAM-09-2015-0052

Wells, J. (2006 , January). *Labour mobilisation in the construction industry*. In CIB W107 Construction in Developing Countries International Symposium entitled Construction in Developing Economies: New Issues and Challenges. Santiago, Chile.

Winch, G. M. (2009). *Managing construction projects*. John Wiley & Sons.

Wish, B. (2024, January 01). Supplier contracts and agreements: Everything you need to know. from UpCounsel: https://www.upcounsel.com/supplier-contracts-and-agreements

Jayanetti, J.K.D.D.T., Perera, B.A.K.S. and Waidyasekara, K.G.A.S., 2024. Key parameters of lean construction maturity: A Delphi study. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 712-726. DOI: https://doi.org/10.31705/WCS.2024.56. Available from: https://ciobwcs.com/papers/

KEY PARAMETERS OF LEAN CONSTRUCTION MATURITY: A DELPHI STUDY

J.K.D.D.T. Jayanetti[1], B.A.K.S. Perera[2], and K.G.A.S. Waidyasekara[3]

ABSTRACT

Lean construction has emerged as a transformative force, seeking to enhance efficiency, minimise waste, and streamline project delivery processes. Despite global recognition and adoption, lean construction maturation exhibits variances across diverse contexts. In Sri Lanka, lean construction remains at an early stage of development. Given the nation's challenges in the construction sector and evolving project management methodologies, Sri Lanka offers a distinctive setting for exploring the maturity of lean construction principles. However, insufficient methods of investigating lean construction maturity in the Sri Lankan context have led to limited adoption of lean practices within the construction sector. Therefore, this study aims to investigate the relevant parameters for assessing lean construction maturity in the context of Sri Lanka. Adopting an interpretive stance, the study employed a qualitative research approach with semi-structured interviews using the Delphi technique. A total of 25 lean construction experts were selected through purposive sampling and 73 interviews were conducted in three Delphi rounds. Findings revealed 18 key lean construction parameters and definitions were developed conforming to Sri Lankan context. The study provides actionable insights for practitioners including identifying relevant lean practices and guidance on lean implementation, enabling them to enhance practices, improve efficiency, reduce waste, and make informed decisions through tailored initiatives and strategies. This study enhances the global understanding of lean construction maturity by identifying lean construction parameters conforming to Sri Lanka, contributing to the existing theory and filling a literature gap.

Keywords: *Defining Lean Construction Parameters; Lean Construction; Lean Construction Maturity.*

1. INTRODUCTION

The construction sector has faced prolonged problems in enhancing productivity and efficiency (Tariq & Gardezi, 2023). The construction industry consistently struggles with numerous challenges, including excessive wastage, recurrent delays, budget overruns, and quality control issues (Nowotarski et al., 2016). In recent years, lean construction has created a paradigm shift in the construction sector, aimed at maximising efficiency, reducing waste, and optimising project delivery processes (Aslam et al., 2024). While

[1] PhD Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, jayanettijkddt.21@uom.lk

[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk

[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk

lean construction principles have been widely acknowledged and adopted globally, the degree of lean construction maturity varies across different countries (Arditi et al., 2021). Especially in the case of Sri Lanka, lean construction is still in its early stages (Ranadewa et al., 2021). Lean construction maturity helps organisations assess the lean journey and obtain a realistic understanding of the status (Likita et al., 2024). Reaching higher lean maturity allows optimising project processes, eliminating waste, enhancing productivity, stakeholder collaboration, and adaptability to change. This will position organisations for sustained success in a competitive marketplace (Agrawal et al., 2024).

Determinants of lean construction maturity were investigated in several countries, i.e., the UK (Nesensohn et al., 2015), Brazil (Rodegheri & Serra, 2020), Saudi Arabia (Sarhan et al., 2020), Ireland (Highways Agency, 2012), Germany (Johansen and Walter, 2007). These studies provide a basic understanding of fundamental lean construction parameters; however, they are developed in specific countries. Therefore, it raises concerns regarding the applicability to Sri Lanka. Moreover, it is clear that the lack of research on lean construction and the lack of means to assess lean construction maturity in the Sri Lankan context has resulted in less lean implementation in the construction sector (Ranadewa et al., 2019). Consequently, there is a clear need to investigate Sri Lankan-specific lean construction parameters to enhance the implementation of lean construction in Sri Lanka. Therefore, this research is aimed at investigating the lean construction parameters specific to Sri Lanka. In the process, research objectives were recognised as identifying key parameters of lean construction maturity relevant to the Sri Lankan context and defining key parameters conforming to the Sri Lankan context. Achieving this aim will bridge the theoretical gap and provide insights for stakeholders to effectively evaluate and enhance lean construction maturity in Sri Lanka. Sri Lanka, with its challenges in the construction sector and evolving project management practices, presents a unique environment for examining the development of lean construction principles. This will ultimately contribute to the advancement and sustainability of the construction sector. Further, the study can be used as a guide for countries with similar socio-economic conditions.

The paper starts with an introduction to the topic and research gap followed by a comprehensive literature review on key lean construction parameters. 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 LEAN MATURITY AND LEAN CONSTRUCTION MATURITY

Lean maturity refers to the degree of skill and efficiency with which an organisation applies lean principles and methods (Hamza-Khan et al., 2024). Lean maturity involves a dynamic journey of organisational growth where the focus is on continuous learning and the seamless integration of new knowledge into everyday operations (Zanon et al., 2021). Lean construction maturity refers to the level of implementation and integration of lean principles and practices within a construction organisation or industry (Jørgensen et al., 2007). It describes how effectively lean concepts such as minimising waste, optimising processes, improving productivity, and enhancing value are adopted and utilised throughout the project lifecycle (Jayanetti et al., 2023). Maturity models play a key role in evaluating organisational maturity. Such models establish a systematic process for achieving excellence, serving as valuable tools for examining and assessing the current state of a process, organisation, or phenomenon (Galichet et al., 2024). MMs help reduce the uncertainties associated with adopting new principles by offering clear assessment tools (Sukrat & Leeraphong, 2023). Lean construction maturity assessment provides organisations with insights into the current status of lean construction implementation, key barriers, and strategies on how to reach higher lean construction maturity (Rodegheri & Serra, 2020).

2.2 KEY PARAMETERS OF LEAN CONSTRUCTION MATURITY

Lean construction parameters outline the broader concept of lean construction principles (Koskela et al., 2007). In describing lean construction maturity, many authors have relied on various lean construction parameters to minimise all kinds of waste and enhance overall construction productivity (Nesensohn et al., 2015). Through a comprehensive literature review, authors identified the most acknowledged parameters of lean construction that are relevant in determining lean construction maturity as shown in Table 1.

Table 1: Key parameters of lean construction maturity

Lean construction parameters	**Source of reference**																	
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**
Reduction of waste	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Continuous improvement	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Deliver exact customer value	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reduction of non-value-adding activities	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Respect	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Quality management	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Optimising the whole	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Transparency in processes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	
Standardisation	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓
Integration of supply chain	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓		✓
Leadership	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓			✓	✓	✓
Increase output flexibility	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				
Minimise uniqueness	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓						

Sources: [A] - Koskela (1992) and Koskela et al. (2002); [B] Ballard (2000) and Ballard et al. (2007); [C] Howell (1999); [D] Tommeline (1998) and Tommeleine (2015); [E] Lean Construction Institute (2023); [F] Tzortzopoulos et al. (2020) and Tzortzopoulos & Formoso (1999); [G] Womack & Jones (1997) and Jones & Womack (2016); [H] Nesensohn et al. (2015) and Nesensohn (2014); [I] Rodegheri & Serra (2020); [J] Hofacker et al. (2008); [K] Carvalho & Scheer (2017); [L] Lean Construction Institute (2016); [M] Arantes (2010); [N] Johansen & Walter (2007); [O] Cookson & Stirk (2019); [P] Sarhan et al. (2020); [Q] Rashidian et al. (2022); [R] Nightingale et al. (2001)

Among the parameters of lean construction, waste elimination, creation and delivery of customer value, continuous improvement, quality management, reduction of non-value-adding activities, and respect for people are noted to be at the forefront. This is understandable since the core of lean construction is the minimisation of all kinds of waste (Koskela et al., 2007). Customer satisfaction and delivering exact customer value is considered a core principle of lean construction (Ballard & Howell, 1998). Upon examining the identified key parameters, it becomes apparent that elements such as leadership, information dissemination, and transparency are prioritised. This extends beyond the construction phase to encompass broader organisational considerations. These factors contribute to a more comprehensive understanding and management of organisational dynamics (Rodegheri & Serra, 2020). Moreover, these lean construction parameters provide a holistic determination of an entity's maturity in lean construction practices.

2.3 LEAN CONSTRUCTION MATURITY IN SRI LANKA

Focusing more on the Sri Lankan construction sector, lean construction is still in the early stages (Ranadewa et al., 2019). Similarly, several scholars claim that lean construction is being practised modestly amongst construction organisations in Sri Lanka, nevertheless, many of those organisations are not certain about creating a lasting lean culture due to the inability to assess lean construction maturity. The critical issue faced by many construction firms is the uncertainty of implementing lean since there is no strategic road map on where it would lead the organisations (Waduwawala et al., 2019). This uncertainty has led organisations to move away from employing lean in the Sri Lankan context. Investigating lean construction maturity in the case of Sri Lanka, there is evidence of literature on maturity, however, not specifically for the construction industry. Maturity in the third-party logistics industry (Gamini et al., 2019), maturity assessment garment industry (Kulasooriya & Chalapathi, 2014), maturity evaluation in the banking sector (Bandara et al., 2019), Building Information Modeling maturity (Jayasena & Wedikkara, 2013) are noteworthy studies on maturity however not directed at lean construction. Therefore, the literature clearly indicates a clear gap in investigating lean construction maturity in the context of Sri Lanka.

3. METHODOLOGY

A qualitative methodology proves beneficial when the aim is to explore respondents' perspectives, knowledge, and expertise (Yin, 2016). Qualitative research offers a means to investigate deeply into a phenomenon and uncover insights to address research questions (Saunders et al., 2009). Given the study's main aim is to investigate the most relevant parameters for Lean construction maturity in the context of Sri Lanka and define them to suit Sri Lankan context, a qualitative approach is chosen. In formulating the research question to achieve the aim, methodologies such as PICOS (Population, Intervention, Comparison, Outcomes, Setting) and CIMO (Context, Intervention, Mechanisms, Outcomes) play a crucial role (Methley et al., 2014). Given the research's emphasis on management and policy, the authors opted for the CIMO approach, and the research question was identified as "What are the essential parameters to successfully determine lean construction maturity in Sri Lanka?"

In answering this research question, the authors adopted the qualitative Delphi method using semi-structured interviews to collect expert opinions. In contemporary research, the Delphi technique allows for an in-depth exploration of a phenomenon by searching for knowledge where the number of experts is limited (Keeney et al., 2011). Since there is a scarcity in Sri Lanka of lean construction experts (Ranadewa et al., 2019), a qualitative

Delphi study would provide a practical approach to gathering rich and meaningful insights into how lean construction maturity is understood in the context of Sri Lanka. Moreover, the Delphi method is a systematic interactive technique involving two or more rounds of structured surveys or interviews, which can be used to obtain the views of an independent expert panel and provide in-built validation (Aghimien et al., 2020). Scholars have noted the importance of the Delphi method in validating collected data, with a consensus level of 75% being commonly accepted (Keeney et al., 2006). To achieve this level of agreement, three rounds of Delphi were conducted, as shown in Table 2 (Mansour et al., 2022). In the Delphi method, the sample is purposively selected strictly considering pre-defined criteria of lean construction maturity which remarkably increases the findings' accuracy compared to data gathered from unstructured interacting groups (Olsen et al., 2021). The selection of experts is crucial in the Delphi process, necessitating a thorough and comprehensive criterion for their selection (Skulmoski et al., 2007). Table 2 explains the selection criteria adopted for selecting lean construction experts. In selecting the experts, compulsory qualifications ensured that experts are equipped with the experience and competency in both lean construction and built environment. Additional qualifications ensure the knowledge of the experts. The sample size was limited to 25 since it reached saturation (Patton, 2002).

Table 2: Delphi rounds and expert's profile

Delphi Round (R)	**Phase (P)**	**Key Objectives**
Delphi round 1	Round I Phase 1 (R1P1)	Identify parameters of Lean construction maturity
Delphi round 2	Round 2 Phase 1 (R2P1)	Identify key parameters of lean construction maturity relevant in the Sri Lankan context
	Round 2 Phase 2 (R2P2)	Recognize important elements for defining Key parameters of lean construction maturity relevant in the Sri Lankan context
Delphi round 3	Round 3 Phase 1 (R3P1)	Define key parameters of lean construction maturity conforming to the Sri Lankan context

	Compulsory (Must satisfy at least one from each)				Additional Qualifications (Must satisfy at least 3)					Participation		
	A		B									
Expert Code	5+ experience in lean construction job role	3+ academic experience in lean construction	10+ experience in built environment	10+ academic experience in built environment	Graduated in built environment discipline	Professional affiliation to Lean-related institution	Member of a professional institution in built environment	Master's qualification in built-environment or lean	2+ indexed publications	Delphi R1 25	Delphi R2 24	Delphi R3 24
E1	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
E2	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
E3	✓		✓		✓	✓	✓	✓		✓	✓	✓
E4	✓		✓		✓		✓	✓		✓	✓	✓
E5	✓		✓		✓		✓	✓		✓	✓	✓
E6	✓		✓		✓		✓	✓		✓	✓	✓
E7	✓		✓		✓		✓	✓		✓	✓	✓
E8	✓		✓		✓	✓	✓	✓		✓	✓	✓
E9	✓		✓		✓		✓	✓		✓	✓	✓
E10	✓		✓		✓		✓	✓		✓	✓	✓
E11	✓		✓		✓		✓	✓		✓	✓	✓
E12	✓		✓		✓		✓	✓		✓	✓	✓
E13	✓		✓		✓		✓	✓		✓	✓	✓
E14	✓		✓		✓		✓	✓		✓	✓	✓
E15	✓		✓		✓		✓	✓		✓	✓	✓
E16	✓		✓		✓		✓	✓		✓	✓	✓
E17	✓		✓		✓			✓		✓	✓	✓
E18	✓		✓		✓			✓		✓	✓	✓
E19		✓		✓	✓			✓	✓	✓	✓	✓
E20		✓		✓	✓			✓	✓	✓	✓	✓
E21		✓		✓	✓			✓	✓	✓	✓	✓
E22		✓		✓	✓			✓	✓	✓	✓	✓
E23		✓		✓	✓			✓	✓	✓	✓	✓
E24		✓		✓	✓			✓	✓	✓	✓	✓
E25		✓		✓	✓			✓	✓	✓		

4. FINDINGS AND ANALYSIS

4.1 KEY PARAMETERS OF LEAN CONSTRUCTION MATURITY RELEVANT TO THE SRI LANKAN CONTEXT (R1P1 AND R2P1)

This section presents the findings of R1P1 and R2P1. In R1P1 experts were tasked with identifying lean construction parameters that constitute lean construction maturity in a general perspective without confining to Sri Lanka. Experts validated twelve parameters identified from the literature and rejected one parameter. Moreover, the authors added one more parameter as well. Consequently, twelve parameters were brought forward to R2P1. In R2P1 experts were requested to identify key parameters relevant specifically for the Sri Lankan context. In the process, authors validated twelve parameters and added six new parameters (In bold text), considering the context of Sri Lanka bringing the total number of parameters to 18. Experts rejected the parameter '*Minimise uniqueness'* as not relevant for Sri Lanka. Table 3 shows the corroborated parameters.

In identifying the key parameters of lean construction maturity in the Sri Lankan construction context, all the authors unanimously corroborated the most visible lean construction parameters such as waste reduction, continuous improvement, delivering exact customer value, reduction of non-value-adding activities, respect for all, quality management, and optimising the whole. E2 added "*well especially in these circumstances of Sri Lankan construction, it is the need of the hour that we really try to reduce all the types of waste. I mean we all talk about this but are we doing enough? So lean construction really makes you think to identify what are the types of waste, how to proactively identify them and how to treat them proactively*". Emphasising the value of continuous improvement E10 mentioned that "*continuous improvement is something that we are lacking in our industry but should be a must. We always rely on conventional methods thinking that they are the best, but we need to think ahead, we need to keep on trying, we need to keep advancing and we need to find room for improvement continuously.* Delivering exact customer value was considered a highly relevant parameter for Sri Lankan lean construction maturity, where all the experts unanimously corroborated. E1 stated, *"As a core lean principle identifying the exact thing customer needs is really important to excel in this industry. It has to be no more no less strategy*". Moving further experts validate the parameter of leadership to be highly relevant in the context of Sri Lanka. Confirming the relevancy of transparency E5 added "*I think transparency is very important since it provides an idea of trustworthiness, and it clears all unnecessary bottlenecks*". Considering the aspect of minimising unique content, authors rejected the parameter as not relevant for Sri Lanka due to several key reasons such as "*diverse project requirements", "localised techniques" and "cultural architectural diversity*". Experts added value engineering as a new aspect stating as mentioned by E25, "*well in many cases we need to come up with novel solutions to give the best solution for our client so that value engineering is a big part of it*".

4.2 DEFINITIONS OF KEY PARAMETERS OF LEAN CONSTRUCTION MATURITY IN THE SRI LANKAN CONTEXT (R2P1, R2P2 AND R3P1)

This section presents to finalised list of parameters and their definitions according to experts' views. In R2P2 experts were asked to recognise important elements for defining key parameters identified in R2P1. Important elements corroborated with more than 75% consensus were taken to the third round. In R3P1 the experts were tasked with developing definitions for the key parameters identified in R2P1 using important parameters identified in R2P2. Table 3 reveals definitions of Key parameters of lean construction maturity in the Sri Lankan context.

Table 3: Key parameters and definitions of lean construction maturity

Parameter	Definition
Reduction of waste	Implementing strategies **to proactively identify wastes** of all kinds, set **systematic measures** to reduce wastes of **all formats**, ensure optimal resource utilisation and embed a **zero-waste culture**.
Continuous improvement	Cultivating a **culture of development and innovation**, where stakeholders **consistently seek** to foster an environment of **continuous learning and improvement**, drawing from **traditional practices and adapting them with modern techniques.**
Deliver exact customer value	Ensuring projects are accurately planned and executed to meet the **precise needs and expectations of clients**, prioritising **customer satisfaction**, and understanding **cultural nuances** and client preferences unique to Sri Lanka's diverse communities.
Reduction of non-value-adding activities	**Pre-emptively identifying** and **removing non-value-adding activities**, **optimizing workflows** and resources to reduce waste, and ensuring **alignment with cultural, social, and environmental values**.
Respect for all	Nurturing a work environment that **values diversity**, promotes **inclusivity**, and treats all stakeholders with **dignity and respect**, regardless of role, background, or position within the industry and ensuring **fair treatment** and **equal opportunities**.
Quality management	**Rigorous quality assurance** and **control measures** to meet standards and regulations, ensuring safety, durability, and high quality by maintaining **stringent quality standards**.
Optimizing the whole	Considering the **interdependence of stakeholders**, **optimising the entire value chain** for maximum efficiency and success by **blending traditional practices with modern methods** to enhance outcomes.
Transparency in processes	Promotes **transparency, honesty, and accountability** across all facets emphasising **open communication** to cultivate trust among stakeholders and encourage collaboration.
Standardisation	Establishing **standardised procedures**, specifications, and **best practices** in the construction industry **adapting global best practices** to **suit local contexts** and **collaborating with industry stakeholders.**
Integration of supply chain	Collaborating closely with all stakeholders fostering **long-term partnerships** with **local suppliers** and **subcontractors** to build a **resilient** and **responsive** supply chain **network**.
Leadership	Providing **strategic direction**, **inspiring and empowering teams** to achieve **common goals**, driving **positive change** within the industry **empowering teams**, and fostering a **culture of innovation and collaboration** to drive industry progress.
Increase output flexibility	Enhancing ability to **adapt to changing requirements**, and **market demands** by fostering **agility** and **resilience** to accommodate **unforeseen challenges** and capitalize on emerging opportunities within the dynamic Sri Lankan construction landscape.
Value engineering	Applying **systematic analysis** and **creative problem-solving** techniques to maximize value while minimizing costs, integrating **local expertise** with **global best practices** to identify cost-effective solutions that **optimize project value**.

Parameter	Definition
Change management	**Proactively manage changes** by identifying **change agents**, empowering them to **drive change**, **managing resistance** through **transparent communication**, and **providing training and support** for successful implementation within the dynamic construction sector.
Technology adoption	Embracing **innovative technologies** to enhance efficiency, by utilizing **emerging technologies** and digital **collaboration platforms** to **optimize project delivery** and **enhance stakeholder engagement.**
Capacity building	Investing in **training, education**, and **skill development** initiatives to **strengthen** the **competencies** of the workforce, and **fill skills gaps** by collaborating with **educational institutions**, **industry associations**, and **government agencies**.
Policy enhancement	Adhering to regulations and industry standards while **actively advocating for necessary policy reforms** by recognizing that **traditional policies may need revision** to foster **innovation**, and to better meet **lean construction objectives**.
Ethical business practices	Upholding ethical standards and principles of **integrity, honesty,** and **fairness** in all aspects to build **trust** and **credibility** within the industry and society.

According to expert perspectives, these definitions aim to capture the reflective essence of lean principles, shifting from conventional approaches to enhancing construction activities by promoting a proactive stance. As stated by experts, these definitions provide an accurate guideline for industry practitioners to better understand how these lean concepts can be utilised effectively to achieve greater project outcomes.

5. DISCUSSION

In identifying parameters relevant to determining lean construction maturity in Sri Lanka, experts' views indicated a positive alignment with the literature. Core lean principles such as waste elimination, respect for everyone, continuous improvement, quality management, optimising the whole and delivering exact customer value, were overwhelmingly validated by experts as suitable for Sri Lankan context. These factors were evident in the existing studies on lean construction maturity and existing maturity models as well (Koskela et al., 2007; Nesensohn et al., 2015). The main reason for this alignment is the fundamental principles of Lean construction, which ensure that the foundational concepts and practices are universally applicable. However, the practical elements need more country-specific validation to account for local conditions and contexts.

Eventhough minimising unique content is accepted as a lean parameter by scholars (Howell, 2014), experts contend that, currently, this principle may not be applicable to the Sri Lankan construction context. Expert's argument is based on several factors including diverse project requirements, localised construction techniques, and the rich cultural architectural diversity prevalent in Sri Lanka. These aspects necessitate a unique approach that integrates local practices and respects cultural differences. Therefore, while Lean principles advocate for minimising variations, the unique characteristics of Sri Lanka's construction landscape call for a balance between standardised Lean practices and adaptable, context-specific approaches. These same factors are noted by several scholars as characteristics unique to the construction sector (Li et al., 2017), supporting the argument made by the experts.

Experts newly suggested and defined six key parameters i.e., (i) value engineering, (ii) change management, (iii) technology adoption, (iv) capacity building, (v) policy enhancement, and (vi) ethical business practices, considering the preliminary level of lean construction in the Sri Lankan context. Among the elements employed to develop definitions of lean construction parameters, several elements identified by experts were visible in the literature as well. Proactive waste identification (Koskela et al., 2002), waste minimisation (Perera & Shandraseharan, 2023), creating a continuous improvement culture (LCI, 2023), identifying precise customer needs (Nesensohn et al.,2015), quality assurance and control (Arditi et al., 2021), optimising workflows are key elements and terminologies which were directly adopted by authors to define parameters. Moreover, strategic direction, inspiring and empowering teams (Sadikoglu et al., 2023), optimising the entire value chain (Ballard & Howell, 1998), and encouraging collaboration (Arditi et al., 2021) are key themes found in the literature that were instrumental in defining key lean construction parameters through expert insights.

Considering the definitions developed for key lean construction parameters, experts underscored several key themes. Considering parameters such as waste elimination and reducing non-value-adding activities, experts emphasised that proactively seeking ways to identify points of waste occurrence in Sri Lankan construction projects is imperative. This idea is well-acknowledged by scholars as well (LCI, 2023). Customer satisfaction entailed various key aspects such as understanding the exact needs of customers and customer satisfaction, which were well accepted by authors and in previous literature (Bernstein & Jones, 2013). Experts added the factor of considering the diverse cultural values due to the country's multicultural status. Defining the lean construction parameter of optimising the whole, experts underlined the value of optimising the entire value chain which was directly corroborated in the literature as well (Koskela et al., 2007). However, the authors suggested the idea of blending traditional practices with modern methods, highlighting some of the unique Sri Lankan construction practices. In defining transparency in the Sri Lankan context, the ideas of experts directly matched with literature highlighting the need for transparency, honesty, and accountability (Herrera et al., 2019). Standardisation was defined by experts through concepts of standardised procedures, specifications and best practices quite similar to findings highlighted by scholars (Cookson & Stirk, 2019). Adapting to changing requirements, and fostering agility and resilience are several key points emphasised in defining increasing output flexibility by Sri Lankan experts which closely aligned with ideas made by several authors (Arditi et al., 2021).

5.1 IMPLICATIONS OF THE RESEARCH

5.1.1 Theoretical Contribution

The study contributes to the global body of knowledge on lean construction maturity by identifying the specific parameters relevant to the Sri Lankan context. By uncovering these region-specific factors, this research adds to the broader theoretical framework of lean construction parameters, offering insights into how cultural, economic, and institutional dynamics influence the maturity of lean practices in different contexts. As a theoretical construction to the local context, this study fills a gap in the literature by investigating key lean construction parameters in Sri Lanka. This research serves as a foundational study for understanding the state of Lean construction maturity. By indicating the key parameters essential for determining Lean maturity in the Sri Lankan construction industry, this study lays the groundwork for future research and practice.

5.1.2 Practical Contribution

The research findings directly impact the construction sector as they provide a clear guide to lean construction parameters relevant to the Sri Lankan context. Understanding these key parameters enables practitioners to focus their efforts on areas vital for successful lean implementation to reach higher lean construction maturity. This will allow organisations to improve efficiency, reduce waste, and enhance project outcomes. Moreover, the study encourages decision-makers in the Sri Lankan construction sector to make informed choices. By realising the precise socio-economic dynamics influencing lean maturity, policymakers and industry stakeholders can develop tailored initiatives and strategies to promote lean practices effectively. This includes the development and reforming of policies, effective training programs, and support mechanisms to address the unique challenges faced in lean implementation in Sri Lanka.

5.2 THE WAY FORWARD

Identifying key parameters presents opportunities for future research to explore their validity and applicability in real-world case scenarios. Furthermore, researchers can explore how each of these parameters impact the overall success of construction projects and they can further investigate key relationships of these parameters in project settings and how their overall integration would affect the final project outcomes. These findings will lead to the development of a comprehensive conceptual model that includes all necessary model elements, providing a strong framework for assessing lean construction maturity.

6. CONCLUSIONS

Lean construction provides an innovative pathway to manage conventional construction problems. However, there is a dearth of research on lean construction and a lack of methods to evaluate lean construction maturity in the Sri Lankan context. This has hindered the utilisation of lean principles. Determining lean construction parameters is imperative to successful implementation and reaching higher lean maturity. Therefore, this study is aimed at investigating key lean construction parameters relevant to lean construction maturity in the Sri Lankan context. The Delphi technique was employed for data collection in three rounds using a qualitative approach. Content analysis was applied to analyse the data. The study unveiled 18 key parameters and proceeded to develop specific definitions for each of these parameters conforming to the Sri Lankan context. In conclusion, lean construction maturity in Sri Lanka portrays a strong alignment with the core lean construction principles as validated by experts and supported in the literature. However, practical application must consider diverse project requirements, localised techniques, and cultural diversity. Defined parameters such as value engineering, change management, and technology adoption reflect local needs while integrating global best practices. These insights emphasise the importance of transparency, standardisation, and flexibility in adapting lean construction principles to Sri Lanka's unique construction landscape. Moving forward, these findings offer a strategic guide for enhancing efficiency in the Sri Lankan construction sector through tailored lean construction practices. These findings significantly contribute to enriching the knowledge base of lean construction maturity and offer tangible benefits to industry stakeholders by providing them with insights to reach higher lean construction maturity.

7. REFERENCES

Aghimien, D. O., Aigbavboa, C. O., & Oke, A. E. (2020). Critical success factors for digital partnering of construction organisations: A Delphi study. *Engineering, Construction and Architectural Management*, *27*(10), 3171-3188.

Agrawal, A. K., Zou, Y., Chen, L., Abdelmegid, M. A., & González, V. A. (2024). Moving toward lean construction through automation of planning and control in last planner system: A systematic literature review. *Developments in the Built Environment*, *18*,(2004). 100419. Retrieved from https://doi.org/10.1016/J.DIBE.2024.100419

Arantes, L. (2010). *Diagnosis of the application of two principles of embedded construction in builders of the building sector* [Unpublished doctoral dissertation]. Federal University of Para.

Arditi, D., & Gunaydin, H. M. (1997). Total quality management in the construction process. *International Journal of Project Management*, *15*(4), 235–243. Retrieved from https://doi.org/10.1016/S0263-7863(96)00076-2

Aslam, M., Baffoe-Twum, E., & Malik, S. (2024). Benchmarking lean construction conformance in Pakistan's construction industry. *Engineering, Construction and Architectural Management,31*(5), 2077-2100. Retrieved from https://doi.org/10.1108/ECAM-11-2023-1125

Ballard, H. G. (2000). *The Last Planner System of Production Control*. [Doctoral dissertation, University of Birmingham]. UBIRA eData Repository. http://etheses.bham.ac.uk/id/eprint/4789

Ballard, G., & Howell, G. (1998). What kind of production is construction. *Proceedings of 6th annual conference, international group for lean construction*, *Brazil.* 13–15 July 1998. (pp. 13-15). International Group for Lean Construction

Ballard, G., Tommelein, I., Koskela, L., & Howell, G. (2007). Lean construction tools and techniques. In R. Best & G. de Valence (Eds.), *Design and construction*, (1st ed., pp. 227-255). Routledge.

Bandara, O. K. K., Tharaka, V. K., & Wickramarachchi, A. P. R. (2019). Industry 4.0 maturity assessment of the Banking Sector of Sri Lanka. *Proceedings of international research conference on smart computing and systems engineering, Sri Lanka*, 28-28 March 2019. (pp. 190–195). University of Kelaniya. IEEE https://doi.org/10.23919/SCSE.2019.8842818

Bernstein, H. M., & Jones, S. A. (2013). *Lean construction: Leveraging collaboration and advanced practices to increase project efficiency.* McGraw Hill Construction. https://lean-construction-gcs.storage.googleapis.com/wp-content/uploads/2022/09/08152925/mcgraw-hill-lean-construction-report.pdf

Carvalho, B. S., & Scheer, S. (2017). Analysis and assessment for lean construction adoption: The DOLC tool. *25th annual conference of the international group for lean construction*, *Greece*. 9-12 July 2017. (pp 429-435). The International Group for Lean Construction. doi.org/10.24928/2017/0117.

Cookson, M. D., & Stirk, P. M. R. (2019). The potential effectiveness of lean construction principles in reducing construction process waste: An input-output model. *Wood and Fiber Science*, *12*(4), 4141-4160,. Retrieved from https://doi.org/10.15282/jmes.12.4.2018.12.0358.

Galichet, G., Affonso, R. C., & Cheutet, V. (2024). Process-oriented maturity framework for lean manufacturing with health-at-work and performance management objectives. *European Journal of Industrial Engineering, 18*(1), 28–74. Retrieved from https://doi.org/10.1504/EJIE.2024.135385

Gamini, G. L. M., Vidanagamachchi, K., & Wickramarachchi, R. (2019). A lean maturity assessment model to improve warehouse operations for the 3PL industry in Sri Lanka. Proceedings of *4th International research symposium on pure and applied sciences,* Sri *Lanka*, 25th October 2019. (pp 109). University of Kelaniya,

Hamza-Khan, M. A., Asadian, E., & Leicht, R. M. (2024). Identifying Elements for Lean Construction Implementation in Trade Contractor Organizations. In J. S. Shane, K. M. Madson, Y. Mo, C. Poleacovschi, and R. E. Sturgill (Eds.), *Proceedings of construction research congress 2024*, 20-23 March 2024. (pp. 496–506). ASCE Library. https://doi.org/10.1061/9780784485286.050

Herrera, R. F., Sanz, M. A., Montalbán-Domingo, L., García-Segura, T., & Pellicer, E. (2019). Impact of game-based learning on understanding lean construction principles. *Sustainability*, *11*(19), 5294. Retrieved from https://doi.org/10.3390/su11195294.

Highways Agency (2012). *Highways agency lean maturity assessment toolkit (HALMAT)*, (Version 2), Department of transport, UK. https://www.aldercross.com/cms/uploads/Bolton%20PPs/Highways%20Agency%20Lean%20Maturrity%20Toolkit%20(HALMAT)%20version%2021.pdf

Hofacker, A., Oliveira, B. D., Gehbauer, F., Freitas, M. D. C. D., Júnior, R. M., Santos, A., & Kirsch, J. (2008). Rapid lean construction-quality rating model. *Proceedings of 16th international group for lean construction conference*, *England*, July 16-18 2008. (pp.1-11). International Group for Lean Construction

Howell, G. A. (1999). What is lean construction-1999. *Proceedings of 7th annual conference of the international group for lean construction*, *USA*, 26 - 28 July 1999. (pp.1-10). International Group for Lean Construction

Howell, J. (2014). Lean construction. In A. T. Carswell (Eds.), *The Encyclopedia of Housing,* (2nd ed.). SAGE Publication Inc. http://dx.doi.org/10.4135/9781452218380.n144

Jayanetti, J. K. D. D. T., Perera, B. A. K. S., Waidyasekara, K. G. A. S. and M. Siriwardena. (2023). Critical analysis of lean construction maturity models: A systematic literature review. *Buildings*, *13*(6), 1508.

Jayasena, H. S., & Weddikkara, C. (2013). Assessing the BIM maturity in a BIM infant industry. *Proceedings of the second world construction symposium, Sri Lanka,* 14-15 June 2013. World Construction Symposium

Johansen, E., & Walter, L. (2007). Lean construction: Prospects for the German construction industry. *Lean Construction Journal*, *3*(1), 19–32.

Jones, D. T., & Womack, J. P. (2016). The evolution of lean thinking and practice.In T.H Netland & D. J Powell (Eds.), *The Routledge Companion to Lean Management*. (pp 3-8) Routledge.

Jørgensen, F., Matthiesen, R., Nielsen, J., & Johansen, J. (2007). Lean Maturity, lean Sustainability. In Olhager, J., Persson, F. (Eds.), *Advances in Production Management Systems. IFIP — The International Federation for Information Processing, vol 246.* (pp371–378). Springer, Boston, MA. https://doi.org/10.1007/978-0-387-74157-4_44

Keeney, S., Hasson, F. and McKenna, H. (2006), Consulting the oracle: ten lessons from using the Delphi technique in nursing research, *Journal of Advanced Nursing*, *53*(2), 205–212, doi: 10.1111/J.1365-2648.2006.03716.X.

Keeney, S., McKenna, H. A., & Hasson, F. (2011). *The Delphi technique in nursing and health research*. (1st Ed). John Wiley & Sons.

Koskela, L. (1992). *Application of the new production philosophy to construction*,(Technichal report No.72), Centre for Integrated Facility Engineering, Stanford University.

Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2007). The foundations of lean construction. In R. Best, G. de Valence (Eds.), *Design and construction* (1st ed, pp. 211-226). Routledge. https://doi.org/10.4324/9780080491080-16

Kulasooriya, D. M. A., & Chalapathi, R. S. (2014). Lean manufacturing maturity assessment in garment industries: A case study from Sri Lanka. *Academicia: An International Multidisciplinary Research Journal*, *4*(5), 193-217.

Lean Construction Institute. (2016). *LCI Lean IPD health and maturity assessment tool 1.0*. Retrieved 25th June 2023 from https://www.leanconstruction.org/learning/tools-and-technologies/

Lean Construction Institute. (2023). *LCI Tenets*. Lean Construction Institute. Retrieved June 25th, 2023 from https://leanconstruction.org/about/lean-tenets/

Li, S., Wu, X., Zhou, Y., & Liu, X. (2017). A study on the evaluation of implementation level of lean construction in two Chinese firms. *Renewable and Sustainable Energy Reviews*, *71*, 846-851. Retrieved from https://doi.org/10.1016/j.rser.2016.12.112

Likita, A. J., Jelodar, M. B., Vishnupriya, V., & Rotimi, J. O. B. (2024). Lean and BIM integration benefits construction management practices in New Zealand. *Construction Innovation*, *24*(1), 106–133. Retrieved from https://doi.org/10.1108/CI-06-2022-0136/FULL/PDF

Mansour, H., Aminudin, E., Omar, B., & Al-Sarayreh, A. (2022). Development of an impact-on-performance index (IPI) for construction projects in Malaysia: A delphi study. *International Journal of Construction Management*, *22*(11), 2003-2012.

Methley, A. M., Campbell, S., Chew-Graham, C., McNally, R., & Cheraghi-Sohi, S. (2014). PICO, PICOS and SPIDER: a comparison study of specificity and sensitivity in three search tools for qualitative systematic reviews. *BMC Health Services Research*, *14*(1), 1–10.

Nesensohn, C. (2014). *An innovative framework for assessing lean construction maturity.* [Doctoral dissertation, Liverpool John Moores University]. *LJMU Research Online. https://researchonline.ljmu.ac.uk/id/eprint/4320*

Nesensohn, C., Bryde, D., Ochieng, D. E. G., & Fearon, D. (2015). Maturity and maturity models in lean construction. *Australasian Journal of Construction Economics and Building*, *14*(1), 45-59

Nightingale, D., Broughton, T., Brown, K., Cool, C., Crute, V., James-Moore, M., & Womersley, M. (2001). *Lean enterprise self assessment tool*. (1st ed). Lean Aerospace Intitiative.

Nowotarski, P., Pasławski, J., & Matyja, J. (2016). Improving construction processes using lean management methodologies: Cost case study. *Procedia Engineering*, *161*, 1037–1042. Retrieved from https://doi.org/10.1016/j.proeng.2016.08.845

Olsen, A. A., Wolcott, M. D., Haines, S. T., Janke, K. K., & McLaughlin, J. E. (2021). How to use the Delphi method to aid in decision making and build consensus in pharmacy education. *Currents in Pharmacy Teaching and Learning*, *13*(10), 1376-1385

Patton, M. Q. (2002). *Qualitative research & evaluation methods*. (3rd ed).Sage Publications. USA

Perera, B. A. K. S., & Shandraseharan, A. (2023). A framework for aggregate base course waste control in road construction projects. *International Journal of Construction Management*, *23*(6), 1009–1020. Retrieved from https://doi.org/10.1080/15623599.2021.1948187

Ranadewa, K. A. T. O., Sandanayake, Y. G., & Siriwardena, M. (2021). Enabling lean through human capacity building: An investigation of small and medium contractors. *Built Environment Project and Asset Management*, *11*(4), 594–610. Retrieved from https://doi.org/10.1108/BEPAM-03-2020-0045

Ranadewa, K. A. T. O., Sandanayake, Y. G., & Siriwardena, M. L. (2019). Lean enabling human capacity building of small and medium contractors in Sri Lanka. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, and T. Ramachandra, (Eds). *Proceedings of the 8th world construction symposium, Sri Lanka*, 8-9 November 2019. (pp. 400-410). World Construction Symposium. doi:10.31705/wcs.2019.40

Rashidian, S., Drogemuller, R., & Omrani, S. (2022). The compatibility of existing BIM maturity models with lean construction and integrated project delivery. *Journal of Information Technology in Construction*,*27*(1), 496-511. doi:10.36680/j.itcon.2022.024

Rodegheri, P. M., & Serra, S. M. B. (2020). Maturity models to evaluate lean construction in brazilian projects. *Brazilian Journal of Operations & Production Management*, *17*(2), 1–21. Retrieved from https://doi.org/10.14488/BJOPM.2020.016

Sadikoglu, E., Jäger, J., Demirkesen, S., Baier, C., Oprach, S., & Haghsheno, S. (2023). Investigating the impact of lean leadership on construction project success. *Engineering Management Journal*, *36*(2), 206–220. Retrieved from https://doi.org/10.1080/10429247.2023.2245317

Sarhan, J. G., Xia, B., Fawzia, S., Karim, A., Olanipekun, A. O., & Coffey, V. (2020). Framework for the implementation of lean construction strategies using the interpretive structural modelling (ISM) technique: A case of the Saudi construction industry. *Engineering, Construction and Architectural Management*, *27*(1), 1–23. Retrieved from https://doi.org/10.1108/ECAM-03-2018-0136

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research Methods for Business Students*.(5th ed), Prentice Hall

Skulmoski, G. J., Hartman, F. T., & Krahn, J. (2007). The delphi method for graduate research. *Journal of Information Technology Education: Research*, *6*(1), 1-21.

Sukrat, S., and A. Leeraphong. (2024). A digital business transformation maturity model for micro enterprises in developing countries. *Global Business and Organizational Excellence, 43*(2), 149–175. Retrieved from https://doi.org/10.1002/joe.22230.

Tariq, J., & Shujaa Safdar Gardezi, S. (2023). Study the delays and conflicts for construction projects and their mutual relationship: A review. *Ain Shams Engineering Journal*, *14*(1), 101815. Retrieved from https://doi.org/10.1016/J.ASEJ.2022.101815

Tommelein, I. D. (1998). Pull-driven scheduling for pipe-spool installation: Simulation of lean construction technique. *Journal of Construction Engineering and Management*, *124*(4), 279-288,. Retrieved from https://doi.org/10.1061/(ASCE)0733-9364(1998)124

Tommelein, I. D. (2015). Journey toward lean construction: Pursuing a paradigm shift in the AEC industry. *Journal of Construction Engineering and Management*, *141*(6), 04015005, Retrieved from https://doi.org/10.1061/(ASCE)CO.1943-7862.0000926.

Tzortzopoulos, P., & Formoso, C. (1999). Considerations on application of lean construction principles to design management. *Proceedings of 7th annual conference of the international group for lean construction, USA*, 26 - 28 July 1999. (pp. 335–344). International Group for Lean Construction.

Tzortzopoulos, P., Kagioglou, M., & Koskela, L. (2020). *Lean Construction: Core Concepts and New Frontiers*. Routledge. https://doi.org/10.1201/9780429203732.

Waduwawala, H. B., Perera, B. A. K. S., & Samaraweera, A. (2019). Creating a sustainable lean culture in the construction organizations of developing countries: The case of Sri Lanka. *CIDA Journal, 2019*, 2-21

Womack, J. P., & Jones, D. T. (1997). Lean thinking—Banish waste and create wealth in your corporation. *Journal of the Operational Research Society*, *48*(11), 1148-1148,. Retrieved from https://doi.org/10.1057/palgrave.jors.2600967.

Yin, R.K. (2016). *Qualitative Research from Start to Finish*, (2nd ed) .The Guilford Press, New York.

Zanon, L. G., Ulhoa, T. F., & Esposto, K. F. (2021). Performance measurement and lean maturity: Congruence for improvement. *Production Planning and Control*, *32*(9), 760–774. Retrieved from https://doi.org/10.1080/09537287.2020.1762136

Ikuabe, M., Aghimien, D., Aigbavboa, C., Oke, A. and Ramaru, P., 2024. Lean techniques for project delivery: Assessing construction professionals' level of awareness. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 727-733. DOI: https://doi.org/10.31705/WCS.2024.57. Available from: https://ciobwcs.com/papers/

LEAN TECHNIQUES FOR PROJECT DELIVERY: ASSESSING CONSTRUCTION PROFESSIONALS' LEVEL OF AWARENESS

Matthew Ikuabe[1], Douglas Aghimien[2], Clinton Aigbavboa[3], Ayodeji Oke[4], and Pretty Ramaru[5]

ABSTRACT

Evidence from practice and literature indicates that the South African construction industry faces various challenges. Notably, the traditional methodologies deployed for project delivery continues failing to attain projects' objectives. Lean construction promotes developing and accomplishing construction projects within its envisaged goals by deploying targeted tools/techniques. Considering the glaring comparative advantage of deploying lean concepts in construction activities, this study assesses the level of awareness of lean techniques among professionals in the South African construction industry. The study adopted a quantitative approach aided by using a well-structured questionnaire that elicited responses from the target respondents. Data analysis methods employed are descriptive and inferential statistics. The study's findings showed that total quality management, waste elimination, and prefabrication are the most known lean techniques among South African construction professionals. Besides, findings indicated that there is a statistically significant disparity in the knowledge of lean techniques among the professionals in the South African construction industry. Conclusively, the study proffered recommendations that would aid in boosting the awareness and knowledge base of the various lean techniques among professionals for better construction delivery.

Keywords: *Awareness; Construction Professionals; Lean Construction; Lean Techniques; South Africa.*

1. INTRODUCTION

The construction industry plays a vital role in any country's national economy and economic improvement; however, there is a significant variation in these roles among various countries. For both developing and developed nations, the construction business

[1] Senior Lecturer, School of Construction Economics and Management, University of the Witwatersrand, South Africa, matthew.ikuabe@wits.ac.za
[2] Senior Lecturer, School of Art, Design and Architecture, Faculty of Arts, Design and Humanities, De Montfort University, UK, aghimiendouglas@gmail.com
[3] Professor, SARChI in Sustainable Construction Management and Leadership in the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa, caigbavboa@uj.ac.za
[4] Associate Professor, Department of Quantity Surveying, Federal University of Technology, Akure, Nigeria, emayok@gmail.com
[5] Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, dpramaru@gmail.com

serves as a critical segment in the establishment of the Gross Domestic Product (GDP) through the use of a segment of the populace, making a sizeable section capital formation and integrates firmly with other sectors (Ikuabe et al., 2021). In addition, Otasowie et al. (2024) indicates that the construction industry of developing countries aids in providing infrastructure such as public utilities spanning housing, schools, roads, railways, hospitals, airports, and other related infrastructure. Over time, the construction sector has been attributed to having an array of challenges plaguing its effective delivery of projects. These challenges cover issues like cost overrun, delays in project delivery, safety problems, and undesired quality (Akinshipe et al., 2024). A significant number of projects are characterised by delay in completion, costs overruns, sub-standard delivery, and often times requiring re-work. Aghimien et al. (2021) noted that many projects are not achieving the required performance regardless of the significant expanse of advancement and the input of recent techniques.

The Lean Concept (LC) is projected as a viable model for project managers seeking to challenge the conventional concept of construction and project management (Ikuabe et al., 2022). The lean concept is defined as a “technique to plan creation frameworks to limit the waste of resources, time, and effort, bearing in mind the end goal to yield the greatest imaginable amount of major cost” (Mossman, 2009 p.4). According to Johansen and Walter (2007), applying lean practice to construction processes is exceptionally restricted and slow. Results from countries that have implemented lean concepts suggest great rewards, however, others are still lagging due to certain factors. One notable reason is the shallow knowledge-base of the concept among industry’s stakeholders (Mossman, 2009). Moreover, Olatunji (2008) asserted that Nigeria's construction professionals' level of awareness of lean concepts is shallow. The same can be said for other developing countries. Furthermore, Aigbavboa et al. (2016) affirmed that there are several limits to the promotion of lean concepts in the processes making up the execution of construction projects. Thus, hindering the numerous overwhelming advantages of its uptake in the value chain of construction project execution. Based on those mentioned earlier, this study is propelled towards ascertaining the level of awareness of lean techniques deployed for project execution within the South African construction industry to proffering recommendations on enhancing the knowledge base of lean techniques for enhanced construction project delivery.

2. THEORETICAL BACKGROUND

Lean techniques serve as the spine of lean concepts in construction, and they seek to mitigate some of the inherent challenges peculiar to the construction industry. According to Kumar et al. (2022), lean techniques are approaches, procedures, systems, concepts, frameworks, and procedures whose application aids organisations in the execution of lean tasks execution. Lean concepts are typified by a variety of lean techniques that aid in the propagation of lean construction. These include Kanban (Pull system), a Japanese word translated as signboard or billboard (Sarhan et al., 2017). This lean technique is deployed to monitor the volume or quantity of apparatuses or materials (Memon et al., 2010). Increased visualisation is deployed as a lean technique for construction project delivery. This approach aids in creating a harmless, easy, and transparent process for all stakeholders on-site (Bajjou et al., 2017). Work standardisation is a lean technique attributed to a set of methods, mechanisms, or strategies which portrays consistency or replication of effective practices termed standard operating strategies (Ullah et al., 2016).

Furthermore, prefabrication is a lean technique that entails using manufactured and modularised construction tools to solve construction-related issues encountered on-site (Thaís da et al., 2012). Al Sehaimi et al. (2014) state that the Last Planner System is a lean technique that is a cooperative preparation approach that makes a usual design through the expansion of the guarantee of work trades development. This approach is reflected as an engaged mechanism whose aim is to regulate workflow and reduce the instability in construction projects.

Value stream mapping is a lean technique targeted at improving the flow of a process by highlighting opportunities for improvement. It is used in upscaling value flow (Yu et al., 2009). This approach aids in the reduction of waste by targeting the causes such as overproduction, relocation, and waiting for inventory. Moreover, waste elimination is a lean technique whose strategy aims to target the causes of waste in project execution (Zhang et al., 2017). This technique is focused on quality defects, relocations, inventory, overproduction, and overprocessing. The Kaizen (Continuous Improvement) lean technique is derived from a Japanese philosophy based on continuous improvement (Sarhan et al., 2017). This technique aims to create an environment whereby there is the assignment of responsibilities to individual workers who are motivated to identify lapses in the delivery chain for efficiency (Sarhan et al., 2017). Furthermore, Total Quality Management (TQM) is applied as a lean technique as a management method that targets the incorporation of all organisational purposes for the attainment of clients' needs and execution targets (Ullah et al., 2017). This technique utilises a fusion of statistical process control and problem-solving teams for the advancement of procedural abilities. Further, using the Five Whys as a lean technique is based on the drive for problem-solving through recognising foundation sources of targeted issues in project delivery (Sarhan et al., 2017). The First-run study is a technique whose implementation process is conducted in four stages. These stages are categorised as plan, do, check, and act (Bajjou et al., 2017). This technique is primarily deployed in redesigning basic projects and auditing work strategies through re-designing and streamlining the unique capability adopted.

3. METHODOLOGY

The study's aim is to appraise the level of awareness of lean techniques among professionals in the built environment in South Africa. Adopting a post-positivism philosophical approach, the study utilised a quantitative method to get data from the target respondents. This was employed to get a wide range of respondents' viewpoints on their awareness of lean construction. These target respondents were construction professionals namely, construction project managers, quantity surveyors, construction managers, architects, and engineers. These professionals were selected because they comprise the critical stakeholders in construction project delivery. A questionnaire was used for the collection of responses from the study's target respondents due to its relative advantage of providing data in a short time frame (Tan, 2011). The questionnaire enquired on the rating of the awareness of the identified lean techniques by the respondents. The employed sampling procedure for the study was convenience sampling due to the limited time frame for the conduct of the research, and this led to the acquisition of 152 questionnaires from the respondents that were suitable for analysis. Mean Item Score (MIS) was used for the ranking of the lean techniques; Kruskal Wallis *h*-test (K-W) was used to ascertain if there was a difference in the respondents' responses regarding their awareness of the identified lean techniques based on their professional designation. The

Student Newman Kauls (SNK) post hoc test was used to differentiate the mean responses of the categorised respondents based on their professional affiliation. Furthermore, using the Cronbach's alpha test, the validity and reliability of the questionnaire was established. The analysis gave an alpha value of 0.811, which indicates good validity and reliability since it is above the threshold of 0.7 and closer to 1.0 (Tavakol & Dennick, 2011).

4. FINDINGS AND DISCUSSION

4.1 LEVEL OF AWARENESS OF LEAN TECHNIQUES

The study respondents conducted the awareness rating of the identified lean techniques and subsequently analysed them. Firstly, as portrayed in Table 1, the result of the MIS conducted shows that the lean technique that is well known among the construction professionals in South Africa is total quality management with a mean score of 3.77, this is followed by waste elimination which is a mean score of 3.36, then followed by prefabrication with a mean score of 3.36.

Table 1: Lean techniques awareness level

Lean Techniques	$\bar{X}$	R	K-W	
			X^2	Sig.
Total quality management (TQM)	3.77	1	9.679	0.714
Waste elimination	3.36	2	3.297	0.593
Prefabrication	3.34	2	2.116	0.339
Standardization	3.31	4	7.024	0.813
First run studies (plan, do, check, and act)	3.22	5	7.936	0.062
Amplified visualisations	3.15	6	2.195	0.021**
5s process (Sort, Set in order, Shine, Standardize, and Sustain)	3.14	7	5.902	0.109
Value stream mapping (VSM)	3.10	8	2.118	0.783
Kaizen	3.04	9	3.274	0.091
Five whys	3.02	9	1.482	0.041**
Just-in-time (JIT)	2.99	11	5.228	0.115
Error proofing /fail-safe for quality and safety (Poka-yoke)	2.91	12	7.218	0.072
Last planner system	2.88	13	6.812	0.592
Ishikawa diagram	2.85	14	8.224	0.002**
Failure mode, effects, and criticality analysis (FMECA)	2.83	15	6.162	0.228

The fourth-ranked lean technique is standardisation, with a mean score of 3.31, while the fifth-ranked lean technique is first-run studies, with a mean score of 3.22. The least ranked lean techniques are failure mode, effects, and criticality analysis, with a mean score of 2.83 and the Ishikawa diagram, with a mean score of 2.85. Secondly, the data was subjected to *the K-W test to ascertain if there was* a statistical difference in the opinions given by the respondents based on their professional designation. The result shows no significant difference based on the respondents' professional affiliation responses for twelve of the lean techniques. These lean techniques had a *p*-value above 0.05. This implies that there is a convergent opinion among the different professionals based on their opinions on the level of awareness of the twelve lean techniques. Besides, it is shown that there is a divergent opinion for three of the lean techniques. These lean techniques have a *p*-value less than 0.05, thus indicating a significant difference in the opinions of the respondents based on their professional designation. The three lean techniques are increased visualisation, five whys, and the Ishikawa diagram.

Table 2 portrays the findings of the conducted analysis of the multiple comparisons test (SNK post hoc test).

Table 2: SNK post hoc test

Groups	**N**	**Subset for alpha=0.05**	
		1	2
Architects	15	2.8115	
Engineers	15	2.9278	
Construction Managers	15		3.1835
Construction Project Managers	15		3.2891
Quantity Surveyors	15		3.5679
Sig.		1.000	.325

The result shows that there is a difference in opinion of the level of awareness of the identified lean techniques among the two groups of professional designations. The first group comprises architects and engineers with corresponding values of 2.8115 and 2.9278 respectively. The second group is constituted of quantity surveyors, construction project managers, and construction managers, with their corresponding values of 3.5679, 3.2891, and 3.1835, respectively.

4.2 DISCUSSION OF FINDINGS

In support of the outcome of this study, Sarhan et al. (2017) noted that there is a seeming progressive awareness of lean techniques in the construction sector. Furthermore, the study corroborates the findings of Johansen and Walter (2007), who opined that there is a growing level of awareness of the applicability of lean concepts in the delivery of construction projects. This has mainly been influenced by establishing a couple of LC Consultants, the Lean Construction Institute, and publicity companies. Furthermore, lean construction education is now being offered by some universities and organisations, which has helped strengthen the general awareness level of the phenomenon. Overall, the findings from the study indicate that there is a moderate level of awareness of the lean concept among construction professionals in South Africa. Respondents asserted that the lean techniques with the highest level of awareness in the South African construction industry are total quality management, waste elimination, and prefabrication. This might not be unconnected with the growing drive to deliver construction projects that align with construction organisations' core mandates. Therefore, it is not quite far off from the tent of total quality management, which is applied as a lean technique as a management method that targets the incorporation of all organisational purposes for the attainment of clients' needs and execution targets (Ullah et al., 2017). Furthermore, the optimisation of construction processes through the enhancement of material utilisation is fast gaining momentum among construction organisations. This is in tandem with waste elimination, a lean technique whose strategy is aimed at targeting the causes of waste in project executions (Zhang et al., 2017). Moreover, findings show that architects and engineers have similar views on the awareness level of lean techniques, while construction managers, quantity surveyors, and construction project managers all have similar opinions on the subject matter. This might be related to their roles in the delivery of construction projects.

5. CONCLUSIONS AND RECOMMENDATIONS

An assessment of the awareness level of lean techniques among professionals within the South African construction space was conducted by the study. Findings showcased that the lean techniques most known by these professionals are total quality management, waste elimination, and prefabrication, which are techniques deployed in delivering construction projects within the ambits of lean concepts. The findings showed that the empirical analysis of the study indicates a moderate level of the identified lean techniques. Hence, the recommendations put forward by the study states that the awareness and adoption of the principles and techniques of lean construction should be propagated among stakeholders and professionals in the industry. Relevant stakeholders are implored to help boost the implementation of lean concepts resulting from the inherent benefits therein. This should be encouraged against the unjustifiable project management approaches currently being utilised in the industry over the years, hence, being replaced by the lean concept approach. Furthermore, the government should prioritise investing in innovative ways of encouraging the uptake of lean techniques with the aid of technology. Cutting-edge research on lean construction needs to be encouraged to provide innovative ways for technological infusion in lean concepts for effective construction processes. It is worth noting that this research was limited to Gauteng province in South Africa.

6. REFERENCES

Aghimien, D., Ikuabe, M., Aigbavboa, C., Oke, A. & Shirinda, W. (2021). Unravelling the factors influencing construction organisations' intention to adopt big data analytics in South Africa. *Construction Economics and Building*, *21*(3), 262-281. https://search.informit.org/doi/10.3316/informit.146188624928155

Aigbavboa, C., Oke, A. & Momoti, T. (2016) Drivers and barriers of lean construction practice in South African construction industry. *International Conference on Innovative Production and Construction*. Perth, Australia, 29-30th September, (pp.195-201). https://hdl.handle.net/10210/213319

Akinshipe, O., Ikuabe, M., Adekunle, S.A., & Aigbavboa, C. (2024). Empirical assessment of the impacts of Sino-African cross border relations in the construction industry: A confirmatory Factor Analysis approach. *International Journal of Building Pathology and Adaptation*, *42*(7), 18-24. https://doi.org/10.1108/IJBPA-06-2023-0075

AlSehaimi, O.A., Tzortzopoulos, P.F. & Koskela, L. (2014). Improving construction management practice with the last planner system: a case study. *Engineering, Construction and Architectural Management*, *21*(1), 51-64. https://doi.org/10.1108/ECAM-03-2012-0032

Bajjou, M.S., Chafi, A., Ennadi, A. & El Hammoumi, M. (2017). The practical relationships between lean construction tools and sustainable development: a literature review. *Journal of Engineering Science and Technology Review*, *10*(4), 170-177. https://doi.org/10.25103/jestr.104.20

Ikuabe, M.O, Aigbavboa, C., Aghimien, D., Ramaru, P., Oke, A., & Akinradewo, O. (2022). Principal Component Analysis of Inhibiting Factors to the Espousal of Lean Construction in Developing Economies. In: Beata Mrugalska (eds) *Production Management and Process Control. AHFE*

(2022) International Conference. AHFE Open Access, vol 36. AHFE International, USA. http://doi.org/10.54941/ahfe1001631

Ikuabe, M., Aigbavboa, C., Oke, A., Aghimien, D. & Thwala, W. (2021). Contextualizing foreign investments in the Nigerian construction industry. *Proceedings of the AHFE 2021 Virtual Conferences on Human Aspects of Advanced Manufacturing, Advanced Production Management and Process Control, and Additive Manufacturing, Modeling Systems and 3D Prototyping*, July 25-29, USA, (pp.277-285). Springer International Publishing. https://doi.org/10.1007/978-3-030-80462-6_35

Johansen, E., & Walter, L. (2007). Lean construction: Prospects for the German construction industry. *Lean Construction Journal*, *3*(1), 19-32. https://nrl.northumbria.ac.uk/id/eprint/1746

Kumar, N., Hasan, S., Srivastava, K., Akhtar, R., Yadav, R., & Choubey, V. (2022). Lean manufacturing techniques and its implementation: a review. Materials Today: Proceedings, *64*(3), 1188-1192 https://doi.org/10.1016/j.matpr.2022.03.481

Memon, A. H., Abdul Rahman, I., Abdullah, M. R., & Abdu Azis, A. A. (2010). Factors affecting construction cost in Mara large construction project: Perspective of project management consultant. *International Journal of Sustain Construction Engineering Technology*, *1*(2), 41-54. https://penerbit.uthm.edu.my/ojs/index.php/IJSCET/article/view/62

Mossman, A. (2009). Why isn't the UK construction industry going lean with gusto?. *Lean Construction Journal*, *5*(1), 24-36.

Olatunji, J. (2008). Lean in Nigerian construction: state, barriers, strategies and "Goto- gemba" Approach. *Proceedings of the 16th annual conference of the international group for lean construction*, Manchester, United Kingdom, 16th-18th July, (pp.287-297).

Otasowie, K., Ikuabe, M., Aigbavboa, C., & Oke, A. (2023). Factors militating against the use of digital technology by sub-contractors in South Africa, In: Arai, K. (eds) *Proceedings of the Future Technologies Conference (FTC), Lecture Notes in Network and Systems*, (pp.749-757). Cham, Springer International Publishing. http://dx.doi.org/10.1007/978-3-031-18458-1_50

Sarhan, J.G., Xia, B., Fawzia, S. & Karim, A. (2017). Lean construction implementation in the Saudi Arabian construction industry. *Construction Economics and Building*, *17*(1), 46-69. https://search.informit.org/doi/10.3316/informit.763708036719779

Tan, W.C.K. (2011). *Practical Research Methods*. Pearson Custom: Singapore.

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's Alpha. *International Journal of Medical Education*, *2*, 53-55. https://doi.org/10.5116%2Fijme.4dfb.8dfd

Thaís da, C.L.A., Milberg, C., & Walsh, K.D. (2012). Exploring lean construction practice, research, and education. *Engineering, Construction and Architectural Management*, *19*(5), 512-525. https://doi.org/10.1108/09699981211259595

Ullah, F., Thaheem, M.J., Siddiqui, S.Q. & Khurshid, M.B. (2017). Influence of six sigma on project success in construction industry of Pakistan. *The TQM Journal*, *29*(2), 276-309. https://doi.org/10.1108/TQM-11-2015-0136

Yu, H., Tweed, T., Al-Hussein, M. & Nasseri, R. (2009). Development of lean model for house construction using value stream mapping. *Journal of Construction Engineering and Management*, *135*(8), 782-790. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:8(782)

Zhang, L., Chen, X. & Suo, Y. (2017). Interrelationships among critical factors of workflow reliability in lean construction. *Journal of Civil Engineering and Management*, *23*(5), 621-632. https://doi.org/10.3846/13923730.2016.1217921

Prabodani, M.K.M., Ranasinghe, S.S. and Halwatura, R.U., 2024. Lifecycle carbon emissions: Adaptive reuse vs new buildings in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 734-746. DOI: https://doi.org/10.31705/WCS.2024.58. Available from: https://ciobwcs.com/papers/

LIFECYCLE CARBON EMISSIONS: ADAPTIVE REUSE VS NEW BUILDINGS IN SRI LANKA

M.K.M. Prabodani[1], S.S. Ranasinghe[2] and R.U. Halwathura[3]

ABSTRACT

The building construction sector stands out as a significant contributor to carbon emissions (CE). Among the sustainable practices available to mitigate this impact, adaptive reuse of historic buildings (ARHB) emerges as a viable option. In tropical developing countries, there is no quantitative research on ARHB and CE to evaluate the effectiveness of the use of ARHB as a solution. This study addresses this gap by conducting a comparative analysis of lifecycle CE between ARHB and an envisioned new building with an identical building envelope. Notably, this is the pioneering case study of its kind in Sri Lanka. A historic building within Galle Dutch Fort serves as the chosen case study, repurposed as a homestay to align with current local trends. Results indicate that annual carbon emission from the ARHB is 37.35 kg.CO_2/m^2, while from the envisioned new building amounting to 48.64 kg.CO_2/m^2, showcasing the significantly reduced environmental impact of ARHBs. In both scenarios, operational energy accounted for the highest proportion of CE, at 73.8% and 62.3% respectively. Subsequently, material production emerged as the next critical stage for both cases. Consequently, this study concludes that ARHB presents a more environmentally friendly option than new building construction. Moreover, the research suggests a focus on operational and material production stages to diminish environmental impact further. Strategies such as altering user behaviour, implementing microclimatic approaches, and embracing circular economic principles are recommended to achieve this objective. This study underscores the potential for ARHB to contribute significantly to sustainability efforts within the building construction sector.

Keywords: *Adaptive Reuse; Carbon Emissions; Historic Buildings; Tropical Developing Countries.*

1. INTRODUCTION

Amidst the global environmental crisis, numerous international agreements have been established since the 1970s to combat global warming and climate change, with a primary objective of reducing carbon emissions (CE) across all industries (Tae et al., 2011). The construction sector plays a pivotal role in realising the objectives set forth by the Paris Agreement, given its substantial contribution to energy consumption and greenhouse gas (GHG) emissions. Recent data from 2022 reveals that the building sector accounted for

[1] Department of Civil Engineering, University of Moratuwa, Sri Lanka, methsi.praba@gmail.com
[2] Department of Agricultural Engineering, University of Ruhuna, Sri Lanka, subashasranasinghe@gmail.com
[3] Department of Civil Engineering, University of Moratuwa, Sri Lanka, rangikauh@gmail.com

34% of total energy consumption and 37% of GHG emissions (International Energy Agency [IEA], 2023; Intergovernmental Panel on Climate Change [IPCC], 2024). Tracking the progress of building sector decarbonisation since 2015, the Global Buildings Climate Tracker (GBCT) highlights a substantial 40-point gap between the current state and the necessary decarbonisation levels to meet Paris Agreement targets (United Nations Environment Programme [UNEP], 2024). Currently, global building construction encompasses an expansive area of 250 billion square meters, with residential spaces occupying 80% of this land (IEA, 2023). Factors such as population growth, evolving lifestyles, changes in household sizes, and urbanisation exert pressure, and energy usage and carbon emissions are expected to witness a notable surge (IPCC, 2014). These trends escalate the urgent need for comprehensive strategies to mitigate environmental impacts and foster sustainable practices within the building construction sector.

The foundational stage in identifying mitigation strategies for GHG emissions and energy usage involves an assessment of current performance. These evaluations serve as the basis for selecting low CE methods, materials, and systems. The implementation of the Kyoto Protocol has promoted numerous studies focused on evaluating building energy usage and GHG emissions (Kumanayake & Luo, 2018). These investigations provide critical insights into the existing state of affairs, guiding the development of effective and targeted solutions to align with sustainability goals.

Throughout their lifecycle, buildings exert substantial environmental impacts, highlighting the critical need to prioritise higher energy efficiency and reduced CE in their design and planning. The significance of material production has attracted particular attention, with numerous studies shedding light on this aspect. For example, a study analysing 78 office buildings in China found that a staggering 75% of CE occurred during the material production stage is from major construction materials (Luo et al., 2016).

Operational use emerges as a critical stage with the highest environmental impact, as highlighted by Pomponi and Moncaster (2017). Despite existing benchmarks for operational energy performance, scholars stress the necessity of a comprehensive Life Cycle Assessment (LCA) to provide a holistic evaluation of environmental impacts (Izaola et al., 2023; Mastrucci et al., 2017). These findings collectively highlight the complex interplay of different lifecycle stages in influencing environmental impacts associated with buildings. They emphasise the importance of considering these factors in the context of sustainable building practices. A predominant proportion of researchers have conducted their investigations employing CE as a primary metric for quantifying environmental impact, owing to its direct association with climate change and global warming phenomena (Izaola et al., 2023; Tae et al., 2011).

The adaptive reuse buildings (ARB) stand out as a sustainable method that the construction sector can adopt to mitigate the environmental impact (Foster & Saleh, 2021; Pomponi & Moncaster, 2017). ARB presents a solution that significantly reduces energy usage and CE across various lifecycle stages, including demolition, material transportation, and waste disposal (Mansfield, 2009). Further highlighting the advantages of rehabilitation over new construction, Erlandsson and Borg (2003) utilised parameters such as acidification and global warming potential to demonstrate the environmental superiority of rehabilitation projects.

The majority of research on ARHB and its environmental impacts has been conducted in developed countries, where building design, energy use, and climate differ significantly from those in many tropical developing nations (Atmaca & Atmaca, 2015).

The findings derived from non-tropical developed countries cannot be directly applied to decision-making processes in tropical developing countries due to distinct differences in energy use and CE. In tropical developing countries, energy consumption is predominantly driven by cooling needs, often without proper insulation methods. Additionally, the energy sources available in these regions tend to have higher CE compared to those in developed countries (Ramesh et al., 2010). Furthermore, inefficient material production technologies prevalent in these areas contribute to increased embodied energy and CE.

Consequently, this research aims to clarify the current state of CE reduction in tropical developing countries, with a specific focus on Sri Lanka, through the application of ARHB. This study intends to conduct a comprehensive comparison of the carbon emissions associated with ARHB and those of a new building constructed using contemporary materials and methodologies. As the first case study of its kind in Sri Lanka, this research seeks to provide valuable insights into the advantages of ARHB in tropical developing regions facing similar challenges and conditions.

2. MATERIALS AND METHODS

2.1 SCOPE OF THE STUDY

The research will comprehensively analyse the whole lifecycle. The Life Cycle Assessment (LCA) framework adopted in this study follows the guidelines outlined in BS EN 15978:2011 (British Standards Institution, 2011). A consistent building lifespan of 50 years will be applied for comparative analysis, with the functional unit measured as square meters per annum. It is noteworthy that this study represents a pioneering effort in directly comparing CE between ARHB and newly constructed counterparts. By providing a quantitative assessment of environmental impact, this research aims to contribute significantly to the understanding of the sustainability implications associated with the ARHB.

2.2 CASE STUDY

This study focuses on the Galle Dutch Fort area, distinguished as the most prominent surviving Dutch colonial city outside Europe, showcasing a unique blend of European and South Asian architectural styles (Refer to Figure 1).

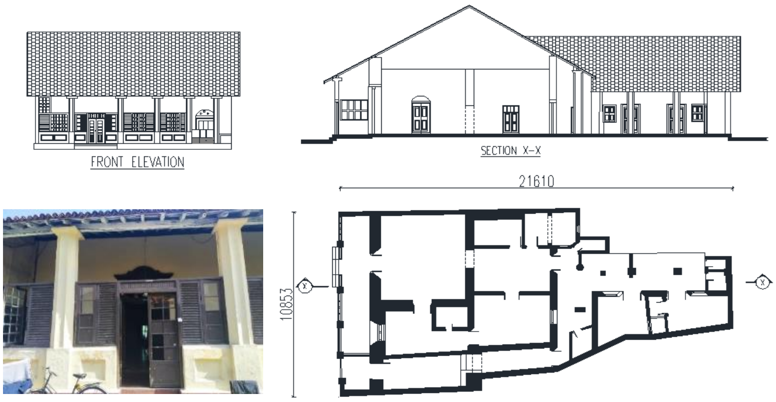


Figure 1: Selected House in Galle Fort

Designated as a UNESCO World Heritage site in 1988, Galle Fort has experienced notable functional transitions attributed to the thriving tourism industry accompanied by shifts in lifestyles and resident requirements (Rajapakse & Silva, 2020).

Through extensive site visits and interviews with experts and residents, No. XX in Galle Fort was identified as an ideal case study subject (Figure 1). This historic building, erected in 1680 and with a floor area of 181 m^2, has retained its original features over the centuries. The necessary information was collected from the Galle Heritage Foundation, the Divisional Archaeological Department, and residents of the area. Noteworthy findings from our investigations revealed a prevailing trend wherein many residential buildings in the area have transitioned into homestays. Subsequent analysis and discussions with construction experts led to the decision to propose homestay as the adaptive reuse option for No. XX, Galle Fort building. The following are the two cases considered in this research.

Case 1: Adaptive reuse of the selected house as homestay (Old Building)

Case 2: Envisioned new building with the same building envelope with the same purpose (New Building)

2.3 ESTIMATING LIFE CYCLE CARBON EMISSIONS

According to the LCA and carbon emissions coefficient (CEC) method, the total CE can be calculated using Equation 01 (Chau et al., 2015). The CE for each specific lifecycle component mentioned in Equation 01 will be further detailed in Equation 02 through 06.

$$C_{LC} = C_M + C_T + C_c + C_{O\&M} + C_D \qquad \textit{(Eq. 01)}$$

Where C_{LC} is the Total Lifecycle CE ($kgCO_2$), C_M is the CE in Material Production ($kgCO_2$), C_T is the CE in Transportation ($kgCO_2$), C_C is the CE in Construction ($kgCO_2$), $C_{O\&M}$ is the CE in Operation and Maintenance ($kgCO_2$), and C_D is the CE in Demolition ($kgCO_2$)

2.3.1 Material Production

Equation 02 gives the CE at the material production stage (Li et al., 2016). Using Equation 2, the carbon emissions (CE) for both the old building and the new building were calculated. The building blueprint was obtained from the Galle Heritage Foundation. Subsequently, the two buildings were modelled using Autodesk Revit software to extract the quantity of materials.

$$C_M = \sum_{i=1}^{n} \left(m_i \times f_{m,i}\right) \qquad \textit{(Eq. 02)}$$

n is the number of materials; m_i is the quantity of material of type i (kg or m^3), and $f_{m,i}$ is the embodied CEC of material type i ($kgCO_2kg^{-1}$ or $kgCO_2m^{-3}$). Sri Lanka does not have a dedicated database for CEC. Consequently, well-accepted databases and relevant literature were utilised for this study (Kumanayake & Luo, 2018; University of Bath UK, 2019).

2.3.2 Transportation

Equation 03 presents the formula for calculating CE from material transportation for the new building. T_i is the number of trips of the transport vehicle, D_i is the average two-way travel distance (km)and $f_{t,i}$ is the CEC for transporting the material type i ($kgCO_2km^{-1}$). Except ready-mixed concrete, other materials were transported using 8-ton trucks (Kumanayake & Luo, 2018). Emission coefficients were extracted from literature and other acceptable databases (Sri Lanka Sustainable Energy Authority, 2015). CE due to transportation for the old building was considered null, as manual methods were predominantly utilised for transportation during that era.

$$C_T = \sum_{i=1}^{n} \left(T_i \times D_i \times f_{t,i}\right) \qquad \textit{(Eq. 03)}$$

2.3.3 Construction

CE due to construction work was calculated using the methodology developed by Pinky Devi and Palaniappan (2014). Construction sector experts were interviewed to gather information on the general practices of the construction sector in Sri Lanka. Using Equation 04, CE from construction activities was calculated, for the new building. This value is considered as zero for the old building, as manual methods were used for construction activities during that time.

$$C_C = \sum_{i=1}^{k} \left(Q_i \times R_i \times f_{c,i}\right) \qquad \textit{(Eq. 04)}$$

When the number of construction activities is equal to k, Q_i is the quantity of on-site construction activity (m^3, m^2 or kg), R_i is the fuel/electricity usage rate for construction activity (Lm^{-3}, kWh kg^{-1} or kWh m^{-2}) and $f_{c,i}$ is the CEC for the energy source used for the construction activity (kg CO_2L^{-1} or kg CO_2kWh^{-1}).

2.3.4 Operation and Maintenance (O&M)

Two separate Design Builder models were used to calculate the operational energy for Case 1 and Case 2. There, energy requirements for cooling and lighting were extracted. In Sri Lanka, households generally get their energy requirement from the national grid. The method used by Roh and Tae (2016) was adopted, and Equation 05 was used to calculate the CE from the operational and maintenance of the building.

$$C_{O\&M} = \left(Q_e \times f_e \times Y\right) + \left(\sum_{i=1}^{j} \left(m_i \times r_i \times f_{m,i} \times \frac{Y}{R}\right)\right) \qquad \textit{(Eq. 05)}$$

Q_e is the electricity consumption per annum (kWh yr^{-1}), f_e is the CEC of the Electricity (kg CO_2 kWh^{-1}), and Y is the lifespan in years. j is the number of material types needed for maintenance and repair. m_i is the quantity of i^{th} material (kg or m^3), r_i is the rate of repair, f_{mi} is the CEC of the i^{th} material ($kgCO_2kg^{-1}$ or $kgCO_2m^{-3}$) and R is the repair intervals (years).

2.3.5 Demolition

In the context of demolition, Case 1 considered the demolition of the building at the end of its lifespan. In contrast, Case 2 involved the demolition of the old building at the beginning and the demolition of the new building at the end of its lifespan. Here, under demolition part CE in the demolition activities, transportation of demolished materials and disposal as landfilling was considered (Equation 06).

$$C_D = \sum_{i=1}^{r}(Q_{d,i} \times f_{d,i}) + [(T \times D \times f_{t,i}) + (M \times f_i)] \quad \textit{(Eq. 06)}$$

In demolition, $Q_{d,i}$ is the quantity of r type demolition, $f_{d,i}$ is the CEC of the r type demolition procedure, T is the number of trips to transport demolished waste, D is the Two-way distance between the building site and the landfill (km), $f_{t,i}$ is the CEC Transporting waste (kg CO_2 km^{-1}), M is the demolished material quantity (kg) and fi is the CEC of the used landfilling machinery ($kgCO_2kg^{-1}$).

3. RESULTS AND DISCUSSION

3.1 MATERIAL PRODUCTION

The predominant materials utilised in the old building are clay, granite, limestone, timber, glass, sand, and limestone. In contrast, the principal building materials in the new constructions consist of clay bricks, concrete, reinforcement, mortar, clay tiles, paint, and granite. Table 1 provides details on the CE values during the material production stage for the old building, while Table 2 presents corresponding values for the new building within the same phase. These tables offer a comparative overview of the environmental impact associated with material production, shedding light on the CE attributed to different construction materials used in the respective buildings.

Table 1: CE at the material production of the old building

Material	Weight	Weight %	f_{mi}	Carbon Emission	Carbon Emission
	kg	%	$kgCO_2/kg$	$kgCO_2$	%
Clay	130,634	16.2	0.255	33,312	35.2
Granite	466,441	58.0	0.079	36,849	38.9
Limestone	150,387	18.7	0.09	13,535	14.3
Timber	3,336	0.4	0.306	1,021	1.1
Glass	125	0.0	1.44	180	0.2
Sand	41,040	5.1	0.007	287	0.3
Lime	12,239	1.5	0.78	9,546	10.1
Total	**804,202**	**100**		**94,729**	**100**

Table 2: CE at the material production of the new building

Material	Weight	Weight %	f_{mi}	Carbon Emission	Carbon Emission
	kg	%	$kgCO_2/kg$	$kgCO_2$	%
Clay Bricks	193,500	35.7	0.24	46,440	57.0
Concrete	24,567	4.5	0.123	3,022	3.7
Reinforcement	319	0.1	1.45	463	0.6
Mortar	21,173	3.9	0.2	4,235	5.2
Clay Tiles	6,411	1.2	0.255	1,635	2.0
Ceramic Tiles	1581	0.3	0.78	1,233	1.5
Paint	418	0.1	2.91	1,216	1.5
Granite	293,858	54.2	0.079	23,215	28.5
Total	**541,827**	**100**		**81,458**	**100**

The material weight of the old building was measured as 4443.1 kg/m^2, whereas the material weight of the new building was 2993.5 kg/m^2. This discrepancy primarily arose from the greater weight of granite in the old building. The material weight of the new building aligns with findings from previous studies (Kumanayake & Luo, 2018; Pinky Devi & Palaniappan, 2014). In the material production stage, the CE of the old building amounted to 523.37 $kg.CO_2/m^2$, whereas the corresponding value for the new building was 450.04 $kg.CO_2/m^2$. Once more, this variance was attributable to the higher mass of granite in the old building. Notably, in the old building, granite accounted for the highest percentage of CE, whereas in the new building, clay bricks exhibited the highest emissions.

3.2 MATERIAL TRANSPORTATION

During ancient times, construction materials were typically transported to the construction site via canal or manual means, as indicated by gathered historical data. The calculation of material transportation emissions for the new building is presented in Table 3. Notably, the highest CE was attributed to clay brick transportation, accounting for 74.5% of the total emissions related to transportation in the new building. The CE due to transportation amounted to 1.05 $kg.CO_2/m^2$ in the new building, while this value was assumed to be negligible in the case of the old building.

Table 3: CE at the transportation stage

Material	Type of Vehicle	No of Trips	Dista-nce	Mileage	Fuel Factor	$f_{(t,i)}$	Carbon Emission
			km	l/km	kg CO_2/l	$kgCO_2/km$	$kgCO_2$
Clay Bricks	8-ton truck	24	5	0.22	2.68	0.59	141.50
Reinforcement	8-ton truck	1	5	0.32	2.68	0.86	8.58
Mortar	8-ton truck	3	5	0.29	2.68	0.78	23.32
Clay Tiles	8-ton truck	3	5	0.17	2.68	0.46	13.67
Ceramic Tiles	8-ton truck	1	2	0.17	2.68	0.46	1.82
Paint	8-ton truck	1	2	0.09	2.68	0.24	0.96
Total							**190**

3.3 CONSTRUCTION ACTIVITIES

The construction activities considered for the new building included concrete mixing, concrete compaction, rebar works, and site lighting. Consultation with industry experts was conducted to gather construction norms specific to Sri Lanka. Notably, site lighting emerged as the activity contributing the highest percentage to the CE, accounting for 99% of the total emissions. The calculation summary is shown in Table 4.

Table 4: CE from construction activities

Activity	Energy use rate		Quantity of Work		Amount of Energy		f $kgCO_2$/l or kg CO_2/kWh	Carbon Emission $kgCO_2$
Site mixed concrete	0.5	l/m^3	10.24	m^3	5.12	l	2.58	13.20
Concrete Compaction	0.21	l/m^3	10.24	m^3	2.15	l	2.58	5.55
Rebar and reinforcement	2	kWh.MT^{-1}	0.319	MT	0.64	kWh	0.6896	0.44
Site Lighting	26	kWh.m^{-2}	181	m^2	4706	kWh	0.6896	3245.26
Total								**3,264**

The CE due to construction activities for the new building was calculated at 18.04 kg.CO_2/m^2. For the old building, emissions in the construction stage were assumed to be negligible.

3.4 OPERATION AND MAINTENANCE

3.4.1 CE due to Operational Activities

For the two cases, two separate buildings were modelled using DesignBuilder software to assess their energy requirements. The results indicated that for the new building, the estimated energy requirement for the entire lifespan was 488,700 kWh, whereas for the old building, it was 470,600 kWh. The total Carbon Emission (CE) from the new building was calculated in 1862 kg.CO_2/m^2, while for the old building, it was 1793 kg.CO_2/m^2. The Carbon Emission Coefficient (CEC) of the electricity grid in Sri Lanka was considered to be 0.6896 kg.CO_2/kWh according to the Sri Lanka Sustainable Energy Authority (2015).

3.4.2 CE due to Maintenance

During the maintenance stage of the new building, both painting and tile replacement were taken into account. However, painting work was only considered for the old building, as it is equipped with granite tiles that do not require replacement within the next 50 years. The painting frequency was set at five years, with a repair rate of 1. For tile replacement, the repair frequency was set at ten years, with a repair rate of 0.1 (Kumanayake & Luo, 2018). The Carbon Emissions (CE) associated with maintenance were evaluated at 56 kg.CO_2/m^2 for the new building and 54 kg.CO_2/m^2 for the old building.

3.5 DEMOLITION

In the demolition phase, only deconstruction, waste transportation, and landfilling were considered. For deconstruction, it was assumed that a Backhoe (1 m^3) and a Giant Breaker (0.7 m^3) were utilised. Additionally, transportation was assumed to employ a 20-ton dump truck, while landfilling involved the use of a Dozer and a Compactor. The calculated CE for demolition were 60.13 kg.CO_2/m^2 for the old building and 18.54 kg.CO_2/m^2 for the new building. The higher CE value for the old building is attributed to its greater material weight, whereas the new building is assumed to be constructed on top of the old wall foundation.

3.6 TOTAL CARBON EMISSION

The carbon emissions (CE) at each stage for both cases are presented, with the total carbon emission percentages illustrated in Figure 2. In both cases, operational energy accounted for the highest percentages, representing 73.8% for Case 1 and 62.3% for Case 2. The second-largest contributions were from the material production stage, comprising 21.5% for Case 1 and 32.6% for Case 2. In Case 1, construction and transportation emissions were assumed to be zero, while in Case 2, transportation emissions were almost negligible in percentage terms. For Case 2, the construction stage's CE was primarily due to site lighting.

The percentages of CE in the maintenance stage were very similar between the two cases. A difference in this stage was observed as the old building did not have ceramic floor tiles, and the available granite tiles did not require replacement or repair even within the next 50 years. In the demolition stage, the main difference was the need to demolish the new house in addition to the demolition of the old house in the initial stage. These findings are consistent with previous studies (Kumanayake & Luo, 2018).

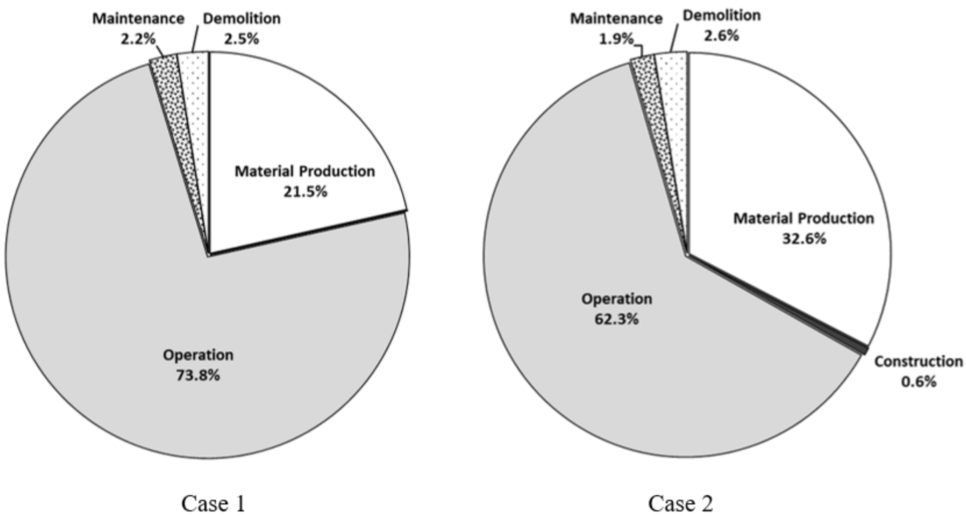


Figure 2: CE percentages for each lifecycle stages

For Case 1, the total CE was 2430 kg.CO_2/m^2, while for Case 2, it was 2989 kg.CO_2/m^2, resulting in a difference of 559 kg.CO_2/m^2. Further analysis was conducted considering the lifespan of the buildings. In this analysis, the material production for the old building was considered from 1680. It was found that the CE of material production after 50 years of lifespan is nearly zero per annum in the old building. For Case 1, the total CE per annum was 37.35 kg.CO_2/m^2, and for Case 2, it was 48.64 kg.CO_2/m^2. These results provide insights into the environmental impact of the buildings over their lifespan, highlighting the significance of operational energy and material production in contributing to carbon emissions. This study provides a quantitative analysis, demonstrating that each life cycle stage of ARHB exhibits lower CE compared to new buildings.

In the Sri Lankan context, there are no directly comparable results. However, Kumanayake and Luo (2018) conducted a study on a university building, which resulted in 31.8 kg CO2/m² per annum. This building was a reinforced structure with seven floors. A similar study in Turkey on a residential building calculated the CE to be 48.87 kg CO2/m² per annum (Atmaca & Atmaca, 2022). Additionally, research in Spain and Portugal reported CE values of 49.33 kg CO_2/m² per annum and 43.34 kg CO_2/m² per annum, respectively (Ortiz-Rodríguez et al., 2010; Rossi et al., 2012).

3.7 CARBON EMISSION REDUCTION MEASURES

Previous studies have also shown a similar pattern of CE for each lifecycle stage, with the operational phase often yielding the highest impact, followed by material production. Notably, building operational energy consumption, particularly for thermal and visual comfort, is significant (Pathirana et al., 2019). Properly applied passive design principles can substantially reduce building energy requirements before considering mechanical systems (Bai et al., 2015). Studies have highlighted that occupants' positive attitudes can significantly reduce operational carbon emissions (Delzendeh et al., 2017). Furthermore, microclimatic modifications achieved through landscaping, natural ventilation, and other passive design strategies (Rajapaksha & Halwatura, 2020) can be utilised to decrease energy consumption during the operational phase.

Replacing conventional materials with mass timber in half of new constructions can reduce global emissions by 9% (Himes & Busby, 2020). Utilising wooden frames instead of aluminium can cut emissions by half and additionally lowers energy demand due to wood's lower heat transmittance properties (Saadatian et al., 2021).

In light of traditional linear economic principles prevalent in the building sector, there is a growing need to transition towards circular economic principles that promote the 3R concept: reduce, reuse, and recycle (Pomponi & Moncaster, 2017). Additionally, incorporating energy-efficient building materials can further diminish the environmental impact of the construction industry. These insights highlight the multifaceted approaches needed to foster a more sustainable and environmentally conscious building sector.

4. CONCLUSIONS

This study aimed to compare the CE of ARHB versus newly constructed buildings. The selected case study building, situated in Galle Dutch Fort, underwent two scenarios: Case 1 involved repurposing the existing building into a homestay. In contrast, Case 2 envisioned constructing a new building with contemporary materials and technology for the same purpose. The CE of both cases was then compared.

Results revealed that Case 1, the ARHB scenario, exhibited a lower annual CE of 37.35 kg.CO_2/m^2 compared to Case 2's CE of 48.64 kg.CO_2/m^2 per annum, demonstrating the reduced environmental impact of ARHB over demolition and new construction. Notably, the analysis of the building's entire lifecycle addressed a previous argument regarding historic buildings' operational energy impact, revealing that the selected building's operational energy was lower than that of the newly constructed building, likely due to its thick walls (approximately 1m).

Furthermore, the study highlighted the operational phase as the most critical in a building's lifecycle concerning CE. Material production stages were also identified as crucial, suggesting that reusing old buildings can significantly reduce CE in both material production and demolition stages. The reuse of historic buildings goes beyond preservation for heritage and architectural significance. These buildings hold personal and cultural identities for communities. However, poorly designed ARHB projects can jeopardise the social and cultural values of these buildings. Hence, it is imperative to assess a building's significance before opting for reuse. To mitigate environmental impacts, the study suggests employing passive building design strategies, fostering positive occupant attitudes, introducing circular economic strategies, utilising locally available energy-efficient materials, and promoting the 3R (Reduce, Reuse, Recycle) concept.

The limitations of this research include the scarcity of recognised literature, challenges in locating building drawings, and potential difficulties in information collection due to the migration of native people. A major limitation of this research was the absence of a national database for CEC, necessitating the use of coefficients from regional literature and global databases. Therefore, there is a strong recommendation to develop a national database for CEC in Sri Lanka to enhance the quality and reliability of future research in this area.

5. ACKNOWLEDGEMENTS

The authors would like to thank the owner of the No. XX, Galle Fort Building.

6. REFERENCES

Atmaca, A., & Atmaca, N. (2015). Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey. *Energy and Buildings, 102*, 417–431. https://doi.org/10.1016/j.enbuild.2015.06.008

Atmaca, A., & Atmaca, N. (2022). Carbon footprint assessment of residential buildings, a review and a case study in Turkey. *Journal of Cleaner Production, 340*. https://doi.org/10.1016/j.jclepro.2022.130691

Bai, G., Gong, G., Yu, C. W., & Zhen, O. (2015). A combined, large, multi-faceted bulbous façade glazed curtain with open atrium as a natural ventilation solution for an energy efficient sustainable office building in Southern China. *Indoor and Built Environment, 24*(6), 813–832. https://doi.org/10.1177/1420326X15602048

British Standards Institution. (2011). *BS EN 15978:201: Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*. British Standards Institution, London. https://knowledge.bsigroup.com/products/sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method?version=standard

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy, 143*, 395-413. https://doi.org/10.1016/j.apenergy.2015.01.023

Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews, 80*, 1061–1071. https://doi.org/10.1016/j.rser.2017.05.264

Erlandsson, M., & Borg, M. (2003). Generic LCA methodology applicable for buildings, constructions and operation services—Today practice and development needs. *Building and Environment, 38*(7), 919–938.https://doi.org/10.1016/S0360-1323(03)00031-3

Foster, G., & Saleh, R. (2021). The circular city and adaptive reuse of cultural heritage index: Measuring the investment opportunity in Europe. *Resources, Conservation and Recycling, 175*, 105880. https://doi.org/10.1016/j.resconrec.2021.105880

Himes, A., & Busby, G. (2020). Wood buildings as a climate solution. *Developments in the Built Environment, 4*, 100030. https://doi.org/10.1016/j.dibe.2020.100030

International Energy Agency (IEA). (2023). *Tracking clean energy progress 2023*. International Energy Agency. https://www.iea.org/reports/tracking-clean-energy-progress-2023

Intergovernmental Panel on Climate Change (IPCC). (2014). *AR5 Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar5/wg3/

Izaola, B., Akizu-Gardoki, O., & Oregi, X. (2023). Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building. *Sustainable Production and Consumption, 40*, 252–264. https://doi.org/10.1016/j.spc.2023.07.001

Kumanayake, R., & Luo, H. (2018). Life cycle carbon emission assessment of a multi-purpose university building: A case study of Sri Lanka. *Frontiers of Engineering Management, 5*(3). https://doi.org/10.15302/J-FEM-2018055

Li, D., Cui, P., & Lu, Y. (2016). Development of an automated estimator of lifecycle carbon emissions for residential buildings: A case study in Nanjing, China. *Habitat International, 57*, 154–163. https://doi.org/10.1016/j.habitatint.2016.07.003

Luo, Z., Yang, L., & Liu, J. (2016). Embodied carbon emissions of office building: A case study of China's 78 office buildings. *Building and Environment, 95*, 365–371. https://doi.org/10.1016/j.buildenv.2015.09.018

Mansfield, J. (2009). Sustainable refurbishment: Policy direction and support in the UK. *Structural Survey, 27*(2), 148–161. https://doi.org/10.1108/02630800910956470

Mastrucci, A., Marvuglia, A., Leopold, U., & Benetto, E. (2017). Life cycle assessment of building stocks from urban to transnational scales: A review. *Renewable and Sustainable Energy Reviews, 74*, 316–332. https://doi.org/10.1016/j.rser.2017.02.060

Ortiz-Rodríguez, O., Castells, F., & Sonnemann, G. (2010). Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. *Science of The Total Environment, 408*(12), 2435–2443. https://doi.org/10.1016/j.scitotenv.2010.02.021

Pathirana, S., Rodrigo, A., & Halwatura, R. (2019). Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. *International Journal of Energy and Environmental Engineering, 10*, 107–120. https://doi.org/10.1007/s40095-018-0295-3

Pinky Devi, L., & Palaniappan, S. (2014). A case study on life cycle energy use of residential building in Southern India. *Energy and Buildings, 80*, 247–259. https://doi.org/10.1016/j.enbuild.2014.05.034

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production, 143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Rajapakse, A., & Silva, K. D. (2020). *Transient heritage values, conflicting aspirations, and endangered urban heritage in the Historic Galle Fort, Sri Lanka.* In K. D. Silva (Ed.), *The routledge handbook on historic urban landscapes in the Asia-Pacific* (pp. 462–475). Routledge, London.

Rajapaksha, M., & Halwatura, R. U. (2020). Poro-therm clay wall panel system for indoor cooling. *2020 From innovation to impact (FITI)*, 1–6. https://doi.org/10.1109/FITI52050.2020.9424896

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings, 42*(10), 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

Roh, S., & Tae, S. (2016). Building simplified life cycle CO2 emissions assessment tool (B-SCAT) to support low-carbon building design in South Korea. *Sustainability, 8*(6), 567. https://doi.org/10.3390/su8060567

Rossi, B., Marique, A.F., Glaumann, M., & Reiter, S. (2012). Life-cycle assessment of residential buildings in three different European locations, basic tool. *Building and Environment, 51*, 395–401. https://doi.org/10.1016/j.buildenv.2011.11.017

Saadatian, S., Freire, F., & Simões, N. (2021). Embodied impacts of window systems: A comparative assessment of framing and glazing alternatives. *Journal of Building Engineering*, *35*, 102042. https://doi.org/10.1016/j.jobe.2020.102042

Sri Lanka Sustainable Energy Authority. (2015). *Sri Lanka energy balance 2015: An analysis of energy sector performance.* Sri Lanka Sustainable Energy Authority. https://www.scribd.com/document/447373758/2015-Energy-Balance

Tae, S., Shin, S., Woo, J., & Roh, S. (2011). The development of apartment house life cycle CO2 simple assessment system using standard apartment houses of South Korea. *Renewable and Sustainable Energy Reviews*, *15*(3), 1454–1467. https://doi.org/10.1016/j.rser.2010.09.053

United Nations Environment Programme (UNEP). (2024). *Global status report for buildings and construction - beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector.* https://doi.org/10.59117/20.500.11822/45095

University of Bath UK. (2019). *Embodied carbon - The ICE database.* Circular Ecology. https://circularecology.com/embodied-carbon-footprint-database.html

Ikuabe, M., Aigbavboa, C., Ebekozien, A. and Adekunle, S., 2024. Making a case for foreign direct investments in the South African construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 747-754. DOI: https://doi.org/10.31705/WCS.2024.59. Available from: https://ciobwcs.com/papers/

MAKING A CASE FOR FOREIGN DIRECT INVESTMENTS IN THE SOUTH AFRICAN CONSTRUCTION INDUSTRY

Matthew Ikuabe[1], Clinton Aigbavboa[2], Andrew Ebekozien[3], and Samuel Adekunle[4]

ABSTRACT

The construction industry plays a significant role in the aggregate output formation of any nation's economy. Financing construction projects are capital intensive, and most developing countries' low gross domestic savings necessitate seeking alternative routes for construction project financing. One such route is encouraging the flow of Foreign Direct Investments (FDI) into the construction industry in South Africa. Therefore, this paper investigates the factors influencing the flow of FDI into the South African construction industry. A quantitative technique was employed using professionals in the built environment as the target population. Data were elicited with the aid of a well-structured questionnaire, while data analysis was conducted with appropriate methods, which include the Cronbach alpha test, mean item score, and one-sample t-test. The findings from the study make theoretical contributions to the conversation on ways of boosting construction financing for improved economic development. It provides guidance to relevant stakeholders and prospective investors on the key factors influencing the flow of FDI in the South African construction industry.

Keywords: *Construction Industry; Developing Economy; Economic Development; Foreign Direct Investment; South Africa.*

1. INTRODUCTION

The importance of the construction industry in the economy of any nation cannot be overemphasised. According to Rangelova (2015), the construction industry is a major contributor to the economic growth of most nations due to its role in the development process. The industry is characterised by the formation of physical assets utilised by other sectors, making up the economy of any nation. This spans industries, power systems, schools, houses, offices, transportation systems, agriculture systems, utility infrastructure

[1] Senior Lecturer, School of Construction Economics and Management, University of the Witwatersrand, South Africa, matthew.ikuabe@wits.ac.za

[2] Professor, SARChI in Sustainable Construction Management and Leadership in the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa, caigbavboa@uj.ac.za

[3] Postdoctoral Research Fellow, SARChI in Sustainable Construction Management and Leadership in the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa, ebekoandy45@yahoo.com

[4] Postdoctoral Research Fellow, SARChI in Sustainable Construction Management and Leadership in the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa, sadekunle135@gmail.com

systems, retail outlets, and townships. The construction industry in South Africa is important as it is a major driver of the nation's Gross Domestic Product (GDP) due to its paramount contribution to socio-economic development (Anugwo et al., 2018; Ikuabe et al., 2022a). This is attained by providing the needed infrastructure, employment, and sanctuary. Notwithstanding the setback brought by the advent of the coronavirus (COVID-19) pandemic in 2020, the construction industry contributed R83 billion ($5 billion approximately) to the nation's GDP ("Value added to gross domestic product (GDP) by the construction industry in South Africa from 2016 to 2023", 2024). Furthermore, the industry employs a large pool of formal and informal labour (Ikuabe et al., 2024; *Gross domestic product: Third quarter 2009,* 2009). All of this highlights the importance of the construction industry to the South African economy.

It has been noted that the current funding model of the South African construction industry is not viable enough to cater to the country's infrastructural deficit (Balogun et al., 2016). Therefore, it impedes the attainment of massive infrastructural output as delivered in most developed countries. To compound this, the construction industry experienced a drop of 0.8% in its quarter-to-quarter assessment of 2017 ("Statistical release P0441: Gross domestic product, fourth quarter 2017", 2018). Considering the government's initiative to eliminate poverty and inequality by 2030 through its National Development Plan (NDP), the construction industry is expected to play a strategic role in its actualisation. Therefore, there is a need to consider other viable options or models of funding for the industry to drive the much-needed infrastructural delivery and provide employment for the general populace. Besides, the country's downgraded rating to BB- by Fitch Ratings due to its unceasing decline in gross domestic savings ("Fitch affirms South Africa at 'BB-'; Outlook negative", 2021), thus giving credence to the notion that the country's economy is experiencing a despondency. Consequently, long-term interest rates are most likely to experience an upsurge and hurt business interest in the country.

The call for alternative funding models in the construction industry is fast gaining attention, and one viable option is FDI. According to Ikuabe et al. (2021), FDI is a cross-border investment undertaken by a country's resident entity to obtain a long-term interest in a business concern of another country. These investments are usually in the form of green investment or Merger and Acquisition (M&A), which entails the acquisition of an existing interest. The host country tends to benefit from the FDI by transferring technology, entrepreneurial skills, and capital flows (Ebekozien et al., 2015; Ikuabe et al., 2022b). Consequently, providing an equilibrium for the host nation by shoring up its inadequacies. With this framework, construction is expected to experience a boost in the financial demands for the delivery of infrastructural projects and their concomitant benefits. This is the basis for which this study intends to ascertain the factors affecting FDI in the South African construction industry and unravel a roadmap for boosting the flow of FDI in the construction industry in South Africa.

2. LITERATURE REVIEW

Most developing countries, such as South Africa, have experienced dwindling government spending on infrastructure in recent years, necessitating adopting other viable options such as FDI. Results have shown that FDI can stimulate economic growth and boost productivity in the host nation (Ikuabe et al., 2021). This has led to most governments' encouragement of FDI inflow (UNCTAD, 2014). However, various factors determine attracting FDI from prospective investors in different countries. According to

Abdelkader (2015), investors are morally opposed to investing in a country with economic and political uncertainty. FDI is hampered by economic barriers and risk concerns, as well as by political and social uncertainty and government policies that must be adhered to (Enoma & Mustapha, 2010). Foreign investors place a premium on economic transparency and trustworthiness for developing countries to attract FDI. Foreign investors are concerned about risks such as market literacy and certainty (Kahraman, 2011). All of this will significantly impact the country's economy, resulting in a lack of investment (Liu & Pang, 2009). External factors influencing a country’s macroeconomic and monetary policies are well-recognised as significant determinants of the flow of FDI (Karim & Azman-Sainib, 2013). Liquidity and the structure of debt repayment for an economy’s enterprises are essential elements that significantly impact investment opportunities. Organisations’ expenditures are expected to rise due to delays in receiving receivables, and new investment projects may be significantly restricted (Bartels et al., 2009). Furthermore, any nation's taxation policy directly impacts the rate of return on an investment made (Santoro & Wei, 2012), which plays a vital role in the flow of FDI.

According to Nnadi and Soobaroyen (2015), inflation is a sign of macroeconomic instability, and a higher rate may scare off current and potential foreign investments. Inflation in the host country reduces FDI by eroding the value of foreign enterprises' earnings. In contrast, low inflation reduces lending rates and thus lowers the cost of capital for foreign investors (Sayek, 2009). Moreover, Antras et al. (2009) opined that weak financial markets decrease the quantity and scope of foreign organisations’ activities in the host country since they cannot raise appropriate capital from financial markets and rely too heavily on the parent company. Bartels et al. (2009) stated that a stable financial market provides potential international investors with efficient, timely, and cost-effective information, thereby increasing the flow of FDI into the host country. Furthermore, the inflexible exchange rate regime creates uncertainty among investors, reducing the quantity of international investment. In addition, it is thought to be more inflationary than a fixed exchange rate regime and might lead to unstable speculation. Calvo and Reinhart (2002) observed that the impacts and options for exchange rate regimes for emerging nations differ significantly from those for developed nations. Developing countries are frequently confronted with issues of legitimacy and limited access to foreign markets. Additionally, political instability has impacted many developing countries, which is not a new issue. Internal conflicts outnumber international conflicts (Collier & Hoeffler, 2004). Political unrest negatively influences people's lives and property, as well as deterring economic activity. Political insecurity is characterised by uncertainty, which hurts developing-country development outcomes by distorting investment opportunities.

3. METHODOLOGY

This study aims to evaluate the factors influencing the flow of FDI into the construction industry in South Africa. The study employed a positivist philosophical stance by utilising a quantitative approach that adopted a questionnaire to collect data. The target respondents of the study comprised built environment professionals, i.e., architects, quantity surveyors, construction managers, construction project managers, and engineers, while the study area was Gauteng province of South Africa. The questionnaire comprised two sections. The first retrieved data on the respondents' background information, while the second inquired about the factors influencing FDI in the South African construction industry by providing the respondents with a list of the factors and asking them to rate their significance using a Likert scale. A total of 90 questionnaires were distributed via electronic means to the target respondents who knew about foreign investments. In contrast, 71 were returned and passed appropriately for analysis. The method of data analysis used by the study was percentage, mean item score, and one-sample *t*-test. The Cronbach alpha test was employed to affirm the reliability and validity of the research instrument. The analysis provided an alpha value of 0.892, which implied the reliability and validity of the research instrument (Tavakol & Dennick, 2011).

4. RESULTS AND DISCUSSION

4.1 BACKGROUND INFORMATION OF RESPONDENTS

The analysis of the data obtained on the background information of the respondents shows that out of a total of 71 respondents, 46% possess a bachelor's degree as their highest educational qualification, while 14% have a master's degree, and 1% have a doctorate. Based on the professional designation of the respondents, 31% of the total respondents were Engineers, 18% were Construction Managers, and 13% were Quantity Surveyors. Besides, 54% of the total respondents have four to eight years of working experience, 31% have nine to 15 years of working experience, and 10 % have up to three years of working experience. Furthermore, 67% of the respondents are male, while 33% are female.

4.2 FACTORS AFFECTING FDI IN THE SOUTH AFRICAN CONSTRUCTION INDUSTRY

The review of extant literature revealed twelve factors that are influential to FDI in the construction industry. Using the one-sample *t*-test, the study attempts to determine the significance of the identified factors as rated by the respondents in the questionnaire. Consequently, a null hypothesis was set, indicating that a factor is insignificant when its mean value is less than or equal to the population mean (H_0: $U \leq U_0$). The alternate mean stipulates that a factor is significant when its value exceeds the population mean (H_a: $U > U_0$). The study adopted 3.50 as the fixed population, while 95% was set as the significance level as this conforms to the conventional confidence level (Pallant, 2020). By implication, when the mean value of a factor is above 3.50, it is deemed significant. Conversely, when the mean value of a factor is less than or equal to 3.50, it is deemed insignificant. Table 1 shows the result of the two-tailed *p*-value of the one-sample *t*-test, indicating the significance of the identified factors influencing FDI in the South African construction industry.

Table 1: One-sample test

Factors	Test Value = 3.50					
					95% Confidence Interval of the Difference	
	T	df	Sig. (2-tailed)	Mean Difference	L	U
Tax rate	4.338	70	.000	.149	.8268	1.7262
Size of market demand	5.193	70	.000	.628	.5122	1.4936
Legislations	2.227	70	.000	.227	.3336	1.1183
Exchange rate stability	1.092	70	.000	.619	.2836	1.3856
Return on investment	1.185	70	.000	.621	.7294	1.0727
Accessibility of resources	5.974	70	.000	.296	.3119	.7381
Market transparency	4.297	70	.000	.774	.0728	1.2295
Macroeconomic stability	6.374	70	.000	.638	.7916	1.3925
Economic certainty	7.379	70	.000	.728	.4007	.5924
Political stability	2.058	70	.000	.375	.3654	1.0287
Market availability	4.297	70	.000	.275	.8202	1.3392
Availability of human capital	5.007	70	.000	.426	.5737	1.4925

L=Lower Limit; U=Upper Limit

The result of the analysis conducted on the factors affecting FDI in the South African construction industry is shown in Table 2.

Table 2: Summary of t-test showing the ranking of the factors influencing FDI in the construction industry

Factors	Mean	Std. Deviation	Sig. (*2-tailed*)	Rank
Return on investment	4.46	1.481	.000	1
Size of market demand	4.31	1.736	.000	2
Macroeconomic stability	4.22	0.274	.000	3
Market availability	4.18	1.085	.000	4
Tax rate	3.97	1.117	.000	5
Exchange rate stability	3.92	0.683	.000	6
Economic certainty	3.89	1.162	.000	7
Accessibility of resources	3.89	0.749	.000	8
Political stability	3.72	0.374	.000	9
Legislations	3.71	1.004	.000	10
Market transparency	3.68	0.238	.000	11
Availability of human capital	3.63	1.184	.000	12

Evidence from Table 2 indicates that all the identified factors have a mean value above 3.50, the fixed population stipulated for the study. Moreover, it is shown that all the identified factors have a *p*-value that is less than 0.05 at a 95% confidence level, thereby indicating that all the factors are significant. The result of the analysis shows that the most significant factors are return on investment (*MIS=4.46, sig.=0.000*), size of market demand (*MIS=4.31, sig.=0.000*), macroeconomic stability (MIS=4.22, sig.=0.000), market availability (*MIS=4.18, sig.=0.000*), and tax rate (*MIS=3.97, sig.=0.000*). While the least significant factors are the availability of human capital (*MIS=3.63, sig.=0.000*) and market transparency (*MIS=3.68, sig.=0.000*). These findings are in tandem with the notion that all investors are considerably particular about the prospective yields of their investments. This is supported by Ikuabe et al. (2021), affirming that one of the motivating drives that boost investors' confidence in undertaking FDI is the guarantee of good financial returns. Factors influencing a country's macroeconomic and monetary policies are well-recognised as significant determinants of the flow of FDI (Karim & Azman-Sainib, 2013). Liquidity and the structure of debt repayment for an economy's enterprises are essential elements that significantly impact investment opportunities. Furthermore, any nation's taxation policy directly impacts the rate of return on an investment made (Santoro & Wei, 2012), which ultimately plays a vital role in the flow of FDI. This is reflected in the outcome of the current study, thereby affirming that the tax rate of a developing economy such as South Africa would be considered influential in investors' choice of destination.

5. CONCLUSIONS AND RECOMMENDATIONS

FDI has been touted as a panacea to the drawbacks characterised by the underfunding of infrastructure projects resulting from governments' low gross domestic savings in most developing countries. It was on this premise that the current study evaluated factors influencing the inflow of FDI in the South African construction industry, using Gauteng Province as the study area. A review of extant literature was conducted, which revealed twelve factors, and subsequently presented to the target respondents of the study for rating based on their significance. Results from the data analysed showed that the most significant factors are return on investment, size of market demand, macroeconomic stability, market availability, and tax rate. The South African construction industry, along with other sectors of the economy, continues to grapple with the repercussions of the COVID-19 pandemic, which severely disrupted many activities in the industry. Hence, it is safe to say that one viable way of placing the industry on a recovery trajectory is the encouragement of FDI in the sector. Therefore, the outcome of this research is timely as it posits the influential factors in the flow of FDI in the South African construction industry. Accordingly, this study recommends that government agencies and policymakers should aid in promulgating laws, policies, and frameworks that would boost return on investments, thereby boosting the inflow of FDI into the South African construction industry.

6. REFERENCES

Abdelkader, H. E. M. (2015, October). Woking paper series: Political instability, uncertainty, democracy, and economic growth in Egypt. *Economic Research Forum Working Paper*. *953,* 2-18. https://erf.org.eg/app/uploads/2015/12/953.pdf

Antras, P., Desai, M. A., & Foley, C. F. (2009). Multinational firms, FDI flows, and imperfect capital markets. *The Quarterly Journal of Economics, 124*(3), 1171-1219. https://doi.org/10.1162/qjec.2009.124.3.1171

Anugwo, I. C., Shakantu, W., Saidu, I., & Adamu, A. (2018). Potentiality of the South African construction SMME contractors globalizing within and beyond the SADC construction markets. *Journal of Construction Business and Management*, *2*(1), 41-49. https://doi.org/10.15641/jcbm.2.1.73

Balogun, O. A., Ansary, N., & Agumba, J. N. (2016). Investigating challenges and barriers facing construction of small, medium-sized enterprises in credit accessibility in the South African construction industry. *International conference of socio-economic researchers ICSR 2016, Serbia.* (pp. 45-65). https://hdl.handle.net/10210/215071

Bartels, F. L., Alladina, S. N., & Lederer, S. (2009). Foreign direct investment in Sub-Saharan Africa: Motivating factors and policy issues. *Journal of African Business, 10*(2), 141-162. https://doi.org/10.1080/15228910903187791

Calvo, G. A., & Reinhart, C. M. (2002). Fear of floating. *The Quarterly Journal of Economics*, *117*(2), 379-408 https://www.jstor.org/stable/2696430

Collier, P., & Hoeffler, A. (2004). Greed and grievance in civil war. *Oxford Economic Papers, 56*(4), 563-595. https://www.jstor.org/stable/3488799

Ebekozien, A., Ugochukwu, S. C., & Okoye, P. U. (2015). An analysis of the trends of foreign direct investment inflows in the Nigerian construction sector. *American International Journal of Contemporary Research*, *5*(1), 53-69. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=20bafb7bd00d98159de334c11ab6288e1f27dc86

Enoma, A. A., & Mustapha, I. (2010). Factor analysis of investment decision in Nigerian insurance companies. *Interdisciplinary Journal of Contemporary Research in Business*, *2*(8), 108–120.

Fitch affirms South Africa at 'BB-'; Outlook negative. (2021, May 21). FitchRatings. https://www.fitchratings.com/research/sovereigns/fitch-affirms-south-africa-at-bb-outlook-negative-21-05-2021

Ikuabe, M., Aigbavboa, C., Oke, A., Aghimien, D. & Thwala, W. (2021). Contextualizing foreign investments in the Nigerian construction industry. In S. Trzcielinski, B. Mrugalska, W. Karwowski, E. Rossi, & M. Di Nicolantonio (Eds.), *Advances in Manufacturing, Production Management and Process Control: Proceedings of the AHFE 2021 Virtual Conferences on Human Aspects of Advanced Manufacturing, Advanced Production Management and Process Control, and Additive Manufacturing, Modeling Systems and 3D Prototyping*, USA, 25-29 July 2021. (pp. 277-286). Springer International Publishing. https://doi.org/10.1007/978-3-030-80462-6_35

Ikuabe, M., Aigbavboa, C., Thwala, W., Chiyangwa, D., & Oke, A. (2022a). Risks of joint venture formation in the South African construction industry. *International Journal of Construction Management, 23*(14), 2391-2399. https://doi.org/10.1080/15623599.2022.2059913

Ikuabe, M., Akinshipe, O., Aigbavboa, C., Ebekozien, A., Oke, A., & Mofokeng, R. (2022b). Foreign direct investments in the South African construction industry: Promulgating the inherent benefits. In S. Nazir (Ed.), *Human factors in management and leadership: AHFE (2022) International Conference, USA.* AHFE International. http://doi.org/10.54941/ahfe1002238

Ikuabe, M. O., Aigbavboa, C. O., Thwala, W. D., Chiyangwa, D., & Oke, A. E. (2024). Critical factors influencing the failure of joint ventures in the South African construction industry: A confirmatory factor analysis approach. *Engineering, Construction and Architectural Management, 31*(4), 1678-1695. https://doi.org/10.1108/ECAM-04-2022-0298

Kahraman, C. (2011). Investment decision making under fuzziness. *Journal of Enterprise Information Management*, *24*(2), 126–129. https://doi.org/10.1108/17410391111106266

Karim, Z. A., & Azman-Saini, W. N. W. (2013). Firm-level investment and monetary policy in Malaysia: Do the interest rate and broad credit channels matter?. *Journal of the Asia Pacific Economy, 18*(3), 396–412. https://doi.org/10.1080/13547860.2012.742686

Liu, J., & Pang, D. (2009). Financial factors and company investment decisions in transitional China. *Managerial and Decision Economics, 30*(2), 91–108. https://doi.org/10.1002/mde.1440

Nnadi, M., & Soobaroyen, T. (2015). International financial reporting standards and foreign direct investment: The case of Africa. *Advances in Accounting, 31*(2), 228-238. https://doi.org/10.1016/j.adiac.2015.09.007

Pallant, J. (2020). *SPSS survival manual: A step-by-step guide to data analysis using IBM SPSS* (7th ed.). Routledge. https://doi.org/10.4324/9781003117452

Rangelova, F. (2015). *Fundamentals of economics in sustainable construction.* Bultest Standard Ltd. Bulgaria. https://www.scribd.com/document/341734549/FUNDAMENTALS-OF-ECONOMICS-IN-SUSTAINABLE-CONSTRUCTION-pdf

Santoro, M., & Wei, C. (2012). A note on the impact of progressive dividend taxation on investment decisions. *Macroeconomic Dynamics, 16*(2), 309–319. https://doi.org/10.1017/S1365100509990964

Sayek, S. (2009). Foreign direct investment and inflation. *Southern Economic Journal, 76*(2), 419-443. https://doi.org/10.4284/sej.2009.76.2.419

Statistical release P0441: Gross domestic product, third quarter 2009. (2009, November 24). Statistics South Africa. https://www.statssa.gov.za/publications/P0441/P04413rdQuarter2009.pdf

Statistical release P0441: Gross domestic product, fourth quarter 2017. (2018). Statistics South Africa. https://www.statssa.gov.za/publications/P0441/GDP_Q4_2017_Media_presentation.pdf

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education, 2*, 53-55. https://doi.org/10.5116%2Fijme.4dfb.8dfd

Value added to gross domestic product (GDP) by the construction industry in South Africa from 2016 to 2023. (2024, March). Statista. https://www.statista.com/statistics/1121217/construction-sector-value-added-to-gdp-in-south-africa/

Sharma, N., Sood, R. and Laishram, B., 2024. Mapping global trends in cost of quality dynamics: A bibliometric study. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 755-768. DOI: https://doi.org/10.31705/WCS.2024.60. Available from: https://ciobwcs.com/papers/

MAPPING GLOBAL TRENDS IN COST OF QUALITY DYNAMICS: A BIBLIOMETRIC STUDY

Nandini Sharma[1], Rhijul Sood[2], and Boeing Laishram[3]

ABSTRACT

In the construction industry, unique projects and complex dynamics pose challenges for maintaining high-quality standards. An inadequate Quality Management System (QMS) can lead to extra costs and delays, highlighting the importance of methodologies such as the Cost of Quality (COQ). Despite extensive knowledge in manufacturing, the construction sector lags in adopting COQ. A systematic review is needed to understand COQ developments in construction, informing better practices and cost reduction strategies. A Systematic Literature Review (SLR) and bibliometric analysis were carried out utilising 27 peer-reviewed papers obtained from the Scopus database. The present study utilises a range of tools, including VOSviewer and Litmaps to facilitate descriptive analysis, bibliometric analysis, and network visualisation. The purpose of this study is to investigate different aspects of the COQ and analyse different patterns and models related to it in the context of the construction industry. The present study systematically presents potential avenues for future research that have been identified in the existing literature.

Keywords: *Construction Industry; Cost of Quality (COQ); Quality Management.*

1. INTRODUCTION

Traditional construction projects have been criticised for their significant challenges. These challenges can be methodically categorised into four cardinal domains i.e. (i) cost, (ii) time, (iii) scope, and (iv) quality, which support the iron triangle criteria for the success of the project. The first three positioned at the periphery of the triangle are comprehensively recognised however the understanding of quality, which occupies a central position inside this triangle, has limitations within the construction industry (Thekkoote, 2022). Accelerated quality issues in construction projects arise from the fact that different definitions of quality are used in literature, varying from one industry to another. In addressing the challenges pertaining to quality, different Quality Management Systems (QMS) such as Total Quality Management (TQM), Lean Six Sigma, the International Organization for Standardization (ISO), and Cost Of Quality (COQ), originally designed for the manufacturing industry are being progressively integrated into the construction industry. Despite the widespread implementation of QMS, construction

[1] Research Scholar, Department of Civil Engineering, Indian Institute of Technology Guwahati, India, nandini.sharma@iitg.ac.in
[2] Research Scholar, Department of Civil Engineering, Indian Institute of Technology Guwahati, India, rsood@iitg.ac.in
[3] Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, India, boeing@iitg.ac.in

industry stakeholders still lack objective and quantitative decision criteria. In this context, a recent surge was observed in the implementation of COQ (Psomas et al., 2022), primarily driven by its capability to measure and document project quality, essential for the proper functioning of QMS (Omar & Murgan, 2014). As interest in COQ increased, a number of researchers and practitioners have carried out significant work in different fields such as business, manufacturing, and construction, to explore the domain of COQ. For instance, Schiffauerova and Thomson (2006) attempted to review various COQ models and underlined their relevancy in the manufacturing industry. Similarly, Lopez and Love (2012) indicated that design-related costs range from 5% to 8% of the contract value. Moreover, the authors engaged in a critical discussion of COQ estimation, yet the research lacks coverage of recent developments, including the classification of COQ costs and breakthroughs in COQ models specific to the construction industry. Despite the growing interest in this field, comprehensive assessments and analyses of COQ study trends are scarce, leading to a lack of literature review studies pertaining to the in-depth practical implications of COQ for quality monitoring. The current study aims to bridge this research gap by conducting a large-scale bibliometric analysis of COQ research, to robust understanding of the concept of COQ within the construction industry. To analyse the developments from extant COQ studies, bibliometric analysis is preferred, as it provides a clear picture of how such trends have evolved.

1.1 COST OF QUALITY

The interpretation of COQ might change across various authors. These expenses are referred to by multiple acronyms, such as *'cost of quality*' *'costs of poor quality*,' '*quality cost*,' '*price of non-conformance*,' and '*economies of quality*.' COQ is commonly understood as the combination of conformance and non-conformance costs (Heravi & Jafari, 2014). Conformance costs entail expenses associated with the prevention and detection of poor quality. In contrast, non-conformance costs encompass the financial implications of poor quality resulting from product and service failures, including internal and external failure costs (Garg & Misra, 2021). The COQ system, which was developed has been formalised into four categories of expenses:

I. Prevention costs are the expenses incurred to prevent the occurrence of defects and non-conformities (Schiffauerova & Thomson, 2006). These costs include quality-related expenditures to prevent unsatisfactory products from being produced in the first place (Abdelsalam & Gad, 2009).
II. Appraisal costs are associated with measuring, evaluating, or auditing products, components, and purchased materials to ensure conformance with quality standards and performance requirements (Jafari & Love, 2013).
III. Internal failure costs occur when products, components, and materials fail to meet quality requirements before the transfer of ownership. These are costs that would not exist if there were no defects in the product (Heravi & Jafari, 2014).
IV. External failure costs occur when a product does not perform satisfactorily after the transfer of ownership to the customer. These costs would also not exist if there were no defects in the product (Abdelsalam & Gad, 2009).

Therefore,

Total quality costs = Prevention costs + Appraisal costs + Internal failure costs + External failure costs

Several quantitative approaches have been recently used to measure the COQ and non-quality in construction. Studies such as Love et al. (1999) and Love and Li (2000) examined the causes and costs associated with rework in Australian construction projects, while Barber et al. (2000) have explored the costs of quality failures in civil engineering projects within the UK. The literature indicates that some construction firms do not measure all three categories of prevention, appraisal, and failure costs, opting instead to focus primarily on failure costs. The terms "defects," "rework," and "quality failure" are synonymous, and the lack of standardised terminology suggests that this research field is still evolving. However, numerous studies have attempted to quantify the costs of rework in civil engineering projects. Despite the development of several construction quality costing systems, these systems are neither widely adopted nor commonly utilised. This limited adoption is largely attributed to a lack of a standardised approach. Many organisations remain unaware of recent advancements in COQ methodologies, leading to inconsistencies in implementation. Furthermore, the inability of these organisations to effectively track and integrate these evolving trends into their existing frameworks exacerbates the problem. As a result, the potential benefits of these COQ systems remain unrealised, hindering overall improvements in QMS.

2. METHODOLOGY

Bibliometrics is a useful tool for analysing literature and identifying breakthroughs in certain fields of study subfields (Udomsap & Hallinger, 2020). This study allows for the assessment of publishing performance, the identification of developing research fields, the evaluation of national/regional cooperation, and the investigation of relevant themes, among other findings. This research used VOSviewer, a text-mining programme, to analyse bibliometric correlations between diverse data in order to better comprehend the COQ concept (Van Eck et al., 2010).

The present study is conducted in six stages, which are outlined in Figure 1.

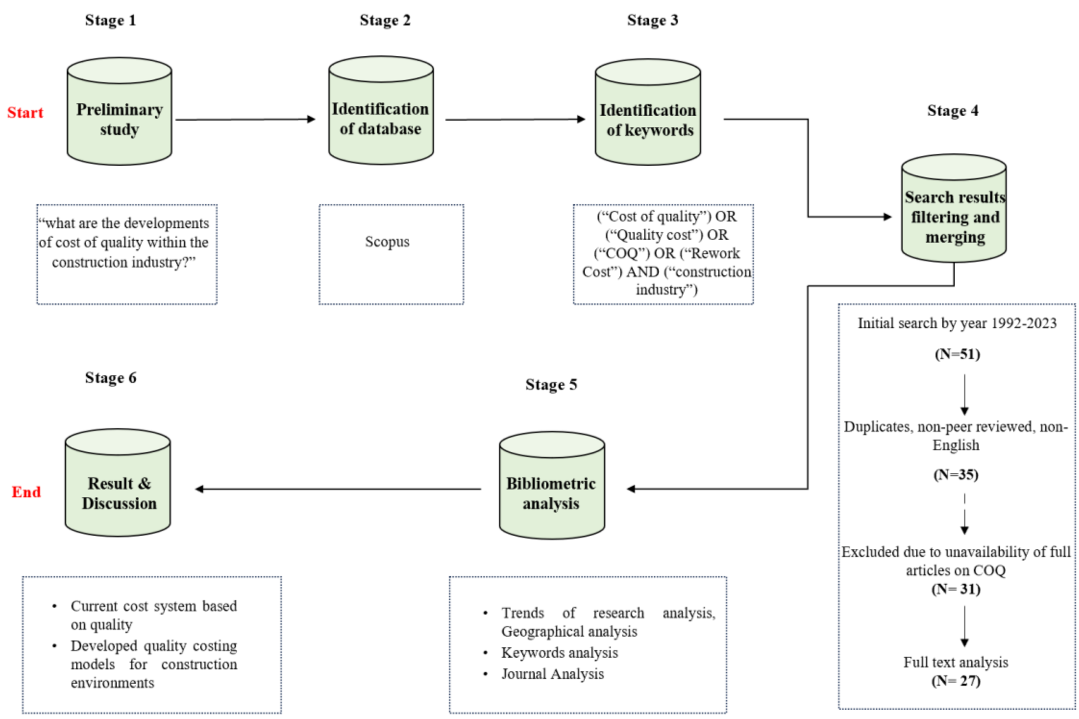


Figure 1: Literature search process

Stage 1: Preliminary study - This stage aims to do a comprehensive literature study to examine the latest and prominent research in COQ through the research objective.

Stage 2: Identification of database - The data collection for this research utilised existing literature retrieved from the Scopus database. Bibliometric studies often rely on a single database to effectively map broad trends (Udomsap & Hallinger, 2020). Scopus was chosen for its extensive coverage of scientific fields and high-quality sources. It is renowned for its efficient indexing process and comprehensive records of abstracts and citations across various disciplines. Additionally, Scopus provides advanced tools for tracking, analysing, and visualising research, enhancing the overall robustness of the study.

Stage 3: Identification of keywords - By utilising the Scopus database, the following search schemes were entered: (TITLE-ABS-KEY) ("Cost of quality") OR ("Quality cost") OR ("COQ") OR ("Rework Cost") AND ("construction industry").

Stage 4: Search results filtering and merging - The search activity included all articles published before December 2023, producing 51 results. After eliminating duplicates, non-English papers, and articles without peer review, 35 articles remained. Next, the titles and abstracts of articles were critically assessed using pre-defined filtering and selection criteria in the database (Jiaa et al., 2018). When it was uncertain whether an article should be retained based on its abstract, the entire article was read. The current research evaluated each article simultaneously, and any issues or discrepancies were resolved by consensus (Roeser & Kern, 2014). After this preliminary screening, 32 papers were selected for further consideration. After exporting the previously filtered articles, a manual full-text analysis was conducted, and 27 papers received consideration for analysis.

Stage 5: Bibliometric analysis of the search results. This strategy effectively reduces the risk of subjective bias from the perspective of the author, since it relies on data retrieved from a database, hence limiting any opportunity for the author's influence to impact the analysis. The present research incorporates bibliometric analysis including the following categories: Trends of research analysis, Geographical analysis, Keyword analysis, and Journal analysis.

Stage 6: Results and Discussion - The conclusion was drawn from the bibliometric analysis that was performed in the previous phases and the following findings.

3. BIBLIOMETRIC ANALYSIS

3.1 TRENDS OF RESEARCH ANALYSIS

The presented data shows an upward trend in the number of articles between 2005 to 2012 with six articles and from 2018 to 2023 with eleven articles published on the COQ subject within the construction industry. The emergence of the fourth industrial revolution began to gain attention after 2011, a factor that may have contributed to the observed rise in the quantity of articles. Furthermore, the research methods used in the articles selected were further studied by bibliometric analysis, as indicated in Figure 2. In accordance with the findings, a total of ten articles used case study methodology, whereas 17 articles utilised different methodologies such as survey (ten), conceptual study (five), and literature review (two). These articles established the foundation for developing the framework regarding the COQ in construction.

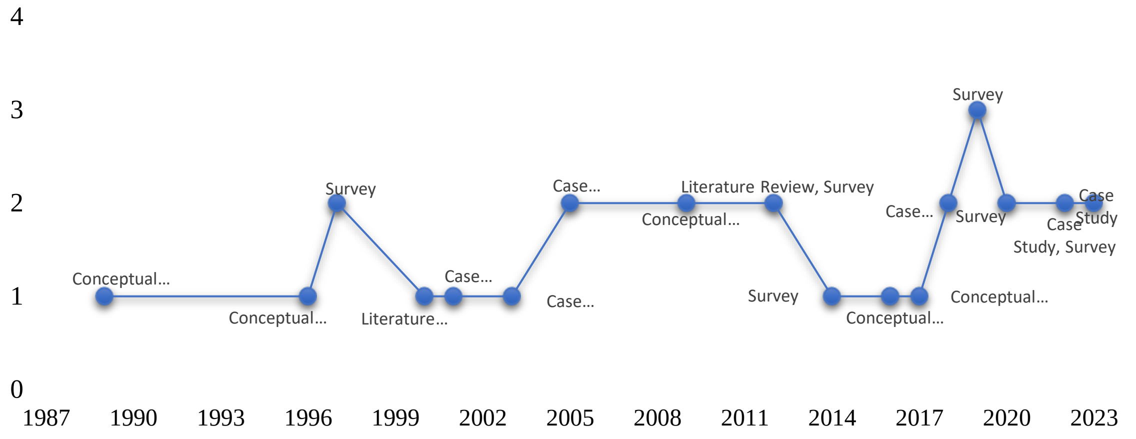


Figure 2: Distribution of articles based on year and type of methodologies

3.2 GEOGRAPHICAL ANALYSIS

The categorisation of research by country is a crucial factor in determining the scope of academic studies worldwide. With respect to the geographical area of the empirical research, a few studies were conducted in Iran, Australia, Turkey, and the UK, while the majority of the articles were carried out in these regions, as shown in Figure 3. The remaining studies were conducted in 16 different countries.

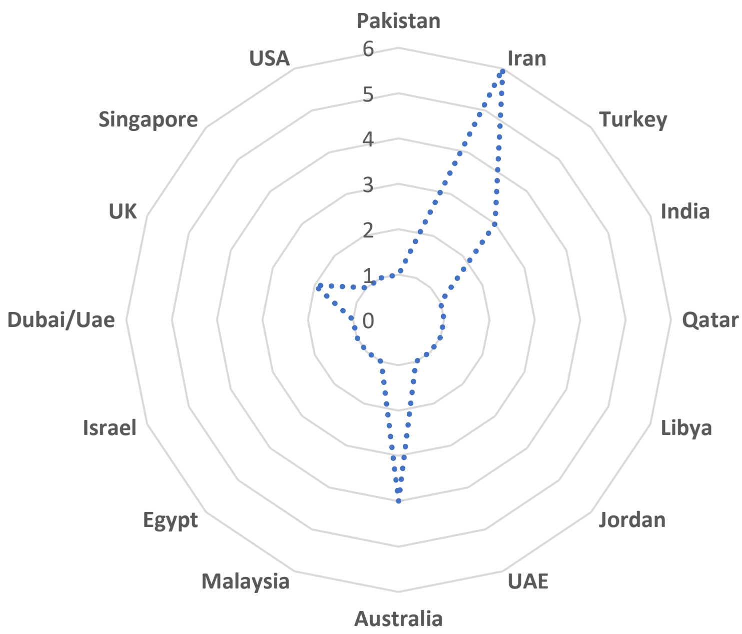


Figure 3: Mapping of articles distributed in different countries

3.3 KEYWORD ANALYSIS

A co-occurrence network of keywords was developed to provide a precise visualisation of the primary research studies and themes explored in the domains of COQ and QMS. In the present research, a set of 50 keywords were chosen and a visual representation of the keyword network is presented in Figure 4. The size of each node in the network corresponds to the frequency of occurrence of the respective keyword. The lines between the nodes indicate the presence of a link between two keywords, while the distance between two nodes reflects the degree of relatedness between them. Furthermore, the size of the circle is proportional to the frequency of the keywords. The keywords that appeared most frequently were "*construction industry*," "*cost of quality*," "*project management*," and "*quality management*".

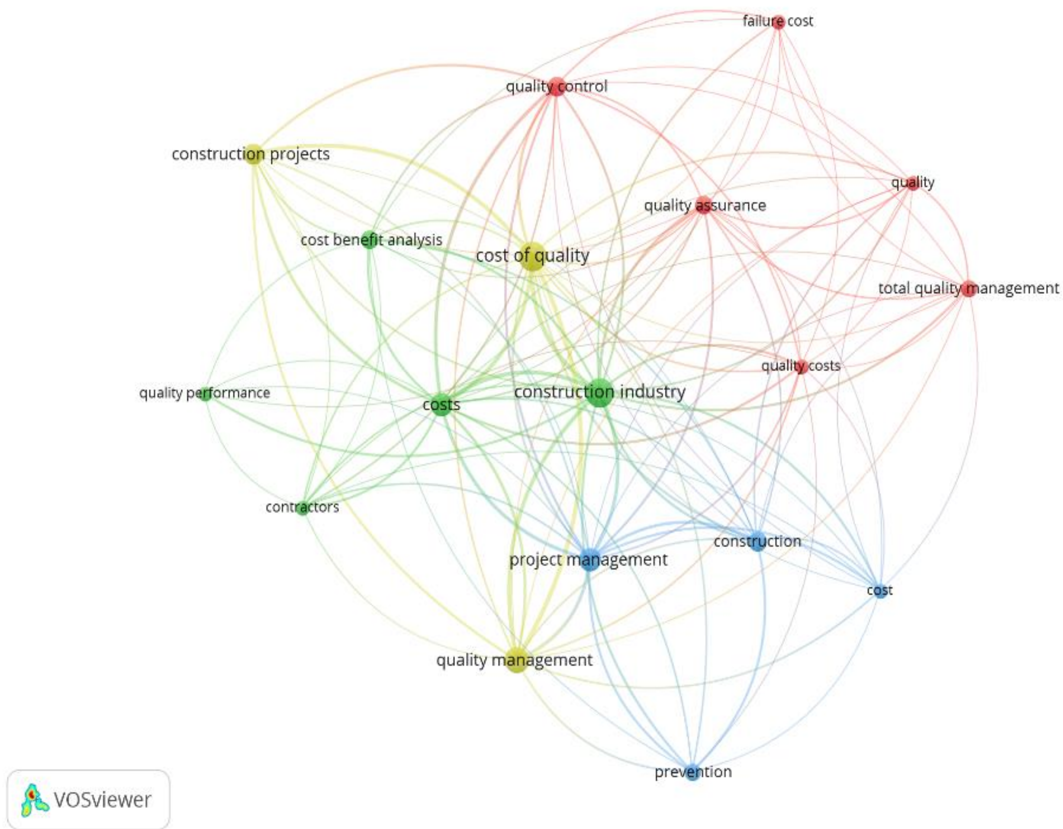


Figure 4: Mapping of keywords

3.4 JOURNAL ANALYSIS

Furthermore, an in-depth review was performed on the cumulative number of publications collected, grouped by journal. This review was carried out to provide researchers with insights into the prominent journals for publishing or accessing COQ-related research, as highlighted in Figure 5. In total, the SLR includes a total of 27 articles that were sourced from a diverse range of 17 academic journals. However, some journals published more COQ articles than others. The study revealed that 37.03% of the sampled articles were published in the three journals identified as follows: *Journal of Construction Engineering and Management* accounted for 14.81% of the articles, followed by the *International Journal of Quality & Reliability Management* and *Construction Management and Economics*, each with 11.11% of the articles.

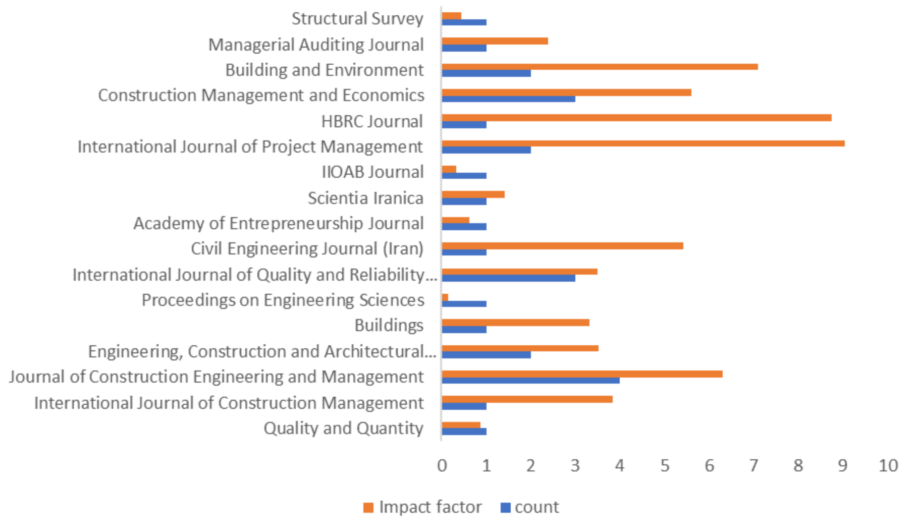


Figure 5: Mapping of publications in particular sources

4. RESULTS AND DISCUSSION

Following the bibliometric analysis, this section summarises the research on the current cost system based on quality and reveals several models adopted for computing COQ.

4.1 CURRENT COST SYSTEM BASED ON QUALITY

Since the early 1980s, a growing focus on the concept of COQ has been observed to improve the QMS within the construction industry (Heravi & Jafari, 2014). The findings of the current study reveal the picture of the COQ technique conducted in multiple countries and on multiple typologies of projects including buildings, industrial, bridges, roadways etc. have been conducted in Iran (Jafari & Love, 2013; Balouchi et al., 2019; Shafiei et al., 2020), Australia (Lopez & Love, 2012; Love et al., 2010; Love & Edwards, 2005; Mills et al., 2009; Love & Li, 2000), the UK (Abdul-Rahman et al., 1996; Barber et al., 2000) India (Garg & Misra, 2021) and Pakistan (Khadim et al., 2023). Despite varied responses and a lack of widespread adoption, the COQ methodology has made significant progress in its implementation across the globe. In addition, several quality issues, such as reworks, failures, and defects, are classified as part of the COQ and reviewed for every construction project, predominantly to minimise the cost and impact on quality. However, few studies have been conducted to identify the type of COQ and examine the limitations and future scope of the studies (e.g., time and cost). For instance, Kazaz and Birgonul (2005) examined a mass housing initiative in Turkey, which included 3100 residential units and required over four years for its completion. Based on the results of the research, it was determined that the average COQ represents approximately 32.36% of the total project cost. The authors of the statement argue that the indicated amount is much higher compared to similar projects, mainly due to a lack of effective management skills and a shortage of contractors with globally recognised accreditation. Similarly, Abdelsalam and Gad (2009) conducted a study on a residential development project in Dubai (UAE), which included the construction of 291 multi-story buildings. The results of this study suggest that the average value of total COQ was 1.3% of the entire project costs, yet the cost incurred due to project failure constituted 0.7% of the overall project cost. The calculation of the external failure cost group was not feasible since the projects under review had not yet been handed to the client. The limited allocation of resources towards failure costs might be justified by the diligent supervision by the client, through a dedicated project management team and a supervisory consultant. As can be observed, Jafari and Love (2013) conducted a study to evaluate the impact of QMS implemented over 18 months for a monorail project in Iran. The project incorporated a COQ technique, which ultimately led to the estimation of a failure cost equivalent to 5% of the contractual value of the project. The allocation of appraisal costs amounted to approximately 2.32% of the contract value and 2.78% of prevention costs through the utilisation of the QMS. The distribution of appraisal costs represented approximately 2.32% of the contractual value and 2.78% of the prevention costs by using the QMS. The biggest factor contributing to the decrease in COQ within the failure domain was found to be the presence of a trained quality team and the repetitive nature of jobs. The use of active performance management and contractor-led inspection enabled the identification of errors and difficulties related to pre-executed plans. Consequently, this resulted in the improvement of performance in the QMS and the optimisation of mechanisms for reducing costs. In addition, several studies have investigated different kinds of construction defects. However, there is a lack of study explicitly focused on the calculation of the COQ, which suggests that the COQ often ranges from 3% to 5% of the original construction cost. In addition, Forcada et al. (2014), Forcada et al. (2017), Balouchi et al. (2019), Garg and Misra (2021) and Khadim et al. (2023) can be referred to in relation to COQ.

4.2 DEVELOPED COQ MODELS FOR THE CONSTRUCTION INDUSTRY

COQ within the construction industry frequently increases when considering the overall project costs, mostly attributable to the complex nature of quantifying construction processes. Bibliometric analysis reveals that various costing systems for construction quality have been formulated; however, their adoption and implementation are not prevalent.

4.2.1 Prototypes-based Models

Davis et al. (1989) developed the Quality Performance Tracking System (QPTS) which incorporated a comprehensive cost coding system to categorise different items. The QPTS model originated from the Quality Performance Management System (QPMS) and is designed to assure the conformity of collected cost data with the work breakdown structure of an individual project. In recent times, the use of QPTS has facilitated the ability to quantitatively analyse project quality, using a methodical strategy to collect and identify the COQ. According to Davis et al. (1989), quality may be defined as "conformance to requirements," which allows for the quantification of the COQ. Furthermore, Ledbetter and Patterson (1989), used the QPMS to monitor the financial implications of QMS across four different projects. It was assumed that the direct rework expenditures were 12.5% of the overall project cost, whereas an analysis revealed that the quality charges accounted for 25% of the project cost. The relationship between the cost of rework and the QMS cost was then established based on the underlying cause of the errors. Although the aforementioned prototype COQ model exhibited simplicity and adaptability, it failed to account for the impact of failure on time-related costs. Similarly, Willis and Willis (1996) used the QMPS approach to an industrial project through a case study. The authors calculated that 12% of all design and construction labour costs went toward Total Quality Cost (TQC), which includes the costs of prevention and appraisal at 8.7% as well as the costs of failure and deviation repair at 3.3 %. Furthermore, Willis and Willis (1996) discovered that the frequency of deviation repairs decreases with use of preventive and monitoring techniques by allocation of resources to the prevention category as it reduces spending on internal failures and inspections.

4.2.2 Software-based Models

Earlier studies proposed techniques for predicting project costs, or determining suitable characteristics for the project, based on initial planning and estimation data. In the field of construction, Jrade and Alkass (2007), developed a software application with the purpose of providing life-cycle costs and parametric cost estimates for future projects. The module utilises many factors, including the total floor area, project type, external wall type, and framing system type, to predict the projected cost of the project. In a similar vein, several software-based concepts have been developed around the globe to compute the COQ. These models include the neural network model (Tawfek et al., 2012) and the fuzzy-based COQ model (de Vries & Steins, 2008), which were employed to investigate the different aspects of COQ both directly and indirectly (Feigenbaum, 1956). Tawfek et al (2012) used multiple neural network architectures to estimate project performance, particularly in the context of cost overrun and contractual claims. Such models were developed using a range of rework indicators and associated cost attributes. Similarly, (Fayek & Rodriguez Flores, 2010) used fuzzy logic for the modeling of quality during the conceptual cost estimation phase. This choice was made due to the compatibility of fuzzy logic with the uncertain, qualitative, and subjective characteristics nature of the evaluation. Moreover, the fuzzy logic-based model has found application in multiple domains within the construction industry, including risk assessment, range estimation, prediction and identification of construction performance, evaluation of working conditions, contractor selection, and determination of cost-estimating relationships (Shaheen et al., 2007; Tah & Carr, 2000). Furthermore, ANNs can play a pivotal role in quantifying the multifaceted repercussions of rework. By considering an array of variables such as project delays, cost overruns, and stakeholder dissatisfaction, ANNs can provide a comprehensive perspective on the true impact of rework on project performance. Armed with such comprehensive knowledge, construction practitioners can make informed decisions, devise targeted interventions, and institute measures that bolster quality, efficiency, and cost-effectiveness throughout the project lifecycle.

4.2.3 Framework-based Models

System Dynamics (SD) and rework Cycle of causal Loop Diagrams (CLD) are two examples of attempted framework-based models. System Dynamics (SD) has been widely used in the framing of dynamic characteristics of projects, particularly pertaining to errors and rework and errors (Han et al., 2013; Lyneis & Ford, 2007). Both the quantitative and qualitative aspects of SD have been used in the construction of models aimed at revealing the behaviour and consequences of rework on project performance. However, Shafiei et al. (2020) utilised the concept of SD in their significant works, which have served as a foundation for understanding the systemic characteristics of rework and are fundamental to understanding the application of SD in construction environments. Furthermore, the "Rework Cycle" is an alternative model that describes processes using CLD that include both rework and unplanned rework. The work rate is influenced by the proficiency, efficiency, and accessibility of the staff workers. Additionally, as the project progressed, the remaining workload was reduced. The completion or discovery of work is dependent upon the quality of the task performed, namely the extent to which it is executed accurately. In the context of unexplored literature, this pertains to inaccuracies that remain unrecognised yet are considered to have been performed. The potential exists for the work performed to fall short of the prescribed standard, hence allowing for the occurrence of error (Forcada et al., 2014). Latent errors, which are not readily detectable, sometimes reveal themselves only after a period of incubation within the system. Over time, these defects are ultimately found or they exhibit their own, leading to the identification of rework, thus augmenting the amount of work for the employees (Love et al., 2021). Similar to the concept of Cognitive Maps (CM), CLDs have consistently depended on interview data as their main source of knowledge. Consequently, the process of retrieving and interpreting information from memory and exercising judgment serves a crucial role in providing a comprehensive understanding of the events that occurred.

4.2.4 COQ-based Models

However, attention is drawn to other methods such as an arrangement of Feigenbaum (1956) known as the Prevention-Appraisal-Failure (PAF) model which would categorise into prevention, appraisal, and failure (internal and external) costs. Prevention costs are associated with actions taken to ensure that a process provides quality products and services, appraisal costs are associated with measuring the level of quality attained by the process, and failure costs are incurred to correct quality in products and services before (internal) or after (external) delivery to the customer. The conventional PAF model is the most commonly used by construction organisations to calculate either prevention or external cost, as discussed by Kazaz et al. (2005), Abdelsalam and Gad (2009), Rosenfeld (2009), Heravi and Jafari (2014), Garg and Misra (2021), and Khadim et al. (2023). However, the PAF categorisation is only a basic concept, and the concrete costing systems still differ considerably from organisation to organisation. However, prior research on the utilisation of COQ within the construction industry has been limited in scope. The construction process has been the primary focus of their attention, while the comprehensive scope of a complete COQ methodology has been ignored.

5. CONTRIBUTION TO THEORY AND PRACTICE

The data obtained from analysing 27 papers spanning from 1992 to 2023 reveals a range of influential discoveries:

i. The fluctuation in articles exploring the COQ, characterised by fewer publications is probably driven by multiple factors within the field of quality management research. Significantly, when considering the timeframe of the sample publications, it is evident that academics have shown an inclination to use cross-sectional data rather than longitudinal data in studying the patterns of COQ. The prominence of such cross-sectional studies may be attributed to their cost-effectiveness and shorter period. Nevertheless, it is important to highlight that longitudinal studies require more resources and time, but they provide a more thorough examination of systems in comparison to cross-sectional research. Emphasising more longitudinal studies in future research could be a valuable methodological approach, enabling a deeper grasp of COQ by uncovering significant relationships between variables that might not be discernible within shorter periods.

ii. The study reveals that case studies are the most used method for undertaking research in the field of COQ, followed by surveys, while there's a dearth of conceptual and literature review papers in the sampled COQ articles. This trend signifies a preference for empirical research over theoretical exploration in the COQ domain. Emphasising empirical evidence is vital for practitioners as it enables the evaluation of theoretical models in real-world scenarios. However, there exists a gap between empirical and theoretical studies in COQ. To address this, future research should focus on conceptual studies and literature reviews with the objective offering a more comprehensive understanding by integrating theoretical perspectives with empirical findings.

iii. The widespread acceptance of PAF in case studies and surveys may be subjected to its simple structure, which enables a methodical and inclusive evaluation of COQ. The explicit categorisation of aspects allows academics and practitioners to identify, quantify, and assess the several cost components linked to the maintenance or improvement of quality. Furthermore, its transparency enables a broad spectrum of companies, irrespective of their size or sector, to easily use it, therefore enabling comparisons and benchmarking endeavours across different environments. The PAF model's usefulness in providing a systematic framework for comprehending quality expenses has significantly led to its extensive use in case studies and surveys within the field of quality management research.

iv. Most of the research on COQ has mostly focused on Australia and China, with a significant lack of academic articles from other countries, such as the USA and UK. To broaden the range of COQ research, future investigations should investigate extending the settings beyond these conventional domains. Significantly, previous research has mostly focused on developed countries such as Singapore, Spain, and Canada. However, considerable research has been conducted in the context of developing countries, particularly India, with notable contributions from Iran. Future studies should focus on comparing and contrasting COQ practices across organisations in developed and developing countries. This comparison study may provide insights into the differing levels of COQ adoption in different economic environments, hence delivering significant information about the worldwide landscape of COQ practices.

6. CONCLUSIONS

In the realm of the construction industry, COQ is a broad discipline that covers a wide range of academic journals focusing on various cost categories such as rework cost, NCR cost, prevention cost, appraisal cost, and failure cost. The distribution of the 27 articles analysed in this SLR reveals the globalisation of the COQ topic.

The comparative analysis of COQ models in the construction industry reveals distinct differences in accuracy, usability, and adaptability. *Prototype-based models,* such as QPTS, excel in detailed cost tracking but lack consideration for time-related costs. Software-based models offer high accuracy and handle complex variables effectively but require substantial data input and technical expertise. Whereas, *Framework-based models,* like SD and CLD, provide deep insights into dynamic interactions and systemic issues but are challenging to implement due to their complexity. In terms of usability, *Prototype-based models* are simple and accessible, while *Software-based models,* despite their detailed insights, demand significant technical setup. *Framework-based models* are useful for complex projects but pose adoption challenges due to their intricacy. The *PAF model* is widely used for its simplicity in categorising costs but suffers from variability in effectiveness due to a lack of standardisation. For scope and adaptability, *Prototype-based models* focus on direct costs, whereas *Software-based models* are versatile and adaptable to various project types. *Framework-based models* are highly adaptable for complex project dynamics, and the PAF model is broadly applicable but varies in comprehensiveness. An integrated approach combining elements from all these models could provide a robust solution, enhancing quality management across the construction industry by leveraging simplicity, predictive accuracy, dynamic analysis, and broad applicability. The adaptation of models to conform to the particular requirements of an organisation frequently leads to the expansion of multiple structures for the COQ. Various costs and elements are classified and designated using specific terminologies. Moreover, there exists a variety of elements that are either incorporated or perceived as irrelevant and thus neglected from the calculations.

However, this study is limited by the application of a single database. To overcome this constraint, researchers could broaden the range of their sources, and investigate other databases such as Web of Science, PubMed, or EBSCO to broaden the scope and inclusiveness of the literature search.

7. REFERENCES

Abdelsalam, H. M. E., & Gad, M. M. (2009). Cost of quality in Dubai: An analytical case study of residential construction projects. *International Journal of Project Management*, *27*(5), 501–511. Retrieved from https://doi.org/10.1016/j.ijproman.2008.07.006.

Abdul-Rahman, H., Thompson, P. A., & Whyte, I. L. (1996). Capturing the cost of non-conformance on construction sites: An application of the quality cost matrix. *International Journal of Quality and Reliability Management*, *13*(1), 48–60. Retrieved from https://doi.org/10.1108/02656719610108314

Balouchi, M., Gholhaki, M., & Niousha, A. (2019). Prioritizing the main elements of quality costs in design-build mass-housing projects. *Civil Engineering Journal*, *5*(5), 1136–1146. Retrieved from https://doi.org/10.28991/cej-2019-03091318

Barber, P., Graves, A., Hall, M., Sheath, D., & Tomkins, C. (2000). Quality failure costs in civil engineering projects. *International Journal of Quality and Reliability Management*, *17*(4), 479–492. Retrieved from https://doi.org/10.1108/02656710010298544

Davis, B. K., Ledbetter, W. B., & Burati, J. L. (1989). Measuring design and construction quality costs. *Journal of Construction Engineering and Management*, *115*(3), 385–400. Retrieved from https://doi.org/10.1061/(ASCE)0733-9364(1989)115:3(385)

de Vries, B., & Steins, R. J. (2008). Assessing working conditions using fuzzy logic. *Automation in Construction*, *17*(5), 584–591. Retrieved from https://doi.org/10.1016/j.autcon.2007.10.004

Udomsap, A.D, & Hallinger, P. (2020). A bibliometric review of research on sustainable construction, 1994–2018. *Journal of Cleaner Production*, *254*(8), 120073. Retrieved from https://doi.org/10.1016/j.jclepro.2020.120073

Fayek, A. R., & Rodriguez Flores, J. R. (2010). Application of fuzzy logic to quality assessment of infrastructure projects at conceptual cost estimating stage. *Canadian Journal of Civil Engineering*, *37*(8), 1137–1147. Retrieved from https://doi.org/10.1139/L10-036

Feigenbaum, A. V. (1956). Total quality control. *Harvard Business Review*, *34*(6), 93–101.

Forcada, N., Alvarez, A. P., Love, P. E. D., & Edwards, D. J. (2017). Rework in urban renewal projects in Colombia. *Journal of Infrastructure Systems*, *23*(2), 04016034. Retrieved from https://doi.org/10.1061/(asce)is.1943-555x.0000332

Forcada, N., Rusiñol, G., Macarulla, M., & Love, P. E. D. (2014). Rework in highway projects. *Journal of Civil Engineering and Management*, *20*(4), 445–465. Retrieved from https://doi.org/10.3846/13923730.2014.893917

Jiaa, F., Zuluagab, L., Adrian Baileyb, X. R. (2018). Sustainable supply chain management in developing countries: An analysis of the literature. *Journal of Cleaner Production*, *189*(2018), 263–278. Retrieved from https://doi.org/10.1016/j.jclepro.2018.03.248

Garg, S., & Misra, S. (2021). Understanding the components and magnitude of the cost of quality in building construction. *Engineering, Construction and Architectural Management*, *29*(1), 26–48. Retrieved from https://doi.org/10.1108/ECAM-08-2020-0642

Han, S., Love, P., & Peña-Mora, F. (2013). A system dynamics model for assessing the impacts of design errors in construction projects. *Mathematical and Computer Modelling*, *57*(9), 2044–2053. Retrieved from https://doi.org/https://doi.org/10.1016/j.mcm.2011.06.039

Heravi, G., & Jafari, A. (2014). Cost of quality evaluation in mass-housing projects in developing countries. *Journal of Construction Engineering and Management*, *140*(5), 4014004. Retrieved from https://doi.org/10.1061/(ASCE)CO.1943-7862.0000837

Jafari, A., & Love, P. E. D. (2013). Quality costs in construction: Case of QOM monorail project in Iran. *Journal of Construction Engineering and Management*, *139*(9), 1244–1249. Retrieved from https://doi.org/10.1061/(asce)co.1943-7862.0000704

Jrade, A., & Alkass, S. (2007). Computer-integrated system for estimating the costs of building projects. *Journal of Architectural Engineering*, *13*(4), 205–223. Retrieved from https://doi.org/10.1061/(asce)1076-0431(2007)13:4(205)

Kazaz, A., & Birgonul, M. T. (2005). Determination of quality level in mass housing projects in Turkey. *Journal of Construction Engineering and Management*, *131*(2), 195–202. Retrieved from https://doi.org/10.1061/(asce)0733-9364(2005)131:2(195)

Kazaz, A., Birgonul, M. T., & Ulubeyli, S. (2005). Cost-based analysis of quality in developing countries: A case study of building projects. *Building and Environment*, *40*(10), 1356–1365. Retrieved from https://doi.org/10.1016/j.buildenv.2004.11.010

Khadim, N., Thaheem, M. J., Ullah, F., & Mahmood, M. N. (2023). Quantifying the cost of quality in construction projects: an insight into the base of the iceberg. *Quality and Quantity*, *57*(6), 5403–5429. Retrieved from https://doi.org/10.1007/s11135-022-01574-8

Ledbetter, W. B., & Patterson, L. (1989). The cost of quality: A management tool. Excellence in the Constructed Project, In *Proceedings of Construction Congress I*, (pp. 100–105), ASCE. https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0063875

Lopez, R., & Love, P. E. D. (2012). Design Error Costs in Construction Projects. *Journal of Construction Engineering and Management*, *138*(5), 585–593. Retrieved from https://doi.org/10.1061/(asce)co.1943-7862.0000454

Love, P. E. D. Mandal, P., & Li, H. (1999). Determining the causal structure of rework influences in construction. *Construction Management & Economics*, 17(4), 505-517. https://doi.org/10.1080/014461999371420

Love, P. E.D., & Li, H. (2000). Quantifying the causes and costs of rework in construction. *Construction management & economics*, 18(4), 479-490. Retrieved from Retrieved from https://doi.org/10.1080/01446190050024897

Love, P. E. D., & Edwards, D. J. (2005). Calculating total rework costs in Australian construction projects. *Civil Engineering and Environmental Systems*, *22*(1), 11–27. Retrieved from https://doi.org/10.1080/10286600500049904

Love, P. E. D., Edwards, D. J., Watson, H., & Davis, P. (2010). Rework in civil infrastructure projects: Determination of cost predictors. *Journal of Construction Engineering and Management*, *136*(3), 275–282. Retrieved from https://doi.org/10.1061/(asce)co.1943-7862.0000136

Love, P. E. D., Matthews, J., & Fang, W. (2021). Envisioning rework in practice: emergent insights from a longitudinal study. *Journal of Construction Engineering and Management*, *147*(1), 06020002. Retrieved from https://doi.org/10.1061/(asce)co.1943-7862.0001960

Lyneis, J. M., & Ford, D. N. (2007). System dynamics applied to project management: A survey, assessment, and directions for future research. *System Dynamics Review*, *23*(2), 157–189. Retrieved from https://doi.org/https://doi.org/10.1002/sdr.377

Mills, A., Love, P., & Williams, P. (2009). Defect costs in residential construction. *Journal of Construction Engineering and Management*, *135*(1), 12–16. Retrieved from https://doi.org/10.1061/ASCE0733-93642009135:112

Omar, M. K., & Murgan, S. (2014). An improved model for the cost of quality. *International Journal of Quality and Reliability Management*, *31*(4), 395–418. Retrieved from https://doi.org/10.1108/IJQRM-05-2012-0066

Psomas, E., Dimitrantzou, C., & Vouzas, F. (2022). Practical implications of cost of quality: a systematic literature review. *International Journal of Productivity and Performance Management*, *71*(8), 3581–3605. Retrieved from https://doi.org/10.1108/IJPPM-10-2020-0524

Roeser, T., & Kern, E. (2014). Surveys in business process management: A literature review. *Business Process Management Journal*, *21*(03), 692–718. Retrieved from https://doi.org/10.1108/BPMJ-07-2014-0065

Rosenfeld, Y. (2009). Cost of quality versus cost of non-quality in construction: The crucial balance. *Construction Management and Economics*, *27*(2), 107–117. Retrieved from https://doi.org/10.1080/01446190802651744

Schiffauerova, A., & Thomson, V. (2006). A review of research on cost of quality models and best practices. *International Journal of Quality and Reliability Management*, *23*(6), 647–669. Retrieved from https://doi.org/10.1108/02656710610672470

Shafiei, I., Eshtehardian, E., Nasirzadeh, F., & Arabi, S. (2020). Dynamic modeling to reduce the cost of quality in construction projects. *International Journal of Construction Management*, *23*(1), 24–37. Retrieved from https://doi.org/https://doi.org/10.1080/15623599.2020.1845425

Shaheen, A. A., Fayek, A. R., & AbouRizk, S. M. (2007). Fuzzy numbers in cost range estimating. *Journal of Construction Engineering and Management*, *133*(4), 325–334. Retrieved from https://doi.org/10.1061/(asce)0733-9364(2007)133:4(325)

Tah, J. H. M., & Carr, V. (2000). A proposal for construction project risk assessment using fuzzy logic. *Construction Management and Economics*, *18*(4), 491–500. Retrieved from https://doi.org/10.1080/01446190050024905

Tawfek, H. S., Mohammed, H. E.-D. H., & Abdel Razek, M. E. (2012). Assessment of the expected cost of quality (COQ) in construction projects in Egypt using artificial neural network model. *HBRC Journal*, *8*(2), 132–143. Retrieved from https://doi.org/10.1016/j.hbrcj.2012.09.009

Thekkoote, R. (2022). Enabler toward successful implementation of Quality 4.0 in digital transformation era: a comprehensive review and future research agenda. *International Journal of Quality and Reliability Management*, *39*(6), 1368–1384. Retrieved from https://doi.org/10.1108/IJQRM-07-2021-0206

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 1–12. Retrieved from https://doi.org/10.1061/(ASCE)EI.1943-5541.0000412

Willis, T. H., & Willis, W. D. (1996). A quality performance management system for industrial construction engineering projects. *International Journal of Quality & Reliability Management*, *13*(9), 38–48. Retrieved from https://doi.org/10.1108/02656719610150605

Gajaba, P. and Dissanayake, P., 2024. Misconceptions in heating, ventilation and air conditioning - Airside strategy implementation of commercial buildings in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 769-778. DOI: https://doi.org/10.31705/WCS.2024.61. Available from: https://ciobwcs.com/papers/

MISCONCEPTIONS IN HEATING, VENTILATION AND AIR CONDITIONING - AIRSIDE STRATEGY IMPLEMENTATION OF COMMERCIAL BUILDINGS IN SRI LANKA

P.A.P.Y. Gajaba[1] and Piumi Dissanayake[2]

ABSTRACT

To lower energy consumption and emission patterns in the building sector, discussions about climate change, the depletion of fossil fuels, and energy conservation are emphasised to create a more sustainable built environment. Thus, this paper examines common misconceptions regarding the implementation of HVAC airside strategies in commercial buildings, with a primary focus on Sri Lankan commercial buildings, where Heating, Ventilation and Air Conditioning (HVAC) systems account for a significant portion of electricity consumption. For this purpose, a comprehensive literature synthesis was conducted, a qualitative research approach was used to pursue the research aim, and an interview survey using semi-structured interviews was conducted targeting 17 experts. The collected data was then analysed using content analysis using the NVivo software. The findings of the research were discussed under three topics i.e., (i) adaptation of HVAC airside strategies to a tropical country, (ii) adaptation of HVAC airside strategies to coastal and highly humid areas, and (iii) sufficiency of prioritising waterside efficiency to gain overall HVAC system efficiency. In conclusion, it was derived that a balanced approach between airside and waterside HVAC systems should be maintained for optimal energy efficiency and the HVAC system can be tailored to diverse environmental conditions buildings are situated in. The knowledge gathered through this study can be used by industry professionals to enhance HVAC energy performance, while aiding academia in researching this sub-branch of HVAC systems in the Sri Lankan context.

Keywords: *Airside Efficiency; Central Air-conditioning System; Commercial Building; Energy Efficiency; Misconceptions.*

1. INTRODUCTION

The present global energy consumption crisis has attracted widespread attention from diverse stakeholders, driven by escalating global energy demands. This surge raises concerns about potential supply constraints, resource depletion, and subsequent environmental repercussions (Zakaria et al., 2023). Notably, energy services associated

[1] Temporary Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, pranidhig@uom.lk
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, piumid@uom.lk

with buildings constitute a significant share, contributing around 33% to the total global demand for final energy and the associated greenhouse gas emissions (Urge-Vorsatz et al., 2013). Within the Sri Lankan context, the building sector stands out as the predominant consumer of primary energy (Selvakkumaran & Limmeechokchai, 2013). The commercial and industrial sector, housing a substantial building inventory, significantly contributes, comprising nearly 60% of the country's electricity consumption, which is highlighted by aggregating the sub-metering data, indicating that HVAC systems constitute approximately 51% of the annual average electricity end-use breakdown in Sri Lanka's buildings (Geekiyanage & Ramachandra, 2018).

Patel et al. (2018) highlight the segmentation of HVAC systems into airside and waterside. Together, these two subsystems optimise the HVAC system's overall energy efficiency. According to Faulkner et al. (2023), to obtain the best energy savings in buildings, it is imperative to consider both waterside and airside components simultaneously. The airside system significantly influences Indoor Air Quality (IAQ), occupant health, and overall productivity (Kang et al., 2021). Similarly, Boyajieff (2017) stated that airside efficiency arguably has the most dramatic financial impact of any Energy Conservation Measure (ECM) where airside efficiency projects have a payback of 2.5 years with an average of 38% energy reduction in buildings. This is especially true for large commercial buildings that have high cooling loads and loads caused by internal heat gain (Ji et al., 2016).

Thus, according to existing literature, the energy consumption of commercial buildings makes up 20% of Sri Lanka's overall electricity consumption (Weerasinghe et al., 2016), with airside HVAC systems accounting for 20% of this total (Amjath et al., 2021). Hence, to reach better efficiency levels, it is important to implement HVAC airside system strategies so that the HVAC system as a whole can yield benefits. Despite the high percentages and the clear necessity, energy efficiency levels are not maintained in commercial buildings due to various reasons and one significant reason is the misconceptions surrounding the implementation of HVAC airside strategies. These misconceptions, observed globally, extend their influence on Sri Lanka, yet remain largely unexplored within the Sri Lankan context. Consequently, this research endeavours to address this gap, thereby paving the way for the implementation of HVAC airside strategies in Sri Lanka. Hence, this study aims to analyse the misconceptions in implementing energy efficiency strategies to the airside HVAC system of commercial buildings in Sri Lanka. Accordingly, the research question was developed as "How do the misconceptions influence the implementation of HVAC airside energy efficiency strategies in commercial buildings?"

2. LITERATURE REVIEW

2.1 ENERGY CONSUMPTION IN COMMERCIAL BUILDINGS

According to Zhan et al., (2018), buildings account for approximately 40% of global energy consumption and 33% of greenhouse gas emissions. About 60% of Sri Lanka's overall energy consumption is accounted for by the residential and commercial sectors combined (Sri Lanka Sustainable Energy Authority [SLSEA], 2020). To lower Carbon emissions and achieve sustainable development goals, the Sri Lankan government has therefore taken steps to improve energy efficiency in the built environment (Kandaudahewa & Melegoda, 2023). Thus, even though Emmanuel and Rogithan (2002) highlight the government's acknowledgement of the critical role of enhancing building energy performance in the national sustainable energy development strategy, they further stated that the scope of the Energy Efficiency Building Code (EEBC) of Sri Lanka was limited to new commercial buildings such as offices, hotels, shopping complexes, hospitals and others voluntarily if they exceed any one of the criteria that are listed as follows:

i. Building height exceeding four stories,

ii. Floor area of 2,000m^2 or greater,

iii. Building enclosed volume of 5,600m^3 or greater, and

iv. Electrical peak demand of 100 kW or greater Air-conditioning cooling capacity of 350 kW (output).

2.2 CENTRAL AIR CONDITIONING SYSTEM

The HVAC system can be categorised into two primary domains: the waterside, encompassing chillers, pumps, and cooling towers, and the airside, which includes VAV terminals, supply and return fans (Patel et al., 2018). Faulkner et al., (2023) stressed the necessity of concurrently addressing both subsystems to enhance energy efficiency in buildings. Sekhar (2016) asserted that the design of airside HVAC systems significantly influences achieving optimal air quality, acknowledging the inherent challenges in this design process. The airside system serves as the key factor determining IAQ by regulating variables such as dry-bulb temperature, indoor relative humidity, and air velocity. Furthermore, it profoundly impacts occupant health and productivity (Kang et al., 2016). Hence, the necessity to achieve airside efficiency for a commercial building is apparent.

2.3 MISCONCEPTIONS IN HVAC AIRSIDE STRATEGY IMPLEMENTATION

The energy consumption of HVAC systems in commercial buildings remains notably high, prompting significant focus on optimising their airside components (Bae et al., 2021). Existing literature underlines ongoing discussions regarding the implementation of HVAC airside strategies in commercial settings, which can be discussed under three sub-topics i.e. (i) adaptation of HVAC airside strategies to a tropical country, (ii) adaptation of HVAC airside strategies to coastal and highly humid areas, and (iii) priority of waterside HVAC system is sufficient for energy efficiency as follows.

2.3.1 Adaptation of HVAC Airside Strategies to a Tropical Country

The adaptability of HVAC airside strategies to tropical countries has been a subject of debate in the literature. Studies by Rahman et al., (2021) and Ahmed et al., (2021) suggest that conventional HVAC systems designed for temperate climates may face challenges in tropical regions due to variations in temperature and humidity. However, contrary to this misconception, successful implementations have been documented in countries such as Singapore and Malaysia, as highlighted by Shao et al. (2022) and Camargo et al. (2023). In these regions, innovative airside strategies effectively address the unique challenges posed by tropical climates, emphasizing the importance of tailoring HVAC systems to local conditions. Adaptation of HVAC airside strategies to coastal and highly humid areas

There has been discussion about research on HVAC strategies in high-humidity and coastal environments. While a study by Meng and Qu (2022) indicates challenges in maintaining efficiency in these environments, recent advancements in technology and design have showcased successful case studies. Ding et al., (2022) discuss the implementation of advanced dehumidification techniques in coastal commercial buildings, demonstrating the feasibility and efficiency of airside strategies. These findings challenge the misconception that HVAC strategies are inherently inefficient in coastal and high-humid areas.

2.3.2 Sufficiency of Prioritising Waterside Efficiency to Gain Overall HVAC System Efficiency

Contrary to the belief that waterside HVAC system strategies alone are sufficient, recent research emphasises the significance of airside strategies in achieving optimal energy efficiency. The research study of Tanriverdi and Gedik (2023) stresses the importance of considering airside factors in HVAC design, as neglecting these aspects can lead to suboptimal performance. Additionally, a study by Kang et al., (2016) provides evidence of energy savings achieved through prioritising airside efficiency over waterside systems, deflating the misconception that waterside strategies alone are satisfactory.

3. METHODOLOGY

Abutabenjeh and Jaradat (2018) suggested that research approaches encompass the plans and procedures guiding research from broad assumptions to detailed methods of data collection, analysis, and interpretation. Accordingly, for this study, a qualitative approach was selected, because it facilitates answering questions about the experiences, perceptive, and thoughts of the participants which cannot be understood in numerical or statistical data. Additionally, a qualitative survey comprising semi-structured interviews was employed, given the significance of comprehending varying viewpoints and misconceptions about the application of energy-efficient strategies to the airside HVAC system in commercial buildings in Sri Lanka. Moreover, semi-structured interviews allow the researchers to repeat or rephrase the interviewee's responses to get additional clarifications and assist them gain a thorough understanding of the issue of interest. According to Okken et al., (2019) adapted from Bertaux and Kohli, (1984), a qualitative survey sample was determined based on achieving data saturation and thorough exploration of the research questions within the specific context of the HVAC industry, hence, for this study, a sample of 17 respondents was chosen who all experts in the HVAC industry are.

The targeted 17 experts (refer to Table 1) are from two categories where one category comprises mechanical/HVAC engineers or facility managers of commercial high-rise buildings (E1-E11) whereas, the rest of the experts are consultants of HVAC, building services, or Building Management System (BMS) of commercial buildings (E12-E17). Experts belonging to Category 1 were selected based on their role, expertise, and experience of current engagement in a commercial high-rise (Building profile given in Table 2), in which the commercial buildings are on par with the Energy Efficiency Building Code (EEBC) as mentioned in Section 2.1. This will enable a comparison between the opinions of the experts as they all belong to the same category of commercial high-rises. The summary of the profile of the respondents is presented in Table 1.

Table 1: Profile of the respondents

Respondent	Designation	Area overlooked/ Area of Specialty	Work experience (years)
E1	Head of Facilities Management	HVAC	12
E2	HVAC Engineer	HVAC	7
E3	Facilities Manager	HVAC	19
E4	HVAC Engineer	HVAC	20
E5	Facilities Manager	HVAC	11
E6	Maintenance Engineer (Mechanical)	HVAC	23
E7	Mechanical Engineer	HVAC	7
E8	Mechanical Engineer	HVAC	5
E9	Head of the Engineering Department	HVAC	7
E10	Assistant Maintenance Engineer	HVAC	8
E11	MEP Manager project	Building Services	15
E12	HVAC consultant	HVAC consultant	42
E13	Assistant Director	MVAC	15
E14	ELV and BMS Consultant	ELV	10
E15	Building Service Engineer	Building Services	25
E16	HVAC System Consultant	Building Services, HVAC system designer	10
E17	Consultant MEP Engineer	HVAC	15

Table 2: Building profiles

Respondent	Total energy consumption (monthly average)	Total HVAC consumption (monthly average)	HVAC as a percentage	Total monthly bill	Peak demand
E1	1.4 Mn kWh	704,359 kWh	50%	Rs. 33 Mn	4200kVA
E2	669,310 kWh	468,517 kWh	65-70%	Rs. 16 Mn	1400 kVA
E3	190,000 kWh	95,000 kWh	50%	Rs. 2 Mn	400 kVA
E4	1.1 Mn kWh	550,000 kWh	50%		4500kVA
E5	580,000 kWh	240,000 kWh	50%	Rs. 14 Mn	1800kVA
E6	1.5 Mn kWh	705,000 kWh	50%	Rs.36 Mn	400 kVA
E7	453,246 kWh	172,694 kWh	40%	Rs. 800,000	1500-1600 kVA
E8	473,342 kWh	129,866 kWh	27.6 %	Rs.800,000	1500 kVA
E9	400,000 kWh	289000 kWh	30%	Rs. 4,700,000	Tower 1-640kVA Tower 2-800kVA
E10	1.4 Mn kWh	704,359 kWh	50%	Rs. 33 Mn	1000 kVA
E11	235,670 kWh	66,480 kWh	30%	Rs. 5,385,740	904 kVA

The analysis of data requires several closely related operations such as the establishment of categories, and the application of these categories to raw data through coding, and tabulation (Mishra et al., 2019). For this study, the content analysis method was used, and it was done using the NVivo software (2010) manufactured by Qualitative Solutions and Research (QSR) International (Pvt) Ltd.

3.1 RESEARCH FINDINGS

Every respondent offered perceptions based on their comprehension of HVAC Airside energy efficiency and the research findings are comprehensively described under three topics hereon.

3.1.1 Adaptation of HVAC Airside Strategies to a Tropical Country

E9 and E3 stated that the adaptation of the airside strategies for a tropical country, with a warm climate, is not possible, whereas E15, E8 and E16 had opposing ideas. According to experts E15 and E16, '*HVAC is a technical system. As far as the technology is concerned it doesn't matter what the country is, as long as the building manager has the knowledge. And in HVAC we don't use H, the heating part in Colombo, because it's a tropical country, but the remaining letters have enough impact*' and, E12 further expressed similar views to that as, the location of the country does not matter, whether it is a tropical or not, '*ASHRAE standard is a general worldwide standard. Not like CIBSE. Hence, we have to select the country climate zone, then you have to refer the particular data tables'* where it was further elaborated as '*. E.g.- SL in climate zone 0-A, when we use data from this category, we comply with ASHRAE 90.1 and reduce energy'*. A comparable opinion was given by E17 as '*being a tropical country we cannot exactly adopt things from ASHRAE, but we have to slightly modify it suitable to our country'*. Adding on to it, E14 stated that, 'tropical country' means Sri Lanka has different RH levels and temperature levels, compared to other countries, and these strategies are adaptable. Hence, many experts agree that this statement is theoretically illogical, and as E10 mentioned, '*people say this, because sometimes, the expected gain may not be there. Certain things may work, but expected output/ gain will be less'*, hence explaining why certain building service facilitators can have misconceptions about airside energy efficiency strategies. Adding on to that, E2 gave examples of HVAC airside strategies that could be easily implemented in the Sri Lankan context as the installation of efficient AHU filters, Variable Air Volume (VAV) system implementation, advanced controls and automation, Variable Speed Drive (VSDs) installation, a control system addressing varying loads, Pre-cooled Air Conditioning System (PAU), Demand Control Ventilation (DCV), night purging and air distribution and balancing.

3.1.2 Adaptation of HVAC Airside Strategies to Coastal and Highly Humid Areas

E7 stated that '*building is close to the sea so that fresh air is salty and equipment getting corroded, so we aren't going for many air efficiency improvements'* and E5 stated that, '*the facility is in the coastal area, so new methods cannot be practised as all the equipment can corrode, and equipment for proper installation would cost money for the organisation*'. Many experts had contradictory views to that of E7 and E5, and E14 generalised this statement by saying, '*corrosion is a problem in the coastal area, and it is applicable to every system. Not only to the HVAC system*'. Adding on to this, E16 stated that' *equipment that is outside, must anyway have the precautions to protect the equipment, it's not related to the energy efficiency of the airside, anyway if you have equipment outside, you need to have a precautionary method to protect the equipment*' hence stating precautions are needed for any equipment that is outside. Furthermore, E14 elaborated his opinion by stating that, considering the airside system, the RH level goes up when getting closer to the sea and the RH level in Colombo goes up to 80-90% whereas the comfort level that should be maintained is 50-55%. Therefore, a high heat load is undertaken by the air conditioning system, to bring down the air from 90% to 55%. That heat load should be undertaken by the air conditioning system, and that is the reason why '*buildings in the coastal area, require different strategies to improve the efficiency of the system, paying more attention to RH controlling. Airside controlling, therefore, is very much needed'* completely opposing the initial opinions by E7 and E5. Further, E15 explained that using his personal experience, '*most of the commercial high-rises are in Colombo. So, the coastal belt. And I have practically implemented these strategies, so it can be done'*, and E13 stated that, '*strategies can be adopted, but when we are designing, we have to design properly to be energy efficient. When designing. equipment selection or equipment should be suitable to the location/area*' where it was disclosed that air-cooled systems (air-cooled chillers, packaged units, split units, etc.) are not used near the sea belt, because of corrosion, hence explaining why selection should be done properly, and highlighting limitations that can exist when implementing HVAC Airside strategies to commercial buildings in the coastal area.

3.1.3 Sufficiency of Prioritising Waterside Efficiency to Gain Overall HVAC System Efficiency

It was observed from the findings that only a few commercial buildings measure the HVAC Airside energy efficiency. E2 said that '*we are always thinking of the chiller side for energy efficiency than AHU side'* and expert E3 stated, '*main part is chiller'* hence expressing that more focus is given to the waterside system explained the reason for this by stating, '*high percentage of energy-saving is with the waterside, that's why people are more focused on it. We have energy-efficient potential in airside, but not much as in the waterside*'. Therefore, his opinion is that, compared to the energy consumed by equipment on the waterside, the airside is not significant. E17 stated a similar opinion by mentioning that there is a logical reason for prioritising the waterside. It was his opinion that, considering the total HVAC energy efficiency, at least 60% is contributed by waterside equipment hence stating why experts prioritise implementing and measuring energy efficiency strategies to waterside than airside. However, the same expert further elaborated that, to gain total HVAC system efficiency, strategies should be adopted for both waterside and airside. E8 stated a different reason for prioritising waterside HVAC, 'im*provements that are to be done for airside equipment has not yet been addressed in the industry. Because we think, putting a blower and AHU that will work efficiently and there is no room to improve it. But still, there are improvements which can be done. Therefore, that analytical part or rather lack of knowledge is one reason*, hence stating why this area is neglected in the industry. This was further, agreed by the E14 and E15, where E14 stated that *'60-70% of the building electricity bill of Sri Lanka is for HVAC and we are compelled to tell it's because of the chiller. Because it's an easy answer'* and that people focus on bigger devices in HVAC (e.g.- chiller, cooling tower saying they consume more electricity).

Hence, in summary, this study has identified three prevalent misconceptions regarding the implementation of HVAC airside strategies in commercial buildings in Sri Lanka. First, there is a misconception that adapting HVAC airside strategies to tropical climates is impractical, despite evidence suggesting the adaptability of such strategies through adjustments in system design and operation. Second, there is a misconception that HVAC airside strategies cannot be effectively implemented in coastal and high-humidity areas due to equipment corrosion risks, overlooking feasible mitigation measures and the importance of RH control in energy efficiency. Lastly, there is a misconception that the waterside HVAC system holds priority over the airside system in achieving energy efficiency, despite potential gains that can be realised through improvements in airside equipment and operations. Addressing these misconceptions is crucial for enhancing energy efficiency practices in commercial buildings, emphasising the need for informed strategies tailored to local conditions and a comprehensive understanding of HVAC system dynamics.

4. DISCUSSION

The findings from the research shed light on the prevailing perceptions and misconceptions regarding the adaptation of HVAC airside strategies in specific contexts. The literature review underlines the debate surrounding the adaptability of airside strategies to tropical countries, emphasising the importance of tailoring HVAC systems to local conditions. As Shao et al. (2022) and Camargo et al. (2023) highlighted, innovative airside strategies effectively address the unique challenges posed by tropical climates, and the same was found from the findings of the research. The second misconception is related to airside strategies in coastal and highly humid areas where a recent study by Ding et al. (2022) discusses the implementation of advanced dehumidification techniques in coastal commercial buildings, demonstrating the feasibility and efficiency of airside strategies. This was also confirmed from the research findings that, it is very practical to implement these Airside HVAC strategies, as experts in Sri Lanka have already implemented them in coastal area commercial buildings and are gaining benefits from it. Furthermore, the study delves into the prioritisation of waterside HVAC systems over airside strategies. While some experts emphasise the significance of waterside systems for energy efficiency, citing higher potential savings, others, such as Tanriverdi and Gedik (2023) and Kang et al. (2016), highlight the importance of considering airside factors to achieve optimal energy efficiency. The research findings highlight the need for a holistic approach, debunking the misconception that prioritising waterside systems alone is sufficient.

5. CONCLUSIONS

In conclusion, the research findings contribute valuable insights into the prevalent perceptions and misconceptions surrounding the adaptation of HVAC airside strategies, particularly in tropical and coastal environments. The literature review establishes a foundation for understanding the ongoing debate, emphasising the necessity of customising HVAC systems to local conditions. Additionally, the research highlights the importance of a balanced approach between airside and waterside HVAC systems, refuting the misconception that prioritising waterside alone is sufficient for optimal energy efficiency. In essence, the research highlights the dynamic nature of HVAC airside strategies, emphasising the need for a nuanced understanding and a tailored approach to system design that considers the diverse environmental conditions buildings may face. Overall, the study emphasises the dynamic nature of HVAC airside strategies and the importance of bridging the gap between theoretical understanding and practical implementation in real-world scenarios.

6. REFERENCES

Abutabenjeh, S., & Jaradat, R. (2018). Clarification of research design, research methods, and research methodology: A guide for public administration researchers and practitioners. *Teaching Public Administration*, *36*(3), 237–258. https://doi.org/10.1177/0144739418775787

Ahmed, T., Kumar, P., & Mottet, L. (2021). Natural ventilation in warm climates: The challenges of thermal comfort, heatwave resilience and indoor air quality. *Renewable and Sustainable Energy Reviews*, *138*, 110669. https://doi.org/10.1016/j.rser.2020.110669

Amjath, M. R., Chandanie, H., & Amarasinghe, S. D. I. A. (2021, July 10). *Energy retrofits for improving energy efficiency in buildings: A review of HVAC and lighting systems*. 9th World Construction Symposium, Sri Lanka. [Online]. https://doi.org/10.31705/WCS.2021.25

Bae, Y., Bhattacharya, S., Cui, B., Lee, S., Li, Y., Zhang, L., Im, P., Adetola, V., Vrabie, D., Leach, M., & Kuruganti, T. (2021). Sensor impacts on building and HVAC controls: A critical review for building energy performance. *Advances in Applied Energy*, *4, 100068*. https://doi.org/10.1016/j.adapen.2021.100068

Bertaux, D., & Kohli, M. (1984). The Life Story Approach: A Continental View on JSTOR. *Annual Review of Sociology*, *10*, 215-237. https://www.jstor.org/stable/2083174

Boyajieff, R. (2017, June 23). *Airside efficiency: A must have ECM*. Energy sustainability solutions. https://essmag.co.uk/airside-efficiency-a-must-have-ecm

Camargo, K. C., González, J., Solano, T., Yuil, O., Velarde, V., & Austin, M. C. (2023). *Energy-Efficiency Measures to Achieve Zero Energy Buildings in Tropical and Humid Climates*. DOI:10.5772/intechopen.1002801

Ding, Z., Yu, X., Ma, Z., Wu, W., Zhang, L., Yu, D. Y. W., & Cheng, D. H. K. (2022). On-site measurement and simulation investigation on condensation dehumidification and desiccant dehumidification in Hong Kong. *Energy and Buildings*, *254, 111560*. https://doi.org/10.1016/j.enbuild.2021.111560

Emmanuel, R., & Rogithan, R. (2018). How energy efficient is the EEBC? Evaluation based on a simulated office building. *Built-Environment: Sri Lanka*, *3*(1). https://www.researchgate.net/profile/R-Emmanuel/publication/306020738_How_energy_efficient_is_the_EEBC_evaluation_based_on_a_simulated_office_building/links/57ff5d8108aeaf819a5f4ac4/How-energy-efficient-is-the-EEBC-evaluation-based-on-a-simulated-office-building.pdf

Faulkner, C. A., Lutes, R., Huang, S., Zuo, W., & Vrabie, D. (2023). Simulation-based assessment of ASHRAE Guideline 36, considering energy performance, indoor air quality, and control stability. *Building and Environment*, *240*, 110371. https://doi.org/10.1016/J.BUILDENV.2023.110371

Geekiyanage, D., & Ramachandra, T. (2018). A model for estimating cooling energy demand at early design stage of condominiums. *Journal of Building Engineering*, *17*, 43–51. https://doi.org/10.1016/j.jobe.2018.01.011

Ji, Y., Xu, P., Duan, P., & Lu, X. (2016). Estimating hourly cooling load in commercial buildings using a thermal network model and electricity submetering data. *Applied Energy*, *169*, 309–323. https://doi.org/10.1016/j.apenergy.2016.02.036

Kandaudahewa, H., & Melegoda, N. (2023). Sustainable development goals (SDGs): Implementation, achievements and challenges faced in Sri Lanka. In *Business Sustainability through Lean and Green Practices: Manufacturing SMEs in Sri Lanka*. (pp. 1-24). Faculty of Graduate Studies, University of Colombo. https://www.researchgate.net/publication/359055559

Kang, S., Ping, T. S., Islam, M. R., & Pwint, M. (2016). *Energy measurement & audit: Reference manual*. Singapore certified Energy Manager. https://www.ies.org.sg/Tenant/C0000005/PDF%20File/Registry/SCEM/EMA(1).pdf

Meng, M., & Qu, D. (2022). Understanding the green energy efficiencies of provinces in China: A Super-SBM and GML analysis. *Energy*, *239*. https://doi.org/10.1016/j.energy.2021.121912

Mishra, P., Pandey, C., Singh, U., Keshri, A., & Sabaretnam, M. (2019). Selection of appropriate statistical methods for data analysis. *Annals of Cardiac Anaesthesia*, *22*(3), 297. https://doi.org/10.4103/ACA.ACA_248_18

Okken, G. J., Jansen, E. P. W. A., Hofman, W. H. A., & Coelen, R. J. (2019). Beyond the 'welcome-back party': The enriched repertoire of professional teacher behaviour as a result of study abroad. *Teaching and Teacher Education*, *86*. https://doi.org/10.1016/j.tate.2019.102927

Patel, N. R., Risbeck, M. J., Rawlings, J. B., Maravelias, C. T., Wenzel, M. J., & Turney, R. D. (2018, July 12). *A case study of economic optimization of HVAC systems based on the Stanford University campus airside and waterside systems*. 5th International High Performance Buildings Conference, Purdue. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1252&context=ihpbc

Rahman, N. M. A., Haw, L. C., & Fazlizan, A. (2021). A literature review of naturally ventilated public hospital wards in tropical climate countries for thermal comfort and energy saving improvements. *Energies 4*(2). https://doi.org/10.3390/en14020435

Sekhar, S. C. (2016). Thermal comfort in air-conditioned buildings in hot and humid climates - why are we not getting it right? *Indoor Air*, *26*(1), 138–152. https://doi.org/10.1111/ina.12184

Selvakkumaran, S., & Limmeechokchai, B. (2013). Energy security and co-benefits of energy efficiency improvement in three Asian countries. *Renewable and Sustainable Energy Reviews*, *20*, 491-503. https://doi.org/10.1016/j.rser.2012.12.004

Shao, X., Zhang, Z., Song, P., Feng, Y., & Wang, X. (2022). A review of energy efficiency evaluation metrics for data centers. *Energy and Buildings*, *271*, 112308. https://doi.org/10.1016/j.enbuild.2022.112308

Sri Lanka Sustainable Energy Authority. (2020). *Sri Lanka Sustainable Energy Authority*.

Tanriverdi, B., & Gedik, G. Z. (2023). Importance of HVAC system selection in reducing the energy consumption of building retrofits–case study: Office building in London. *Civil Engineering and Architecture*, *11*(1), 217–227. https://doi.org/10.13189/cea.2023.110118

Urge-Vorsatz, D., Petrichenko, K., Staniec, M., & Eom, J. (2013). Energy use in buildings in a long-term perspective. *Current Opinion in Environmental Sustainability*, *5*(2), 141–151. https://doi.org/10.1016/j.cosust.2013.05.004

Weerasinghe, A., Ramachandra, T., & B Rotimi, J. O. (2016). A simplified model for predicting running cost of office buildings in Sri Lanka. In P. W. Chan and C. J. Neilson (Eds.), *Proceedings of the 32nd Annual ARCOM Conference*, *Manchester*. https://www.researchgate.net/publication/337992269_A_Simplified_Model_for_Predicting_Running_Cost_of_Office_Buildings_in_Sri_Lanka

Zakaria, Z., Kamarudin, S. K., Salehmin, M. N. I., Ahmad, N. N. R., Aminuddin, M. A., Hanapi, I. H., Osman, S. H., & Mohamad, A. A. (2023). Energy scenario in Malaysia: Embarking on the potential use of hydrogen energy. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.05.358

Zhan, J., Liu, W., Wu, F., Li, Z., & Wang, C. (2018). Life cycle energy consumption and greenhouse gas emissions of urban residential buildings in Guangzhou city. *Journal of Cleaner Production*, *194*, 318–326. https://doi.org/10.1016/j.jclepro.2018.05.124

Chauhan, U.S., Saikia, S. and Johari, S., 2024. Identifying mitigation measures for conflicting situations on Indian construction sites. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 779-788. DOI: https://doi.org/10.31705/WCS.2024.62. Available from: https://ciobwcs.com/papers/

MITIGATION MEASURES FOR CONFLICTING SITUATIONS ON INDIAN CONSTRUCTION SITES

Uttam Singh Chauhan[1], Sudarshan Saikia[2], and Sparsh Johari[3]

ABSTRACT

This study focuses on conflict in construction workers and the identification of mitigation measures to effectively control conflicts. The Analytic Hierarchy Process (AHP) technique was used in the study to rank various alternatives by their relative efficacy as viewed by construction industry representatives. Upon initial review of the literature, it became apparent that eight significant conflict areas have been identified: delayed payments, insufficient training, discrimination, inadequate resources, excessive workload, unclear site circumstances, time constraints, and lack of safety measures. There were recommendations in the form of specific and distinct mitigation measures, which have been christened M1 to M11 for the respective areas. These tactics were chosen to ensure that the root causes will be treated sufficiently for several reasons. An offline questionnaire was distributed, and more emphasis was placed on the comparative assessment of the proposed mitigation measures. This had the advantage of providing a holistic view of the efficiency of each method described by construction project managers, site engineers, and safety officials managing sites. From the AHP analysis, training and resource management solutions were rated the highest regarding their effectiveness in conflict management. Considering the above results, the study offers lessons on whom and where to focus preventive measures and interventions to achieve better organisational workplace relations and operational effectiveness in construction settings. This study benefits the construction industry by providing a parameter and source for enhancing the conflict resolution framework and ensuring a safer and more efficient building environment.

Keywords: *Analytical Hierarchy Process (AHP); Conflict; Conflict Mitigation Measures; Construction Workers.*

1. INTRODUCTION

Conflict is inevitable in human relations, which can be contained in various severity and spheres of the construction industry. Conflicts in construction projects could result from several factors, including a clash of stakeholders' interests, misunderstanding of project specifications, differences in goals or objectives, and competition for limited resources. If these concerns are not dealt with, this results in time delays and cost overheads and

[1] Undergraduate Student, Department of Civil Engineering, Indian Institute of Technology Guwahati, India, c.uttam@iitg.ac.in
[2] Post-graduate Student, Department of Civil Engineering, Indian Institute of Technology Guwahati, India, s.saikia@iitg.ac.in
[3] Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, India, sparshjo@gmail.com

strains the relations between the various project stakeholders, greatly affecting the project's success (Yu et al., 2010).

Conflict thus remains a continuous and significant issue within construction, which over time results in undesirable effects, most prominently on productivity, timelines, and results of projects. The root of this problem is multi-faceted, as it involves behavioural, contractual, and technical concerns. Poorly defined tasks and changes in building plans often contribute to increased disputes (Mitkus & Mitkus, 2014). Conflicts need to be resolved because identifying the causes of the conflicts in the first place is essential for implementing efficient management measures (Iyiola & Rjoub, 2020).

Conflict regulation is one of the key aspects that, when practised, enables organisations to provide the best working conditions for the employees, enhancing the workers' productivity. Comparable to other settings, it is imperative to identify systematic and systemic antecedents of conflicts in construction. This has deemed it fit to formulate the proper conflict management framework for the construction industry, as this social unit has its peculiarities and challenges (Nielsen et al., 2023).

This research aims to investigate conflict at the workplace and specifically in construction sites to establish how that conflict can be effectively managed. Hence, the study identified the mitigation measures of conflicts and subsequently, which mitigation measures are more prevalent to mitigate conflicts have been identified. The study offers recommendations regarding the problem and evaluates the efficiency of proposed solutions. The research aims to improve construction site conditions to become safer, more productive, and free of conflict.

2. LITERATURE REVIEW

2.1 CONFLICTS

The causes of conflict are behavioural issues and clashes made by contracts, technological challenges, changes in site conditions, delays, and claims involving modification (Sabri et al., 2022). These adverse effects of worker conflict have been acknowledged as a causal factor of safety issues on construction sites. It has implications for the workforce's well-being, leading to accidents in executing work activities in unfavourable work environments (Kim et al., 2022). Biswal et al. (2023) stated that conflicts in construction projects can arise from limited resources, such as insufficient time, money, labour payment, quality of technical specifications, availability of information, administration, and management. Other common problems include misunderstanding and having varying ideas, ways, aims, and purposes. The literature review shows the crux of the matter is a close relationship between disputes and time overruns in building projects. Conflicts affect project management strategies and could cause complications, slowing the process (Tariq & Gardezi, 2022).

2.2 CONFLICT MITIGATING MEASURES

Workers' dissatisfaction often arises from payment delays, which can substantially impact project schedules. By incorporating sophisticated financial management systems and escrow services, the availability and timely cash disbursement may be guaranteed. Well-defined payment terms of a contract, which outline precise timetables, deadlines, and conditions, help reduce uncertainties and disagreements. Consistent monitoring and supervision are essential for tracking progress and promptly rectifying deviations. This ensures financial transparency and fosters worker confidence (Samaraweera et al., 2019). Training is crucial for sustaining elevated levels of craftsmanship and ensuring safety on building sites. Customised training programs designed by industry professionals or educational institutions guarantee that employees stay with the most recent methods and safety procedures. Mentorship programs utilise the expertise of experienced employees to establish a supportive learning environment that improves the overall skills of the workforce and promotes a culture of continuous professional growth (Vignoli et al., 2021). To address discrimination, it is crucial to cultivate an atmosphere characterised by inclusivity and regard for others. Conventional sensitivity training and seminars can teach workers and management about the significance of cultural diversity and inclusion. Confidential reporting systems and a solid and effective anti-discrimination policy guarantee that employees may report problems without any apprehension of negative consequences, thus fostering justice and equality across the workplace.

Inadequate resources can severely impair a project's effectiveness and result in worker dissatisfaction. Performing comprehensive initial appraisals of project requirements and ongoing reassessments enables flexible resource allocation. By employing state-of-the-art inventory and resource tracking technology, one can guarantee the availability of the appropriate resources at the required time and location, enhancing workflow efficiency and minimising periods of inactivity (Tereso et al., 2004). Excessive workload is a notable concern that can adversely affect health and reduce productivity. Implementing explicit guidelines for overtime, which delineate remuneration rates and terms, guarantees the prevention of worker exploitation and the maintenance of work within safe thresholds. Ensuring fair distribution of work and enforcing required breaks are crucial for preserving both physical and mental well-being, improving overall efficiency and worker contentment (Kuroda & Yamamoto, 2019). Flexibility and proactive management are necessary due to the unpredictable nature of building sites. Expanding worker training to incorporate adaptive skills and problem-solving helps equip the workforce to handle unforeseen developments. Effective coordination and frequent communication between project managers and workers enable prompt adaptation to change in site circumstances, guaranteeing the smooth progress and safety of the project (Ayres & Malouff, 2007). The imperative to adhere to project deadlines frequently leads to hasty work, compromising the outcome's result and security. Implementing efficient project management strategies, such as completing tasks in phases and setting realistic deadlines, enables a balance between the urgency of meeting timeframes and the requirement for completeness. Regular audits and progress reviews enable timely modifications and ensure the achievement of project milestones without placing excessive strain on staff (Cheng et al., 2012). Maintaining worker safety necessitates constant attentiveness and strict compliance with rigorous safety measures. Regular training sessions on safety protocols, periodic safety audits, and providing safety equipment are vital. Involving employees in safety dialogues and motivating them to participate in safety strategising actively empowers them and fosters a culture that prioritises safety (Burke et al., 2006).

3. METHODOLOGY

3.1 IDENTIFICATION OF MITIGATING MEASURES

The study began with a comprehensive literature analysis, which was done to identify and define common conflict scenarios that occur at construction sites. The eight conflicting scenarios, including Payment Delays (PD), Lack of Training (LT), Discrimination (DC), Insufficient Resources (IR), Overwork (OW), Unclear Site Conditions (USC), Time Pressure (TP), and Lack of Safety (LS), have been extracted from the study conducted by Biswal et al. (2023). Concurrently, the literature research gathered viable ways to reduce each conflict. These sources included academic publications, industry reports, and case studies. A list of mitigating measures was developed, taking expert advice into account. All 11 mitigating measures are designated as M1 through M11, as indicated in Table 1.

Table 1: Conflict mitigating measures

Sl. No.	Mitigating Measures	Sources
M1	Implementing financial management tools, escrow services, regular monitoring, and increased supervision is essential for streamlining payment workflows, tracking progress, and correcting unsafe behaviour	Ishrat (2020)
M2	Conducting regular safety audits to identify and rectify potential hazards	Rozenfeld et al. (2010); Anandraj & Vijayabaskaran (2020)
M3	Establishing regular training programs for workers to enhance their skills and knowledge. Collaborating with industry experts or educational institutions to design practical training modules	Schwatka et al. (2019); Hussain et al. (2020)
M4	Implementing mentorship programs where experienced workers guide and train their less-experienced counterparts	Afolabi et al. (2019)
M5	Promoting a continuous learning culture among the workers	Cheng et al. (2004)
M6	Comprehensive evaluation of project requirements, the use of technology for efficient resource management, and the integration of rigorous planning with timely adaptation	Bellamy et al. (2001); Lam (2005)
M7	Promoting equal workload distribution among workers, preventing excessive burdens, and enforcing breaks and rest periods to avoid burnout and enhance overall well-being	Maiti (2008); Yi & Chan (2013)
M8	Promoting open communication between project managers and workers addresses resource issues and establishes confidential reporting mechanisms for discrimination incidents among workers.	Gillard & Johansen (2004); Lee et al. (2021)
M9	Incentives ensure that workers are compensated as they achieve specific project goals.	Meng and Gallagher (2012); Ogwueleka and Udoudoh (2018)

Sl. No.	Mitigating Measures	Sources
M10	Crafting contracts with explicit and detailed payment terms. Specifying payment schedules, deadlines, and conditions, reducing ambiguity and potential disputes	Koc and Gurgun (2022)
M11	Establishing clear policies regarding overtime work, ensuring that it is reasonable, compensated, and follows safety regulations	Goldenhar et al. (2003)

3.2 PRIORITISING THE IDENTIFIED FACTORS

The Analytic Hierarchy Process (AHP) was employed to prioritise mitigation measures by leveraging survey results, facilitating the systematic decision-making process. This entailed establishing a hierarchical structure to accurately represent the connection between the goal, the criteria, and the sub-criteria. The objective is to ascertain the most efficient resolution for minimising conflicts on building sites. The survey found eight primary indices correlating to the key conflicts. Sub-criteria refer to eleven secondary indicators that reflect methods of reducing the impact of each primary conflict category. These indicators are illustrated in Figure 1.

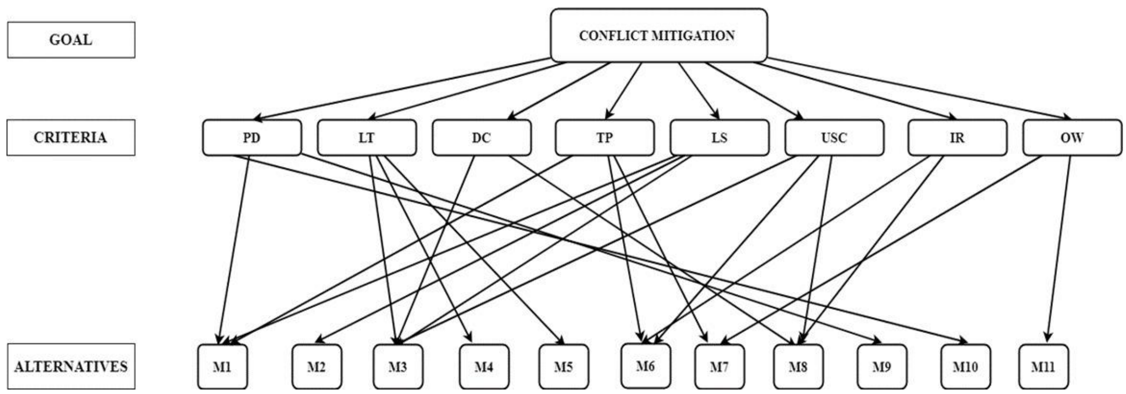


Figure 1: The AHP hierarchy model

Individual experts were tasked with developing pairwise comparison matrices at each level, where they provided opinions on the relative relevance of each component in effectively mitigating conflicts.

3.2.1 Data Collection

Participants were given paper-based surveys to collect data. The data was acquired using a questionnaire survey, where experts provided pairwise comparisons of criteria and alternatives.

3.2.2 Data Analysis

The eigenvalue approach was utilised to ascertain the weights for every criterion and sub-criterion. Consistency ratios were analysed to validate the precision of judgments. The prioritisation weights obtained from the AHP were used to rank the mitigation options according to their effectiveness.

3.2.3 Validity and Reliability

To ensure the study's validity and reliability, a pre-test of the questionnaire was conducted with a small group of construction experts. The feedback from the pilot test was used to improve the survey. Subsequently, a comprehensive analysis was conducted to assess the reliability of the AHP model. Subsequent adjustments were made to ensure a consistency ratio below 0.1, thereby ensuring the dependability of decision-making.

3.2.4 Consistency Check in AHP

The Consistency Ratio (CR) calculation is used to evaluate the coherence of the pairwise comparisons provided by participants. An evaluation of the matrix's Consistency Index (CI) about the Random Index (RI) is conducted, as proposed by Saaty (1987). The formula $CR=\frac{CI}{RI}$ is used, with the random index derived from a sample of randomly generated pairwise comparison matrices. The formula for computing the consistency index is $CI=\frac{\lambda max-n}{n-1}$. Here, λ_{max} refers to the eigenvalue of the matrix, while n represents the number of items being compared. A Consistency Ratio (CR) below 0.1 is a reliable indicator of consistency in pairwise comparisons. Participants are kindly asked to adjust their evaluations if the CR exceeds the acceptable limit. This comprehensive methodology ensures the reliability of the decision-making process, enhancing the credibility of the results and providing a systematic approach to resolving disputes on construction sites.

4. RESULTS AND DISCUSSION

A recognition of the potential of eleven mitigation measures to address workplace conflicts has been evaluated by the utilisation of the AHP. The effectiveness of all these measures was quantified statistically from the respondents' ratings, giving this approach a clear focus on where to invest efforts and how to enforce measures (M1 to M11). As shown in Table 2, the weights and sequences of all measures are given below.

Table 2: Weights of each mitigating measure

Mitigation measures	PD 0.17	LT 0.15	DC 0.03	IR 0.18	OW 0.12	USC 0.03	TP 0.10	LS 0.22	Weights
M1	0.28	0	0	0	0	0	0.17	0.22	0.11
M2	0	0	0	0	0	0	0	0.32	0.07
M3	0	0.29	0.18	0	0	0.45	0	0.47	0.16
M4	0	0.52	0	0	0	0	0	0	0.08
M5	0	0.19	0	0	0	0	0	0	0.03
M6	0	0	0	0.58	0	0.20	0.53	0	0.16
M7	0	0	0	0	0.19	0	0.66	0	0.09
M8	0	0	0.82	0.42	0	0.35	0	0	0.11
M9	0.32	0	0	0	0	0	0	0	0.05
M10	0.40	0	0	0	0	0	0	0	0.07
M11	0	0	0	0	0.81	0	0	0	0.10

The alternative weights derived from the AHP analysis highlight the emerging strategic priorities. M3 (0.16) and M6 (0.16) were the most effective strategies, emphasizing their crucial roles in comprehensively enhancing training and managing projects. M1 (0.11) and M8 (0.11), with a strong emphasis on financial management and open communication, have shown considerable potential for making a significant impact. M11 (0.10) has proven to be highly effective in regulating overtime work, making it a crucial tool for promoting fair labour practices and ensuring safety. Strategies such as M7 (0.09), M4 (0.08), and M10 (0.07) demonstrated moderate effectiveness, suggesting they play beneficial yet less crucial roles. M2 (0.07), M9 (0.05), and M5 (0.03) were given lower priority in the AHP ranking, indicating potential areas for improvement or specific circumstances in which these strategies may be more effective. Emphasising the importance of regular, structured training programs and technology integration in project management, the prioritisation of M3 and M6 is evident. These strategies are crucial in improving skill levels and efficiently managing resources, which are fundamental for addressing worker competence and resource scarcity conflicts. M1 and M8 focus on enhancing financial transparency and overcoming communication barriers. The focus on these strategies underscores the significance of transparent and responsible economic management and the necessity of effective communication channels to address conflicts and discrimination. The emphasis on overtime policies in M11 highlights the importance of implementing fair work practices that prioritise worker safety and satisfaction. These practices have a direct impact on morale and productivity. The effectiveness of M7, M4, and M10 can be attributed to their contribution to distributing workload evenly, promoting a mentoring culture, and providing clarity on contractual terms. It is crucial to prioritise establishing a harmonious work environment and well-defined expectations. This proactive approach can effectively minimise conflicts and prevent any potential misunderstandings. M2, M9, and M5 are essential strategies focusing on safety and incentives. Although they may have a lower ranking, these strategies are vital in certain situations, such as hazardous work environments or projects with strict time constraints.

5. RECOMMENDATIONS

Implementing mitigation measures on construction sites significantly affects contracts. Enhancing financial management tools and establishing precise payment schedules should incorporate specific contract terms and conditions to ensure punctual payments and financial transparency. Contracts should include provisions for mandatory training sessions and adherence to safety regulations. Regular safety audits (M2) and extensive training programs (M3) are essential for ensuring safety and compliance. Programs aimed at mentoring and fostering a learning culture imply a dedication to continuous professional development through contractual obligations. Establishing clear regulations regarding resource allocation and task distribution in contracts is crucial to prevent conflicts arising from insufficient resources and excessive workloads. This will ensure effective resource management and equal distribution of tasks. Maintaining open communication channels through a contract is essential to encourage open communication and establish clear guidelines for overtime work. The contractual stipulations address conflicts, ensure compliance, and foster a safer and more productive work environment.

6. CONCLUSIONS

By employing the AHP, this research paper has comprehensively analysed conflicts in the construction workplace and ranked the mitigation measures. The research pointed to eight broad conflict areas and created strategies for each.

Mitigating measures have extensive influences on contracts used in building construction. For instance, one of the approaches is related to the improvement of the financial management tools (M1), where the necessity of the introduction of specific types of contracts and clauses, which will define the payment periods and other issues connected with payments between the parties is stated (M10). Contracts must contain specifications for 'required training meetings' or a reference to safety standards. This is necessary for opportunities where there is a periodic revision of safety (M2) and training general sessions (M3). The hypotheses that may be deduced from the data for mentoring (M4) and promoting the learning culture of staff (M5) suggest contractual accountability for constant professional development. Because conflicts over lack of resources and work stress are common, resource management (M6) and the distribution of tasks (M7) involve establishing provisions over the distribution of resources and the safeguards for workloads in the agreement. Policies should be used to extend contractual provisions to cover places, formal communication on the issue, and set up protocols regarding extra working hours (M8 & M11). These are contractual provisions offered to avoid claims, to receive assurances, and to prevent the formation of a less risky and the best situation at the place of work.

To ensure fewer conflicts on construction sites, it is important to make necessary changes to the contracts of the construction. Contracts have become an essential component of the legal structures governing construction conflicts due to clarifying the responsibilities and powers of the contracting parties. This is the initial instance that can be used in handling a disagreement to cut its probability of developing into bigger ones. Negligence and duty of care come under tort law; they encourage implementing policies that minimise risks. Employment law regulates the contract between employer and employee; this includes matters regarding wages and work conditions and how the employer and the employee can resolve their disagreements. It guarantees that employees' conditions of service are respected, and that justice prevails within the company to avoid workers stoning each other or drifting into strike actions.

This study examines conflict management strategies for construction sites, emphasising effective communication, well-defined conflict resolution methods, and promoting a cohesive work environment. The study presents pragmatic and implementable approaches to reduce conflicts and enhance productivity. The study is grounded in an extensive literature analysis and seeks to provide a valuable understanding of successful conflict management strategies. Nevertheless, the study is constrained by its dependence on pre-existing literature, inherent biases, and the possibility that its findings may not universally apply to all construction sites. Furthermore, the study lacks actual data or direct input from construction workers. Therefore, future studies can be conducted on the limitations of this study to validate the results.

7. REFERENCES

Afolabi, A. O., Akinbo, F. T., & Akinola, A. (2019). Improving career development through a women mentoring program in the construction industry. *Journal of Physics: Conference Series, 1378*(4). https://doi.org/10.1088/1742-6596/1378/4/042031

Anandraj, A., & Vijayabaskaran, S. (2020). Construction safety audit and analysis – A conceptual approach on needy implementation for the metropolitan city-Chennai, India. *Scholars Bulletin*, *6*(8), 189–197. https://doi.org/10.36348/sb.2020.v06i08.001

Ayres, J., & Malouff, J. M. (2007). Problem-solving training to help workers increase positive affect, job satisfaction, and life satisfaction. *European Journal of Work and Organizational Psychology, 16*(3), 279–294. https://doi.org/10.1080/13594320701391804

Bellamy, J. A., Walker, D. H., McDonald, G. T., & Syme, G. J. (2001). A systems approach to the evaluation of natural resource management initiatives. *Journal of Environmental Management, 63*(4), 407–423. https://doi.org/10.1006/jema.2001.0493

Biswal, A., Husam, S., & Johari, S. (2023). Conflicting situations affecting performance of construction workers at sites. In *Proceedings of the 11th World Construction Symposium* (pp. 380–391). Sri Lanka. https://doi.org/10.31705/WCS.2023.32.

Burke, M. J., Sarpy, S. A., Smith-Crowe, K., Chan-Serafin, S., Salvador, R. O., & Islam, G. (2006). Relative effectiveness of worker safety and health training methods. *American Journal of Public Health, 96*(2), 315–324. shttps://doi.org/10.2105/AJPH.2004.059840

Cheng, E. W. L., Li, H., Love, P., & Irani, Z. (2004). A learning culture for strategic partnering in construction. *Construction Innovation*, *4*(1), 53–65. https://doi.org/10.1191/1471417504ci057oa.

Cheng, E. W. L., Ryan, N., & Kelly, S. (2012). Exploring the perceived influence of safety management practices on project performance in the construction industry. *Safety Science, 50*(2), 363–369. https://doi.org/10.1016/j.ssci.2011.09.016

Gillard, S., & Johansen, J. (2004). Project management communication: A systems approach. *Journal of Information Science, 30*(1), 23–29. https://doi.org/10.1177/0165551504041675

Goldenhar, L. M., Hecker, S., Moir, S., & Rosecrance, J. (2003). The 'Goldilocks model' of overtime in construction: Not too much, not too little, but just right. *Journal of Safety Research, 34*(2), 215–226. https://doi.org/10.1016/S0022-4375(03)00010-0

Hussain, R., Pedro, A., Lee, D. Y., Pham, H. C., & Park, C. S. (2020). Impact of safety training and interventions on training-transfer: Targeting migrant construction workers. *International Journal of Occupational Safety and Ergonomics, 26*(2), 272–284. https://doi.org/10.1080/10803548.2018.1465671

Ishrat, Z. (2020). Compendious research of Escrow payment - focusing on future considerations, trends, and applications. *European Journal of Business and Management Research*, *5*(4), 4–6. https://doi.org/10.24018/ejbmr.2020.5.4.347

Iyiola, K., & Rjoub, H. (2020). Using conflict management in improving owners and contractors relationship quality in the construction industry: The mediation role of trust. *SAGE Open*, *10*(1). https://doi.org/10.1177/2158244019898834

Kim, S., Lee, H., Hwang, S., Yi, J. S., & Son, J. W. (2022). Construction workers' awareness of safety information depending on physical and mental load. *Journal of Asian Architecture and Building Engineering, 21*(3), 1067–1077. https://doi.org/10.1080/13467581.2021.1908899.

Koc, K., & Gurgun, A. P. (2022). Ambiguity factors in construction contracts entailing conflicts. Engineering, *Construction and Architectural Management, 29*(5), 1946–1964. https://doi.org/10.1108/ECAM-04-2020-0254

Kuroda, S., & Yamamoto, I. (2019). Why do people overwork at the risk of impairing mental health? *Journal of Happiness Studies, 20*(5), 1519–1538. https://doi.org/10.1007/s10902-018-0008-x

Lam, W. (2005). Investigating success factors in enterprise application integration: A case-driven analysis. *European Journal of Information Systems, 14*(2), 175–187. https://doi.org/10.1057/palgrave.ejis.3000530

Lee, Y., Li, J. Y. Q., & Tsai, W. H. S. (2021). The role of strategic internal communication in workplace discrimination: A perspective of racial minority employees. *International Journal of Strategic Communication, 15*(1), 37–59. https://doi.org/10.1080/1553118X.2020.1855591

Maiti, R. (2008). Workload assessment in building construction related activities in India. *Applied Ergonomics, 39*(6), 754–765. https://doi.org/10.1016/j.apergo.2007.11.010

Meng, X., & Gallagher, B. (2012). The impact of incentive mechanisms on project performance. *International Journal of Project Management, 30*(3), 352–362. https://doi.org/10.1016/j.ijproman.2011.08.006

Mitkus, S., & Mitkus, T. (2014). Causes of conflicts in a construction industry: a communicational approach. *Procedia - Soc. Behav. Sci., 110*(1), 777–786. https://doi.org/10.1016/j.sbspro.2013.12.922.

Nielsen, K., Ng, K., Guglielmi, D., Lorente, L., Pătraş, L., & Vignoli, M. (2023). The importance of training transfer of non-technical skills safety training of construction workers. *International Journal of Occupational Safety and Ergonomics, 29*(1), 444–452. https://doi.org/10.1080/10803548.2022.2052624

Ogwueleka, A. C., & Udoudoh, F. P. (2018). The impact of risk and reward dynamics in incentive compensation plans in the Nigerian construction industry. *International Journal of Construction Management, 18*(3), 247–259. https://doi.org/10.1080/15623599.2017.1315545

Rozenfeld, O., Sacks, R., Rosenfeld, Y., & Baum, H. (2010). Construction job safety analysis. *Safety Science, 48*(4), 491–498. https://doi.org/10.1016/j.ssci.2009.12.017

Saaty, R. W. (1987). The analytic hierarchy process—What it is and how it is used. *Mathematical Modelling, 9*(3), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Sabri, O., Lædre, O., & Bruland, A. (2022). A structured literature review on construction conflict prevention and resolution: A modified approach for engineering. Organization, Technology and *Management in Construction, 14*(1), 2616–2630. https://doi.org/10.2478/otmcj-2022-0006

Samaraweera, P. D. P., Perera, B. A. K. S., & Dewagoda, K. G. (2019). Management of payment delays in government-funded construction projects in Sri Lanka. In *Proceedings of the 9th World Construction Symposium* (pp. 411–421). Sri Lanka. https://doi.org/10.31705/WCS.2019.41.

Schwatka, N. V., Goldenhar, L. M., Johnson, S. K., Beldon, M. A., Tessler, J., Dennerlein, J. T., Fullen, M., & Trieu, H. (2019). A training intervention to improve frontline construction leaders' safety leadership practices and overall job site safety climate. *Journal of Safety Research, 70*(1), 253–262. https://doi.org/10.1016/j.jsr.2019.04.010

Tariq, J., & Gardezi, S. S. S. (2022). Study the delays and conflicts for construction projects and their mutual relationship: A review. *Ain Shams Engineering Journal, 14*(1), 101815. https://doi.org/10.1016/j.asej.2022.101815.

Tereso, A. P., Araújo, M. M. T., & Elmaghraby, S. E. (2004). Adaptive resource allocation in multimodal activity networks. *International Journal of Production Economics, 92*(1), 1–10. https://doi.org/10.1016/j.ijpe.2003.09.005

Vignoli, M., Nielsen, K., Guglielmi, D., Mariani, M. G., Patras, L., & Peirò, J. M. (2021). Design of a safety training package for migrant workers in the construction industry. *Safety Science, 136*, 105124. https://doi.org/10.1016/j.ssci.2020.105124

Yi, W., & Chan, A. P. C. (2013). Optimizing work-rest schedule for construction rebar workers in a hot and humid environment. *Building and Environment, 61*(1), 104–113. https://doi.org/10.1016/j.buildenv.2012.12.012

Yu, A. T., Shen, G. Q., & Chan, E. H. (2010). Managing employers' requirements in construction industry: Experiences and challenges. *Facilities, 28*(7/8), 371-382.. https://doi.org/10.1108/02632771011042473

Prasadinee, W.K.R., Hadiwattage, C. and Ilangakoon, I.W.M.A.D., 2024. Navigating sustainability and digitalisation in the construction industry: A literature review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 789-801. DOI: https://doi.org/10.31705/WCS.2024.63. Available from: https://ciobwcs.com/papers/

NAVIGATING SUSTAINABILITY AND DIGITALISATION IN THE CONSTRUCTION INDUSTRY: A LITERATURE REVIEW

W.K.R. Prasadinee[1], C. Hadiwattage[2], and I.W.M.A.D. Ilangakoon[3]

ABSTRACT

This critical literature review explores the intersection of sustainable practices and digitalisation within the construction industry. Though digitalisation offers promising avenues for addressing challenges faced by the construction industry, its impact on sustainability remains underexplored. Drawing from a comprehensive synthesis of the literature, this review identifies key challenges in traditional construction industry practices, examines the benefits and challenges of digitalisation, and assesses its implications for sustainability. However, the adoption of digitalisation in the construction industry faces hurdles such as legal ambiguities, financial constraints, and resistance to change. Moreover, its impact on sustainability spans economic, environmental, and social dimensions. While digitalisation offers cost savings, improved project delivery, and enhanced worker safety, it also raises concerns about electronic waste, energy consumption, and job displacement. A holistic understanding of sustainability is crucial in navigating these complexities, encompassing economic viability, environmental stewardship, and social equity. Integrating digital technologies in construction industry practices presents opportunities and challenges for advancing sustainability goals. Ultimately, embracing sustainable digitalisation in the construction industry is essential for fostering long-term resilience and competitiveness in the dynamic construction landscape.

Keywords: *Construction Industry; Digitalisation; Sustainability.*

1. INTRODUCTION

The Construction Industry (CI) is an indispensable part of the economy, and it contributes significantly to the Gross Domestic Product (GDP) product in most countries (Saka & Adegbembo, 2022; Shiha & Dorra, 2023). Furthermore, the CI is characterised by complex operational requirements in both its internal and external environments, making it a dynamic, risky, and hazardous field (Ibem et al., 2011). According to Zhang, (2023) construction project management is indeed a challenging task due to the inherent complexity, uncertainties, and multitude of activities involved in a single project environment. Despite rapid growth, the industry faces persistent challenges such as

[1] Student, Department of Building Economics, University of Moratuwa, Sri Lanka, prasadineewkr@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, chandanieh@uom.lk
[3] Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, ashinsanai@uom.lk

collaboration issues, low productivity, resource wastage, and project delays (Pinto, 2023; Korke et al., 2023). Collaboration issues, particularly regarding trust and information sharing, significantly hinder project success (Mahmudnia et al., 2022). Moreover, documentation problems and payment failures are other challenges in traditional construction practices (Mahmudnia et al., 2022). According to Zulu et al. (2023), the absence of adequate digital expertise and technology adoption within the construction industry has also been linked to these challenges.

Embracing technological advancements in construction industry practices yields numerous benefits by overcoming the challenges faced by traditional construction industry practices, including reduced rework, reduced coordination problems, better communication between various stakeholders, reduced document errors, fewer claims, reduced paperwork, reduction in time and cost overrun, and reduction in lifecycle cost (Li et al., 2019). However, when implementing the digital application, sustainability aspects also need to be considered (Balasubramanian et al., 2022). The concept of sustainability has evolved to encompass not only environmentalism yet economic and social development as well (Ford & Despeisse, 2016). Furthermore, sustainability concepts showcase the significant value of the construction industry (Stanitsas et al., 2021). Beltrami et al. (2021) highlighted that both digital applications and sustainability have gained momentum in academic, managerial, and policy debates. According to Balasubramanian et al. (2022), digital applications impact the Triple Bottom Line (TBL) of sustainability in both positive and negative ways in the construction industry. Therefore, examining the influence of sustainable digitalisation on the perspective of the construction industry is essential.

The implementation of the digitalising construction industry globally has been discussed in numerous research studies (Maskuriy, Selamat, Ali, et al., 2019; Newman et al., 2021). However, as noted by Balasubramanian et al. (2022), the previous literature is unable to provide much clarity on the relationship between digitalisation and sustainability. Reliable and comprehensive information addressing the sustainable digitalisation of the construction industry is limited.

Therefore, the study aims to review how the integration of sustainable practices and digitalisation can address the challenges faced by the construction industry and to assess the implications of such integration on the economic, environmental, and social dimensions of sustainability. Three objectives have been set up to achieve this aim i.e. (i) identify challenges in the traditional construction industry practices, (ii) define sustainable digitalisation, and (iii) assess positive and negative implications of construction industry practices digitalisation aligned with the sustainable perspectives.

2. METHODOLOGY

A substantial amount of literature delves into the historical development of the subject and highlights significant sources, enriching the understanding of key themes (Saunders et al., 2014). Expanding on this idea, Snyder (2019) stressed the importance of a comprehensive synthesis of the literature to establish the theoretical foundations of a study. Therefore, this paper extends upon the insights garnered from a thorough analysis of the literature to review how to sustainably digitalise the construction industry.

To summarise these insights, a meticulous evaluation of the literature was conducted. This involved an exhaustive review of various sources including books, reports, theses, journals, magazines, and conference proceedings. The objective was to identify challenges in the traditional construction industry practices, define sustainable digitalisation and identify positive and negative implications of construction industry practices aligned with the sustainable perspectives. To ensure a comprehensive synthesis, search terms such as ‘Construction industry, 'Digitalisation in the construction industry', 'Issues of the construction industry, and ‘Sustainable digitalisation were carefully filtered using prominent search engines such as 'Scopus,' 'Google Scholar,' 'Emerald,' and 'Science Direct.' The selection of these databases was informed by their widespread use and comprehensive coverage of relevant literature. The inclusion of the 'Emerald' database alongside other common databases was due to its extensive repository of journals and publications focused on management and business practices, which are highly relevant to the construction industry.

3. RESULTS AND FINDINGS

3.1 CHALLENGES FACED IN TRADITIONAL CONSTRUCTION INDUSTRY PRACTICE

The traditional construction industry faces numerous challenges, impacting project performance, worker productivity, and overall efficiency (Pinto, 2023). Collaboration issues, particularly regarding trust and information sharing, significantly hinder project success (Rodrigues & Lindhard, 2023). Mahmudnia et al. (2022) highlight the critical role of trust in effective information sharing and collaboration in construction projects, noting that a lack of trust leads to inefficiencies and project delays. Furthermore, Korke et al. (2023) emphasise that low productivity in construction project management practices results in inefficient labour output, resource wastage, cost overruns, and project delays. Fragmentation across various stakeholders and organisations involved in complex projects leads to communication difficulties, scheduling problems, delays, and disputes during projects (Cakir et al., 2022). Therefore, establishing trust and information sharing among these separate entities is crucial (Pamidimukkala et al., 2023). Moreover, paper-based or inefficient electronic documentation systems create problems with information loss, security vulnerabilities, and a lack of transparency (Mahmudnia et al., 2022). This can lead to wasted time, rework due to misinterpretations, and damaged trust between project parties in construction practices (Sun et al., 2020). Furthermore, payment failures can cause significant cash flow problems and strain relationships between stakeholders (Mahmudnia et al., 2022). In addition, health and safety hazards, along with a predominant focus on cost and productivity over worker well-being, highlight additional systemic challenges (Tao et al., 2023). Figure 1 illustrates the challenges faced in the traditional construction industry identified throughout the existing literature.

3.2 DIGITALISATION AND CONSTRUCTION INDUSTRY

The construction industry has been notably hesitant to adopt technological innovations compared to sectors such as banking, manufacturing, and retail (Osunsanmi et al., 2018). However, the construction industry needs to digitalise its business processes due to the continual rise in competition and challenges, coupled with the swift development of digital technologies (Stoyanova, 2020). The historical evolution of the industry is marked by four phases, each industrial revolution contributing significantly to the current state of digital development (Sajjad et al., 2023).

Digitalisation in construction offers substantial benefits; however, it faces significant challenges to widespread adoption. Cost savings are achievable through mechanisation, robotics, and automated workflows, reducing labour expenses and material losses (Pakhale & Pal, 2020). Elimination of paper-based processes lowers project overhead costs and saves time (Mesároš & Mandičák, 2017; Ibrahim et al., 2021). Enhanced documentation enables early error detection, thereby improving project quality (Luo et al., 2022). Moreover, digitalisation improves communication, collaboration among stakeholders, and workflow efficiency (Mahmudnia et al., 2022; Oesterreich & Teuteberg, 2016), enhancing workplace safety by proactively identifying and mitigating risks (Stoyanova, 2020). Despite these benefits, the widespread adoption of digitalisation in construction is hindered by several challenges. Legal uncertainties and inadequate government policies inhibit industry growth (Lau et al., 2019; Taher, 2021), compounded by high initial implementation costs (Alaloul et al., 2020; Lau et al., 2019). Low technological competency and resistance to change pose additional barriers, with some workers hesitant to adopt new digital workflows (Shafei et al., 2022; Balasubramanian et al., 2022). Technological and security challenges further complicate digitalisation efforts (Lau et al., 2019), alongside operational incompatibilities and a lack of top management support for innovation (Alaloul et al., 2020; Oesterreich & Teuteberg, 2016).

3.3 DIGITALISATION OF THE CONSTRUCTION INDUSTRY FROM A SUSTAINABILITY PERSPECTIVE

Digitalisation in the construction industry has significant potential to enhance sustainability by balancing environmental, economic, and social development (Sajjad et al., 2023). Sustainability is a holistic and integrative concept, which addresses long-term decision-making about how to manage resources and the associated effects (Finlay, 2023). However, integrating digital technologies in construction must consider sustainability aspects (Balasubramanian et al., 2022). The concept of sustainability has evolved to encompass not only environmentalism yet economic and social development as well (Ford & Despeisse, 2016). According to Holden et al. (2014), sustainability is defined as a development that meets the present needs to reconcile economic, social, and environmental aspects (triple bottom line) without compromising future generations to meet their own needs. Sustainability concepts play a crucial role in construction projects, showcasing significant value (Stanitsas et al., 2021). The construction sector, a major global consumer of natural resources, generates significant waste annually, underscoring its environmental impact (Jain, 2021). Additionally, it holds substantial economic and social importance, contributing significantly to GDP (Alaloul et al., 2021) and employing millions of people (Babalola & Aigbavboa, 2022). Consequently, according to Goh et al. (2020), a strong link exists between construction and the three key pillars of sustainability: economy, society, and environment. Since the first industrial revolution in the 18th century, the world has faced the challenge of producing more goods from limited and diminishing natural resources to meet the increasing consumption demand, all while minimising negative environmental and social impacts (Kar & Jha, 2021). Therefore, according to Beltrami et al. (2021), both digitalisation and sustainability have gained momentum in academic, managerial, and policy debates. Consistently, the sustainability impacts of digitalisation and its potential contributions to sustainable economic, environmental, and social development are increasingly gaining attention. (Ghobakhloo, 2020).

3.3.1 Sustainable Digitalisation in Construction

Sustainable digitalisation in the construction industry involves the integration of digital tools with sustainable practices to achieve economic growth, environmental responsibility, and social well-being (Nikmehr et al., 2021). While digitalisation has the potential to positively impact sustainability, it poses challenges that need to be managed (Wang & Guo, 2022). A triple-bottom-line perspective is crucial because the various sustainability impacts of digitalisation may conflict with each other (Balasubramanian et al., 2022). For instance, blockchain could improve operational efficiency and reduce costs (enhancing economic sustainability); however, it may also increase the energy required to power the associated algorithms (diminishing environmental sustainability) (Du Plessis & Sherratt, 2020). Efforts to increase awareness and usage of digital technologies in the construction industry are essential for driving sustainable digitalisation practices forward. Figure 1 illustrates the impact of digital technologies on the triple bottom line of sustainability, encompassing both positive and negative aspects in the construction industry.

3.3.2 Digitalisation Construction Industry and Environmental Sustainability

The environmental aspect of sustainability is described as the preservation of global life-support systems, involving the ongoing protection of natural resources to prevent exceeding their limits (Moghayedi et al., 2021). Digital technologies have both positive and negative environmental implications. Digitalisation can enhance process optimisation and contribute positively to environmental sustainability by enabling more efficient resource usage (Franco et al., 2022), and a reduction in waste production (Tahmasebinia et al., 2020). On the environmental front, digital technologies can gather precise, real-time data and use analytics to gain deep insights into material usage and waste statistics, thereby reducing energy consumption and emissions (Balasubramanian et al., 2022). Alternatively, it can lead to increased waste production, such as electronic waste, and higher energy resource demand (Nikmehr et al., 2021).

3.3.3 Digitalisation of Construction Industry and Economic Sustainability

Hübner et al. (2022) define the economic aspect of sustainability as the organisation of finances to ensure a consistent flow of income in the future. The positive economic impact of digitisation primarily arises from the translation of positive environmental benefits into economic advantages (Balasubramanian et al., 2022). Digital technology helps reduce costs, including manual labour costs, inspection and supervision costs, and savings from the automation of routine administrative tasks, thereby lowering overall construction costs (Balasubramanian et al., 2022). Moreover, artificial intelligence and machine learning algorithms can accurately predict project costs and detect possible crashes, delays, and changes in the construction process (Aung et al., 2023). Additionally, according to Ahmed (2019), improvements in tracking and scheduling, timely access to project information, reduction in labour hours, quality improvement, and reduction in project completion time. Furthermore, sustainable digitalisation significantly reduces the efforts required in conventional construction monitoring and reporting procedures (Adepoju & Aigbavboa, 2020). However, negative impacts such as the high upfront cost of implementation, costs associated with employee training, upskilling, and coordination costs across various partnering firms in the value chain, and uncertain return on investments (Ejsmont et al., 2020; Newman et al., 2021).

3.3.4 Digitalisation in Construction Industry and Social Sustainability

Pieterse (2011) states that social sustainability is actions and policies that seek to ensure equitable access and distribution of rights to enhance the quality of life in society. Social sustainability has several positive and negative implications (Chan, 2020). The positive implications include improved health and safety for workers (Tender et al., 2022). This is promising because construction is one of the sectors that constitute the largest percentage of worker deaths by accidents and injuries. Furthermore, the use of digital technologies enhances accuracy by monitoring operations and reduces effort and human errors (Qureshi et al., 2022). However, digitalisation brings several adverse societal implications. There needs to be more discourse from an ethical and humanitarian perspective on the potential job losses among unskilled blue-collar workers and their future roles in the sector (Marenco & Seidl, 2021). Increased surveillance of employees raises concerns about their freedom and privacy (Calvetti, Magalhães, et al., 2020). Additionally, further discussion is needed on issues related to data privacy, cybersecurity, and data breaches associated with digitalisation (Balasubramanian et al., 2022).

4. DISCUSSION

The traditional construction industry grapples with fragmentation, inefficient documentation, and payment failures. However, digitalisation has significantly improved project management, communication, collaboration, and risk management, leading to cost savings, better project timelines, enhanced quality control, and safer working environments. Despite these benefits, the industry faces obstacles such as legal uncertainties, insufficient government support, technological challenges, resistance to change, and data security and privacy concerns.

Sustainability is crucial in construction, and the impact of digitalisation on sustainability needs careful consideration. Sustainable digitalisation combines digital tools with sustainable practices to achieve economic growth, environmental responsibility, and social well-being. Economically, digitalisation reduces manual labour costs and automates administrative tasks, leading to lower overall construction costs and improved project efficiency. Artificial intelligence and machine learning can predict project costs and identify potential issues, contributing to economic sustainability. However, high upfront costs and training expenses pose challenges. Environmentally, digitalisation enhances process optimisation and resource efficiency, leading to reduced waste production and energy consumption. Real-time data and analytics help monitor material usage and waste statistics, positively impacting environmental sustainability. Nonetheless, digitalisation can also increase electronic waste and demand for energy resources. Socially, digital technologies improve worker health and safety by monitoring operations and reducing human errors. However, there are concerns about potential job losses among unskilled workers and issues related to data privacy and surveillance. Addressing these ethical considerations is crucial to ensuring that digitalisation contributes to social well-being.

Embracing sustainable digitalisation in the construction industry is essential for achieving long-term viability, resilience, and competitiveness in the evolving digital landscape. A balanced approach that considers economic, environmental, and social aspects is necessary for sustainable digitalisation. Efforts to increase awareness and usage of digital technologies, coupled with supportive policies and regulations, can drive sustainable practices forward. Additionally, ongoing research and development are needed to address challenges and uncertainties associated with digitalisation and maximise its benefits for sustainability.

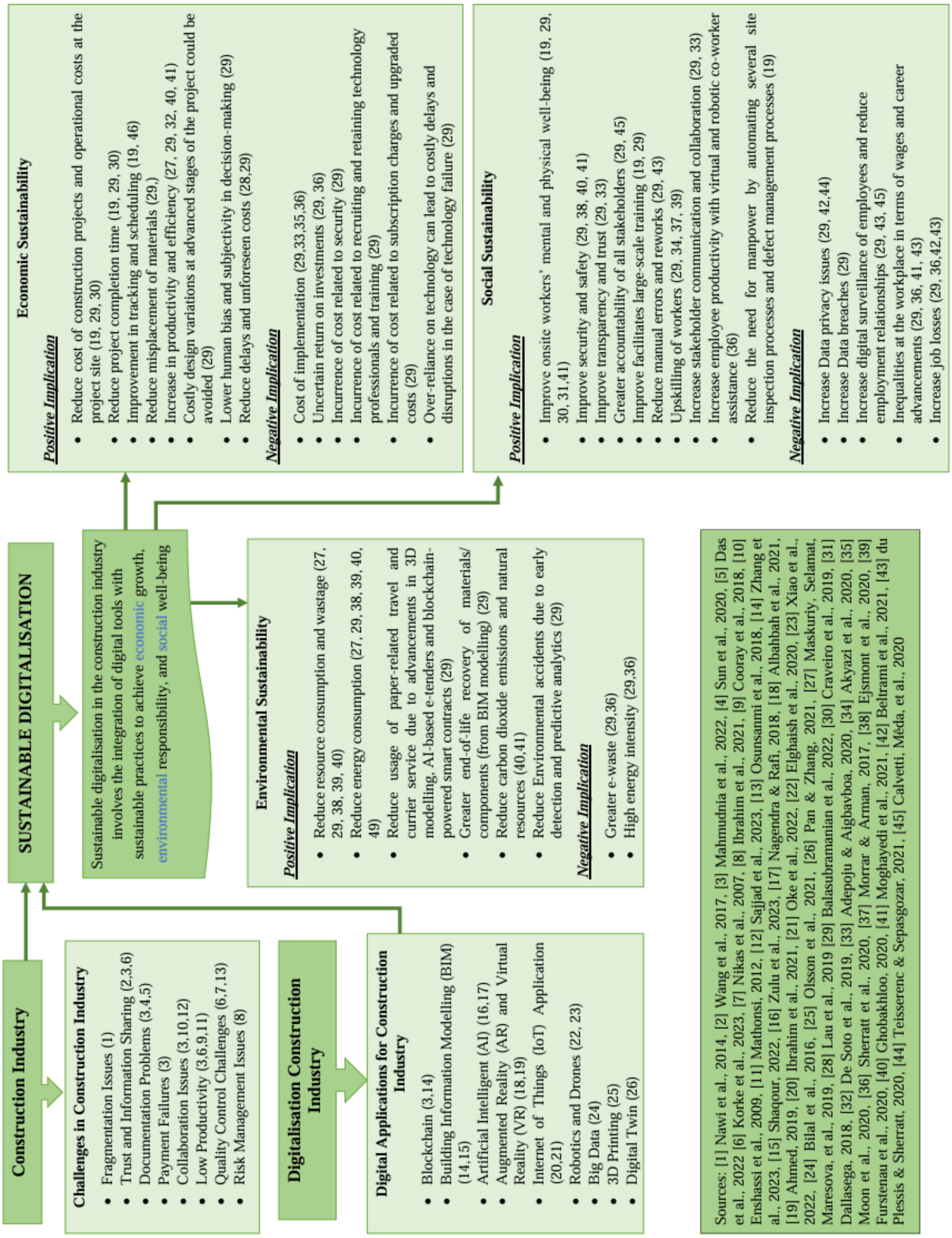


Figure 1: Summary of Literature Findings

5. CONCLUSIONS

In summary, this study delves into the challenges inherent in CI practices, explores the benefits and challenges of digitalisation in CI, and highlights the positive and negative implications of CI practices aligned with sustainable perspectives. By synthesising existing literature, this research contributes significantly to understanding how to sustainably digitalise CI. The analysis initially elucidates the hurdles faced within CI practices, providing a comprehensive review of the multifaceted challenges confronting the construction industry. Subsequently, the discussion navigates through the landscape of digitalisation in CI, elucidating both its advantages and challenges. Furthermore, the study examines how CI practices intersect with sustainability concerns, elucidating the nuanced impacts on economic, environmental, and social dimensions.

One of the primary contributions of this research lies in its thorough review of the challenges within CI practices and its exploration of digitalisation's effects on sustainability. By filling gaps in existing literature, this study provides a valuable resource for industry practitioners and researchers seeking to enhance sustainability within CI. Moving forward, industry practitioners must prioritise sustainable digitalisation within CI. This entails identifying strategies and frameworks to integrate digital technologies while ensuring alignment with sustainable principles. The findings of this research underscore the importance of proactive measures to navigate the complexities of digitalisation while promoting sustainability goals. Considering the study's outcomes, several recommendations emerge. Firstly, industry practitioners are encouraged to elevate the importance of sustainable digitalisation within their organisations, allocating resources and attention accordingly. Additionally, further research is warranted to conduct detailed surveys and practical analyses to inform the implementation of sustainable digitalisation strategies within CI practices on a global scale. Ultimately, by embracing the findings of this study and prioritising sustainable digitalisation within CI, industry stakeholders can pave the way for a more resilient, efficient, and environmentally responsible construction sector. The study is limited by the scope of the literature reviewed, potentially excluding recent research and emerging trends in digitalisation and sustainability in the construction industry. It may exhibit geographical bias due to reliance on region-specific sources, affecting the generalisability of findings across different countries. Additionally, the review broadly covers digitalisation but lacks an in-depth analysis of specific technologies such as BIM, IoT, AI, and blockchain, each of which has unique advantages, challenges, and sustainability implications that require more focused examination.

6. REFERENCES

Adepoju, O. O., & Aigbavboa, C. O. (2020). Implementation of construction 4.0 in Nigeria: Evaluating the opportunities and threats on the workforce. *Academic Journal of Interdisciplinary Studies*, *9*(5), 254. https://doi.org/10.36941/ajis-2020-0102

Ahmed, S. (2019). A review on using opportunities of augmented reality and virtual reality in construction project management. *Organization, Technology & Management in Construction*, *11*(1), 1839–1852. https://doi.org/10.2478/otmcj-2018-0012.

Akyazi, T., Alvarez, I., Alberdi, E., Oyarbide, Z. A., Goti, A., & Bayon, F. (2020). Skills needs of the civil engineering sector in the European Union Countries: Current situation and future trends. *Applied Sciences*, *10*(20), 7226. https://doi.org/10.3390/app10207226.

Alaloul, W. S., Liew, Zawawi, N. A. W. A., & Kennedy, I. B. (2020). Industrial revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders. *Ain Shams Engineering Journal*, *11*(1), 225–230. https://doi.org/10.1016/j.asej.2019.08.010.

Alaloul, W. S., Musarat, M. A., Rabbani, M. B. A., Iqbal, Q., Maqsoom, A., & Farooq, W. (2021). Construction sector contribution to economic stability: Malaysian GDP distribution. *Sustainability*, *13*(9), 5012. https://doi.org/10.3390/su13095012.

Albahbah, M., Kıvrak, S., & Arslan, G. (2021). Application areas of augmented reality and virtual reality in construction project management: A scoping review. *Journal of Construction Engineering, Management & Innovation*, *4*(3). https://doi.org/10.31462/jcemi.2021.03151172.

Aung, N. T., Liana, S. R., Htet, A., & Bhaumik, N. A. (2023). Using machine learning to predict cost overruns in construction projects. *Journal of Technology Innovations and Energy*, *2*(2), 1–7. https://doi.org/10.56556/jtie.v2i2.511.

Babalola, I. H., & Aigbavboa, C. O. (2022). Evaluating communication features of human resource management practices: The construction industry in Lagos State, Nigeria. *Businesses*, *2*(4), 471–485. https://doi.org/10.3390/businesses2040030.

Balasubramanian, S., Shukla, V., Islam, N., & Manghat, S. (2024). Construction industry 4.0 and sustainability: An enabling framework. *IEEE Transactions on Engineering Management*, *71*, 1–19. https://doi.org/10.1109/tem.2021.3110427.

Beltrami, M., Orzes, G., Sarkis, J., & Sartor, M. (2021). Industry 4.0 and sustainability: Towards conceptualization and theory. *Journal of Cleaner Production*, *312*, 127733. https://doi.org/10.1016/j.jclepro.2021.127733.

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., Owolabi, H. A., Alaka, H. A., & Pasha, M. (2016). Big data in the construction industry: A review of present status, opportunities, and future trends. *Advanced Engineering Informatics*, *30*(3), 500–521. https://doi.org/10.1016/j.aei.2016.07.001.

Cakir, I., Kaya, H. D., Dikmen, I., Atasoy, G., & Birgonul, M. T. (2022). An exploratory study on communication complexity in mega construction projects. *Earth and Environmental Science*, *1101*(4), 042045. https://doi.org/10.1088/1755-1315/1101/4/042045.

Calvetti, D., Magalhães, P. N. M., Sujan, S. F., Gonçalves, M. C., & De Sousa, H. J. C. (2020). Challenges of upgrading craft workforce into construction 4.0: Framework and agreements. *Management, Procurement and Law*, *173*(4), 158–165. https://doi.org/10.1680/jmapl.20.00004.

Calvetti, D., Mêda, P., Gonçalves, M. C., & Sousa, H. (2020). Worker 4.0: The future of sensored construction sites. *Buildings*, *10*(10), 169. https://doi.org/10.3390/buildings10100169.

Chan, P. W. (2020). Briefing: Industry 4.0 in construction: Radical transformation or restricted agenda?. *Management, Procurement and Law*, *173*(4), 141–144. https://doi.org/10.1680/jmapl.20.00036.

Cooray, N. H. K., Somathilake, H. M. D. N., Wickramasinghe, M., Dissanayake, T. D. S. H., & Dissanayake, D. M. M., I. (2018). Analysis of cost control techniques used on building construction projects in Sri Lanka. *Social Science Research Network*, *5*(23), 909–923. https://doi.org/10.2139/ssrn.3311303.

Craveiro, F., Duarte, J. P., Bartolo, H., & Bartolo, P. J. (2019). Additive manufacturing as an enabling technology for digital construction: A perspective on construction 4.0. *Automation in Construction*, *103*, 251–267. https://doi.org/10.1016/j.autcon.2019.03.011.

Dallasega, P. (2018). Industry 4.0 fostering construction supply chain management: Lessons learned from engineer-to-order suppliers. *IEEE Engineering Management Review*, *46*(3), 49–55. https://doi.org/10.1109/emr.2018.2861389.

Das, M., Tao, X., Liu, Y., & Cheng, J. C. (2022). A blockchain-based integrated document management framework for construction applications. *Automation in Construction*, *133*, 104001. https://doi.org/10.1016/j.autcon.2021.104001.

De Soto, B. G., Agustí, J. I., Joss, S., & Hunhevicz, J. (2019). Implications of construction 4.0 to the workforce and organizational structures. *International Journal of Construction Management*, *22*(2), 205–217. https://doi.org/10.1080/15623599.2019.1616414.

Du Plessis, C. & Sherratt, F. (2020). Construction 4.0 and built assets in-use creating an e-topia or dystopia?. *Management, procurement and law*, *173*(4), 182–189. https://doi.org/10.1680/jmapl.19.00054.

Ejsmont, K., Gladysz, B., & Kluczek, A. (2020). Impact of industry 4.0 on sustainability—bibliometric literature review. *Sustainability*, *12*(14), 5650. https://doi.org/10.3390/su12145650.

Elghaish, F., Matarneh, S., Talebi, S., Kagioglou, M., Hosseini, M. R., & Abrishami, S. (2020). Toward digitalization in the construction industry with immersive and drone technologies: A critical literature review. *Smart and Sustainable Built Environment*, *10*(3), 345–363. https://doi.org/10.1108/sasbe-06-2020-0077.

Enshassi, A., Mohamed, S. & Abushaban, S. (2009). Factors affecting the performance of construction projects in the Gaza Strip. *Journal of Civil Engineering and Management*, *15*(3), 269–280. https://doi.org/10.3846/1392-3730.2009.15.269-280.

Finlay, E. (2023). Editorial. *Development in Practice*, *33*(1), 1–2. https://doi.org/10.1080/09614524.2022.2155621.

Ford, S. & Despeisse, M. (2016). Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150.

Franco, de A. B. J., Domingues, A. M., Almeida, A. N., Deus, R. M. & Battistelle, R. A. G. (2022). Sustainability in the civil construction sector supported by industry 4.0 technologies: Challenges and opportunities. *Infrastructures*, *7*(3), 43. https://doi.org/10.3390/infrastructures7030043.

Furstenau, L. B., Scott, M. K., Kipper, L. M., Machado, E. L., Lopez, R., J. R., Dohan, M. S., Cobo, M. J., Zahid, A., Abbasi, Q. H., & Imran, M. A. (2020). The link between sustainability and industry 4.0: Trends, challenges and new perspectives. *IEEE Access*, *8*, 140079–140096. https://doi.org/10.1109/access.2020.3012812.

Ghobakhloo, M. (2020). Industry 4.0, digitization, & opportunities for sustainability. *Journal of Cleaner Production*, *252*, 119869. https://doi.org/10.1016/j.jclepro.2019.119869.

Goh, C. S., Chong, H., Jack, L., & Faris, A. F. M. (2020). Revisiting triple bottom line within the context of sustainable construction: A systematic review. *Journal of Cleaner Production*, *252*, 119884. https://doi.org/10.1016/j.jclepro.2019.119884.

Holden, E., Linnerud, K., & Banister, D. (2014). Sustainable development: Our common future revisited. *Global Environmental Change*, *26*, 130–139. https://doi.org/10.1016/j.gloenvcha.2014.04.006.

Hübner, D., Moghayedi, A., & Michell, K. (2022). The impact of industry 4.0 technologies on the environmental sustainability of commercial property by reducing energy consumption. *Earth and Environmental Science*, *1101*(6), 062018. https://doi.org/10.1088/1755-1315/1101/6/062018.

Ibem, E. O., Anosike, M. N., Azuh, D. E., & Mosaku, T. O. (2011). Work stress among professionals in the building construction industry in Nigeria. *Construction Economics and Building*, *11*(3), 45–57. https://doi.org/10.5130/ajceb.v11i3.2134.

Ibrahim, F. S., Esa, M., & Rahman, R. A. (2021). The adoption of IoT in the Malaysian construction industry: Towards construction 4.0. *International Journal of Sustainable Construction Engineering & Technology*, *12*(1). https://doi.org/10.30880/ijscet.2021.12.01.006.

Jain, M. S. (2021). A mini-review on generation, handling, and initiatives to tackle construction and demolition waste in India. *Environmental Technology & Innovation*, *22*, 101490. https://doi.org/10.1016/j.eti.2021.101490.

Kar, S., & Jha, K. N. (2021). Exploring the critical barriers to and enablers of sustainable material management practices in the construction industry. *Journal of Construction Engineering and Management*, *147*(9). https://doi.org/10.1061/(ASCE)co.1943-7862.0002125.

Korke, P., Gobinath, R., Shewale, M., & Khartode, B. (2023). Role of artificial intelligence in construction project management. *E3S Web of Conferences*, *405*, 04012. https://doi.org/10.1051/e3sconf/202340504012.

Lau, S. E. N., Aminudin, E., Zakaria, R., Chai, C. S., Abidin, N. I., Ahmad, R., Hamid, Z. A., Zain, M. Z. M., & Lou, E. (2019). Revolutionising the future of the construction industry: Strategising and redefining challenges. In Transactions on the Built Environment 2019, Seville, Spain 09-11 October 2019, (pp. 105–115). WIT Press. https://doi.org/10.2495/BIM190101.

Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction*, *102*, 288–307. https://doi.org/10.1016/j.autcon.2019.02.005.

Luo, H., Lin, L., Chen, K., Antwi, A., M. F., & Chen, L. (2022). Digital technology for quality management in construction: A review and future research directions. *Developments in the Built Environment*, *12*, 100087. https://doi.org/10.1016/j.dibe.2022.100087.

Mahmudnia, D., Arashpour, M., & Yang, R. (2022). Blockchain in construction management: Applications, advantages and limitations. *Automation in Construction*, *140*, 104379. https://doi.org/10.1016/j.autcon.2022.104379.

Marenco, M., & Seidl, T. (2021). The discursive construction of digitalization: A comparative analysis of national discourses on the digital future of work. *European Political Science Review*, *13*(3), 391–409. https://doi.org/10.1017/s175577392100014x.

Maskuriy, R., Selamat, A., Ali, K. N., Maresova, P., & Krejcar, O. (2019). Industry 4.0 for the construction industry—how ready is the industry?. *Applied Sciences*, *9*(14), 2819. https://doi.org/10.3390/app9142819.

Maskuriy, R., Selamat, A., Maresova, P., Krejcar, O., & David, O. O. (2019). Industry 4.0 for the construction industry: Review of management perspective. *Economies*, *7*(3), 68. https://doi.org/10.3390/economies7030068.

Mesároš, P., & Mandičák, T. (2017). Exploitation and benefits of BIM in construction project management. *Materials Science and Engineering*, *245*, 062056. https://doi.org/10.1088/1757-899x/245/6/062056.

Moghayedi, A., Awuzie, B., Omotayo, T., Jeune, K. L., Massyn, M., Ekpo, C. O., Braune, M., & Byron, P. (2021). A critical success factor framework for implementing sustainable innovative and affordable housing: A systematic review and bibliometric analysis. *Buildings*, *11*(8), 317. https://doi.org/10.3390/buildings11080317.

Moon, S., Ham, N., Kim, S., Hou, L., Kim, J., & Kim, J. (2020). Fourth industrialization-oriented offsite construction: Case study of an application to an irregular commercial building. *Engineering Construction and Architectural Management*, *27*(9), 2271–2286. https://doi.org/10.1108/ecam-07-2018-0312.

Morrar, R., & Arman, H. (2017). The fourth industrial revolution (industry 4.0): A social innovation perspective. *Technology Innovation Management Review*, *7*(11), 12–20. https://doi.org/10.22215/timreview/1117.

Nagendra, V. S., & Rafi, N. (2018). Application of artificial intelligence in construction project management. *International Journal of Research in Engineering, Science and Management*, *1*(12), 423–427. https://www.ijresm.com/Vol_1_2018/Vol1_Iss12_December18/IJRESM_V1_I12_99.pdf

Nawi, M. N. M., Baluch, N., & Bahauddin, A. Y. (2014). Impact of fragmentation issue in the construction industry: An overview. *MATEC Web of Conferences*, *15*, 01009. https://doi.org/10.1051/matecconf/20141501009.

Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W. D., & Rillie, I. (2020). Industry 4.0 deployment in the construction industry: A bibliometric literature review and UK-based case study. *Smart and Sustainable Built Environment*, *10*(4), 557–580. https://doi.org/10.1108/sasbe-02-2020-0016.

Nikas, A., Poulymenakou, A., & Kriaris, P. (2007). Investigating antecedents and drivers affecting the adoption of collaboration technologies in the construction industry. *Automation in Construction*, *16*(5), 632–641. https://doi.org/10.1016/j.autcon.2006.10.003.

Nikmehr, B., Hosseini, M. R., Martek, I., Zavadskas, E. K., & Antucheviciene, J. (2021). Digitalization as a strategic means of achieving sustainable efficiencies in construction management: A critical review. *Sustainability*, *13*(9), 5040. https://doi.org/10.3390/su13095040.

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, *83*, 121–139. https://doi.org/10.1016/j.compind.2016.09.006.

Oke, A. E., Arowoiya, V. A., & Akomolafe, O. T. (2020). Influence of the internet of things application on construction project performance. *International Journal of Construction Management*, *22*(13), 2517–2527. https://doi.org/10.1080/15623599.2020.1807731.

Olsson, N. O., Arica, E., Woods, R., & Madrid, J. A. (2021). Industry 4.0 in a project context: Introducing 3D printing in construction projects. *Project Leadership and Society*, *2*, 100033. https://doi.org/10.1016/j.plas.2021.100033.

Osunsanmi, T. O., Aigbavboa, C., & Oke, A. (2018). Construction 4.0: The future of the construction industry in South Africa. *International Journal of Civil and Environmental Engineering*, *12*(3), 206–212. https://doi.org/10.5281/zenodo.1315923.

Pakhale, P. D., & Pal, A. (2020), Digital project management in infrastructure project: A case study of Nagpur metro rail project. *Asian Journal of Civil Engineering*, *21*(4), 639–647. https://doi.org/10.1007/s42107-020-00224-4.

Pamidimukkala, A., Kermanshachi, S., & Kamali Rad, S. (2023). Ranking and weighting effective project-based communication indicators for primary and secondary stakeholders in construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *15*(1). https://doi.org/10.1061/(ASCE)LA.1943-4170.0000581.

Pan, Y., & Zhang, L. (2021). A BIM-data mining integrated digital twin framework for advanced project management. *Automation in Construction*, *124*, 103564. https://doi.org/10.1016/j.autcon.2021.103564.

Pieterse, E. (2011). Recasting urban sustainability in the South. *Development*, *54*(3), 309–316. https://doi.org/10.1057/dev.2011.62.

Pinto, H. W. (2023). Exploring the implementation of agile project management in the United States construction industry: Benefits, challenges, and success factors. *Journal of Entrepreneurship & Project Management*, *7*(7), 11–23. https://doi.org/10.53819/81018102t4163.

Qureshi, A. H., Alaloul, W. S., Hussain, S.J., Murtiyoso, A., Saad, S., Alzubi, K. M., & Ammad, S. (2022). Evaluation of photogrammetry tools following progress detection of rebar towards sustainable construction processes. *Sustainability*, *15*(1), 21. https://doi.org/10.3390/su15010021.

Rodrigues, M. R., & Lindhard, S.M. (2023). Benefits and challenges to applying IPD: Experiences from a Norwegian mega-project. *Construction Innovation*, *23*(2), 287–305. https://doi.org/10.1108/CI-03-2021-0042.

Sajjad, M., Hu, A., Waqar, A., Falqi, I. I., Alsulamy, S. H., Bageis, A. S., & Alshehri, A. M. (2023). Evaluation of the success of industry 4.0 digitalization practices for sustainable construction management: Chinese construction industry. *Buildings*, *1*(7), 1668. https://doi.org/10.3390/buildings13071668.

Saka, N., & Adegbembo, F. T. (2022). An assessment of the impact of the construction sector on the gross domestic product (GDP) of Nigeria. *Journal of Surveying, Construction & Property*, *13(*1), 42–65. https://doi.org/10.22452/jscp.vol13no14.

Saunders, M., Lewis, P., & Thornhill, A. (2014). *Research methods for business students* (5th ed.). Pearson Education Limited, London.

Shafei, H., Radzi, A. R., Algahtany, M., & Rahman, R. A. (2022). Construction 4.0 technologies and decision-making: A systematic review and gap analysis. *Buildings*, *12*(12), 2206. https://doi.org/10.3390/buildings12122206.

Shaqour, E. N. (2022). The role of implementing BIM applications in enhancing project management knowledge areas in Egypt. *Ain Shams Engineering Journal*, *13*(1), 101509. https://doi.org/10.1016/j.asej.2021.05.023.

Sherratt, F., Dowsett, R., & Sherratt, S. (2020). Construction 4.0 and its potential impact on people working in the construction industry. *Management, Procurement and Law*, *173* (4), 145–152. https://doi.org/10.1680/jmapl.19.00053.

Shiha, A., & Dorra, E. M. (2023). Resilience index framework for the construction industry in developing countries. *Journal of Construction Engineering and Management*, *149*(4). https://doi.org/10.1061/JCEMD4.COENG-12942.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039.

Stanitsas, M., Kirytopoulos, K., & Leopoulos, V. (2021). Integrating sustainability indicators into project management: The case of the construction industry. *Journal of Cleaner Production*, *279*, 123774. https://doi.org/10.1016/j.jclepro.2020.123774.

Stoyanova, M. (2020). Good practices and recommendations for success in construction digitalization. *TEM Journal*, *1*, 42–47. https://doi.org/10.18421/TEM91-07.

Sun, J., Lei, K., Cao, L., Zhong, B., Wei, Y., Li, J., & Yang, Z. (2020). Text visualization for construction document information management. *Automation in Construction*, *111*, 103048. https://doi.org/10.1016/j.autcon.2019.103048.

Taher, G. (2021). Industrial revolution 4.0 in the construction industry: Challenges and opportunities. *Management Studies and Economic Systems*, *6*, 109–127. https://platform.almanhal.com/Files/2/242186

Tahmasebinia, F., Sepasgozar, S. M., Shirowzhan, S., Niemela, M., Tripp, A., Nagabhyrava, S., Mansuri, K. K. Z., & Alonso-Marroquin, F. (2020). Criteria development for sustainable construction manufacturing in Construction Industry 4.0. *Construction Innovation*, *20*(3), 379–400. https://doi.org/10.1108/ci-10-2019-0103.

Tao, Y., Hu, H., Xu, F., & Zhang, Z. (2023). Ergonomic risk assessment of construction workers and projects based on fuzzy Bayesian network and D-S evidence theory. *Journal of Construction Engineering and Management*, *149*(6). https://doi.org/10.1061/JCEMD4.COENG-12821.

Teisserenc, B., & Sepasgozar, S. (2021). Adoption of blockchain technology through digital twins in the construction industry 4.0: A PESTELS approach. *Buildings*, *11*(12), 670. https://doi.org/10.3390/buildings11120670.

Tender, M., Fuller, P., Vaughan, A., Long, M., Couto, J. P., Damien, P., & Chow, V. (2022). Lessons from the implementation of key technological developments to improve occupational safety and health processes in a complex UK-based construction project. *Earth and Environmental Science*, *1101*(9), 092016. https://doi.org/10.1088/1755-1315/1101/9/092016.

Wang & Guo, F. (2022). Towards sustainable development through the perspective of construction 4.0: Systematic literature review and bibliometric analysis. *Buildings*, *12*(10), 1708. https://doi.org/10.3390/buildings12101708.

Wang, Wu, P., Wang, X., & Shou, W. (2017). The outlook of blockchain technology for construction engineering management. *Frontiers of Engineering Management*, *4*(1), 67. https://doi.org/10.15302/J-FEM-2017006.

Xiao, B., Chen, C., & Yin, X. (2022). Recent advancements of robotics in construction. *Automation in Construction*, *144*, 104591. https://doi.org/10.1016/j.autcon.2022.104591.

Zhang, M. (2023). Research on construction management in construction project management. *Industrial Engineering and Innovation Management*, *6*(4). https://doi.org/10.23977/ieim.2023.060408.

Zhang, T., Doan, D. T., & Kang, J. (2023). Application of building information modeling-blockchain integration in the architecture, engineering, and construction/facilities management industry: A review. *Journal of Building Engineering*, *77*, 107551. https://doi.org/10.1016/j.jobe.2023.107551.

Zulu, S. L., Saad, A. M., & Omotayo, T. (2023). The mediators of the relationship between digitalisation and construction productivity: A systematic literature review. *Buildings*, *13*(4), 839. https://doi.org/10.3390/buildings13040839.

Jayasena, H. S., 2024. O2E2: A framework for evolving cost estimation in BIM workflow. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 802-814. DOI: https://doi.org/10.31705/WCS.2024.64. Available from: https://ciobwcs.com/papers/

O_2E_2: A FRAMEWORK FOR EVOLVING COST ESTIMATION IN BIM WORKFLOW

Himal Suranga Jayasena[1]

ABSTRACT

This study proposes a novel framework and workflow, termed Object-Oriented Evolutionary Estimating (O_2E_2), for integrating cost estimation with Building Information Modelling (BIM). An inductive approach to theory, informed by a systematic literature review, was adopted to synthesise the knowledge necessary to develop the proposed framework. The developed O_2E_2 framework facilitates data exchange using Industry Foundation Classes (IFC) and enables the generation of evolving cost estimates through the design and construction process as BIM information evolves through different Levels of Detail (LOD). The framework separates elemental and construction operations cost estimation for improved accuracy and integrates cost estimates with project schedules via Object-to-Schedule Maps to facilitate comprehensive cost views within the BIM workflow. It relies on a single Model View Definition (MVD) within IFC for data exchange between cost-estimating software and other BIM tools. The framework adopts an agile approach, treating cost estimation at each LOD as a sprint within the overall workflow. Building on existing knowledge, this study presents a promising approach for BIM-based cost estimation, enabling more informed decision-making through the design and construction phases. Future research should focus on validating the framework through practical applications and evaluating its key components in individual studies.

Keywords: *Building Information Modelling (BIM) Workflows; Cost Estimation; Industry Foundation Classes (IFC); Levels of Detail (LOD); Object-Oriented Data.*

1. INTRODUCTION

Since the introduction of Building Information Modelling (BIM) nearly three decades ago, cost-estimating practices have also advanced in parallel. BIM is already being established as a standard information practice in construction and is also recognised as an effective approach for high cost-estimating accuracy (Babatunde et al., 2019). The need to develop tools, techniques, technologies, and work practices is emphasised to streamline cost estimation with BIM practices to maximise the quality of cost services with improved reliability (Stanley & Thurnell, 2014). The general approach is to link cost estimation standards to work and material quantity take-offs from BIM models (Fazeli et al., 2020). The ability of BIM technology to automate the cost estimation process, especially the time-consuming quantity take-off process within it, which can enhance accuracy and efficiency compared to manual cost estimation methods, is now well understood (Hasan & Rasheed, 2019). Despite this advancement, cost estimation has yet to achieve its best potential in a BIM environment. One of the key barriers is the limitations of current BIM

[1] Senior Lecturer, Dept. of Building Economics, University of Moratuwa, Sri Lanka, suranga@uom.lk

cost-estimating practices, which prevent full integration of cost estimation with the BIM workflow. While the need for aligning the cost practices for effective information sharing in BIM-based project delivery has long been recognised (Silva & Jayasena, 2013), the focus of developments has been on using BIM to automate conventional cost-estimating methods (Babatunde et al., 2019; Cerezo-Narváez et al., 2020; Hussain et al., 2024). Consequently, the focus on aligning cost estimation with BIM workflow has been largely neglected.

Addressing the above gap, this study proposes an alternative approach: O_2E_2, a cost-estimating practice to align it with the BIM workflow. The aim of this study is to identify a framework that integrates cost estimation with the BIM workflow of the delivery phase of a construction project. The framework addresses two key objectives i.e.:

i. identify the alignment needs of cost estimating with the BIM information schema, and
ii. identify the alignment needs of cost-estimating process with the BIM workflow

The first objective is to understand how the data structure within a BIM model can be best utilised for cost estimation and cost information sharing purposes. The second objective focuses on exploring how the evolving information through BIM workflow can be effectively integrated into the cost-estimating process.

2. LITERATURE SYNTHESIS

The existing knowledge addressing these two objectives was first synthesised from the extant literature. The literature synthesis is presented in three sections. The first section identifies the IFC schema as the appropriate information structure to review when developing the framework for sharing cost estimate information. The second section reviews ISO 19650 parts 1 and 2 to identify the requirements for aligning the cost-estimating process with the BIM workflow. The third section synthesises the specific research questions of the study.

2.1 BIM INFORMATION STRUCTURE

To ensure seamless collaboration across various software programs, the Architecture Engineering and Construction (AEC) industry has adopted Industry Foundation Classes (IFC) as the international standard for building information exchange. The International Alliance for Interoperability (IAI) initiated the IFC in 1994 (Laakso & Kiviniemi, 2012). IFC acts as a common language, allowing interoperability across different BIM applications. It defines building components with properties and connections, encompassing both physical elements (walls, windows, etc.) and non-physical ones (rooms, floors, etc.) (Silva & Jayasena, 2013). This ensures smooth data sharing across platforms, supporting collaboration, and efficiency in construction projects. Additionally, IFC data have built-in intelligence, enabling the automated computer analysis of building information (Tang et al., 2020).

The adoption of proprietary BIM systems has increased over time owing to factors such as functionality, market shares of software vendors, success stories, and technological advancements within the industry (Epasinghe et al., 2018; Won et al., 2013). Adopters often choose BIM software based on their features, the reputation of software vendors, and observations of successful implementation. Therefore, the market mechanism has been promoting proprietary BIM systems in BIM infant industries and relatively mature industries (Jayasena et al., 2023). These systems also use object-oriented information schemas compatible with IFC. They can write to and read from the IFC schema using translators with varying levels of compatibility (Lee et al., 2021). It is important to note that the underlying information structure of all systems remains compatible with the IFC. This compatibility is what enables interoperability among different BIM systems and among BIM software from different vendors (Jiang et al., 2019). Consequently, for effective and efficient cost information sharing, the IFC information structure becomes the target information schema for conceptualising cost information within the BIM workflow.

2.2 EVOLUTION OF INFORMATION THROUGH THE BIM PROCESS

The international standard addressing BIM workflow is BS EN ISO 19650-2:2018 (British Standards Institution, 2019b). It focuses on the broader workflow of information management in the delivery phase of a building and includes steps such as assessment of need, invitation to tender, tender response, and appointment. The workflow was designed to ensure efficient information management using BIM. This document emphasises the need to manage the evolving BIM information by defining the minimum information requirement for each participant at each stage of the project. Section 5 specifies the approach to achieve this by establishing the project's information requirements, information delivery milestones, and information standards, as well as the information production methods and procedures.

By establishing the appointing parties' (i.e., the clients) information requirements, the ISO specifies to "establish the level of information need required to meet each information requirement" (British Standards Institution, 2019b, p. 7) to ensure that each appointed party (i.e. project team members) will fulfil the information production and delivery at specific information levels to maintain efficient and effective BIM workflow. "A responsibility matrix should be generated as part of the information delivery planning process in one or more levels of detail" (British Standards Institution, 2019a, p. 22). A high-level responsibility matrix is first prepared as part of appointing the parties' information requirements, which is used by the appointed party in preparing their BIM execution plan. The high-level responsibility matrix is later refined into a detailed one identifying (British Standards Institution, 2019b, pp. 13-14):

- what information is to be produced,
- when the information is to be exchanged and with whom, and
- which task team is responsible for its production.

The level of information needed to meet each information requirement is established next. The details of such information are identified in each team member's Task Information Delivery Plan (TIDP) and the aggregated Master Information Delivery Plan (MIDP) of the overall delivery team.

ISO 19650 part 4 "*specifies the detailed process and criteria for decision-makings when executing an information exchange and details the implementation of the concepts in ISO 19650-1 and is applicable to any information exchange within the delivery stages covered by ISO 19650-2*" (British Standards Institution, 2022, p. 1). It emphasises how an information reviewer should take steps to ensure communication efficiency, content continuity, conformance, consistency, and completeness of information exchange. It is not prescriptive of data formats but supports IFC, among others.

ISO 19650 Part 2 specifies that team members "*shall not generate information that exceeds the required level of information need*" (British Standards Institution, 2019b, p. 18). This is further elaborated in ISO 19650 Part 1: Concepts and Principles, where the level of information needed is discussed in detail. It highlights that the purpose of the concept is to establish a framework for defining the extent and granularity of information required and that it aims to prevent the delivery of excessive information.

The practical approach taken to establish the level of information needed is by defining them using the Level of Development (LOD). The LOD framework defines the level of information and development of building elements within a BIM model. LOD allows appointed parties to depict building elements at various levels of development, ranging from basic approximations to highly detailed representations (Alshorafa & Ergen, 2019). This framework shall be used to identify the level of information needed and available for cost estimation and to define the level of cost information to be shared at a given point in the project timeline.

2.3 SPECIFIC RESEARCH QUESTIONS

Specific research questions are essential for a research study as they help to focus the research to ensure that the study remains on track and addresses the intended objectives. These questions play an important role in addressing the main purpose of the study (Barroga & Matanguihan, 2022; Creswell & Creswell, 2018).

From the extant knowledge outlined in Section 2.1, the specific research question to address the first objective, that is, identifying the alignment needs of cost estimation with the BIM information schema, can be synthesised as to how the IFC schema can be best utilised for cost estimation and cost information sharing. To address the second objective: identify the alignment needs of the cost estimating process with the BIM workflow, Section 2.2 presents knowledge that can be interpreted to define its specific research question as how the evolving levels of reliable details within a BIM LODs can effectively be integrated into the cost estimating process. However, it is observed that the first question is intertwined with the second question, presenting a challenge to address it with rigour. Consequently, the specific research questions were redefined as follows:

- RQ1: What is the appropriate methodology for writing back cost information to the IFC or other parametric BIM models?
- RQ2: How can an evolving cost estimate be produced along with BIM LOD evolution or other increasing levels of information development, as defined in the BIM workflow?

RQ1 addresses how IFC schema can be utilised for cost information sharing, while RQ2 addresses how information schema can be utilised for cost estimation with a specific focus on understanding how this could be done with evolving levels of reliable details, as may be defined by LOD or similar methods. Other parametric BIM models are accounted for in RQ1 because the review in Section 2.1 identified that they also have a similar structure; thus, the knowledge can contribute to the first objective.

3. RESEARCH METHODOLOGY

Since the answers to the specific research questions were to be explored, the theoretical approach to the study was inductive. While various research methods were viable, when the recent rise in BIM cost estimating research is considered, a knowledge-based approach emerged as the most strategic choice. This approach allowed drawing upon existing knowledge to synthesise answers to the specific RQs of the study.

3.1 RESEARCH APPROACH

A search for a technological solution in industry practices that addresses the objectives of this study was not found. Consequently, reliable data representing the experiences of a practical solution were unavailable. A preliminary search of the literature revealed a relatively high amount of research that had been carried out on BIM cost estimating. However, none of them had specifically addressed the RQs of this research, while a few had useful insights that helped address those questions. To capture the knowledge in current research that can contribute to this study, a Systematic Literature Review (SLR) was identified as the appropriate approach to this research.

SLRs are recognised for their rigorous and structured approach to collecting, analysing, and synthesising existing research (Page et al., 2021). Initially widespread in the medical sciences, SLRs have gradually gained recognition and adoption in diverse fields, such as social sciences, management, psychology, and computer science (Brewster et al., 2021). SLR has become a preferred approach for synthesising existing knowledge (Page et al., 2021), as required in this study.

A large majority of research on BIM cost estimation has focused on the automation of quantity take-offs. This focus is also aligned with the current technology and practice within the industry. They would not contribute much to this study, except when at a later stage LOD, an estimate based on accurate quantities is expected by stakeholders. These studies were excluded from the review because these approaches are now common knowledge. However, any other approach to cost estimation would have potential usefulness. To bring that knowledge in, another research question was defined.

- RQ3: How to produce an early design stage cost estimate that does not rely on detailed quantities extracted from BIM models (such as parametric estimates)?

The three research questions were addressed through the SLR guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al., 2021). While this study itself is not a full-fledged SLR, utilising the PRISMA principles is intended to enhance the transparency and clarity of the review process. The documents selected through the process were thematically analysed for three RQs. The findings were synthesised to develop the proposed framework.

3.2 SEARCH STRATEGY AND SELECTION CRITERIA

3.2.1 Search Strategy

To identify potentially relevant literature, a comprehensive search was conducted in April 2024 in the Scopus database using the following search string:

TITLE-ABS-KEY (bim AND cost AND estimat*) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp"))

This search string aimed to identify studies published from 2019 to the day of the search that focused on Building Information Modelling (BIM) and cost estimation. The search was limited to articles (ar) and conference papers (cp) to ensure the inclusion of relevant research.

Scopus is a leading curated database known for its rigorous selection processes and extensive coverage in the science and technology field (Baas et al., 2020). Many authors have chosen the Scopus search for BIM-related research (Mongeon & Paul-Hus, 2016; Radzi et al., 2023; Yin et al., 2019). Its focus on rigour and comprehensiveness permits the identification of relevant and reliable studies for this BIM cost-estimating research.

3.2.2 Selection Process

Clear reporting of the literature selection process of this study brings validity and reliability to the review findings through several means. At first, it offers transparency on how the different documents were identified and selected. It then allows other researchers to replicate and verify the results. It should also help in identifying potential selection biases, increasing the trustworthiness of the review.

The selection process followed a three-stage approach:

(i) Title Review: Titles were screened to identify studies potentially related to BIM-based cost estimating or cost information-sharing approaches. Irrelevant studies were excluded. This initial screening resulted in 261 documents being rejected, and 106 documents being moved on to the next stage.

(ii)Abstract Review: Abstracts of the remaining studies were reviewed to determine if the research explored methodologies to write cost information to IFC or other parametric BIM models, or if they link cost estimates to different levels of information in BIM at different stages of a project. Three specific RQs previously defined guided this review.

The test question was, "does this paper likely identify, explain, propose, or prompt an answer for any of the three RQs?" Studies that did not address any of these three questions were excluded. This stage resulted in the rejection of 95 documents, leaving eleven for a full-text review.

(iii) Full-text review: The full text of the remaining documents was to be reviewed for the detailed analysis. However, limited access to two studies necessitated contacting the authors for full-text access. Only one author replied along with the requested document. Consequently, altogether ten documents were retrieved and reviewed for selection.

The same three RQs were used to assess whether the research was directly linked to BIM information schema and/or evolving levels of information in BIM. The test questions this time required an answer with higher certainty: "does this paper identify, explain, propose, or prompt an answer for any of the three RQs?" Studies that did not address any of these questions were excluded.

A research paper by Abdel-Hamid and Abdelhaleem (2023) on developing a conceptual framework for 5D-BIM in cost control and management did not identify sharing cost information in IFC nor estimating practices with evolving levels of information in BIM, and hence rejected. Consequently, nine full-text papers were identified for the final review.

4. FINDINGS OF THE SYSTEMATIC LITERATURE REVIEW

A summary of the SLR is presented in Table 1. It presents key findings from the selected articles in reverse chronological order. It concisely identifies what each study is about and how each can contribute to the objectives of this study. However, this does not account for the full contribution of each study. Their contributions are elaborated further in the discussion in this section.

Table 1: Summary of literature findings

Source	Summary of Study	Contribution to Current Study
Hussain et al., 2024	A conceptual governance framework for integrating 5D BIM to enhance cost management and control.	Classifies cost estimates based on the maturity level of the project, aiding in budget approval during different project milestones. Also emphasises the importance of LODs in it.
Hussain et al., 2023	A conceptual framework for 5D-BIM in cost control and management.	Classifies cost estimation aligning the estimating process with the development of project scope and financial decision-making processes.
Alzraiee, 2022	A BIM cost estimating system using Structured Query Language (SQL).	Uses dynamic mapping to link the relevant work items, created by the estimator, to the corresponding BIM elements in a parametric environment. Involves creating a relational database of work items by the estimator.
Rouhanizadeh et al., 2021	An automated tool for cost estimation in transportation projects.	Utilises BIM and IFC to estimate costs at different stages of the project. An estimation mechanism that operates in a continuous spectrum from the study phase to the construction phase.
Ren & Zhang, 2021	A new framework for addressing BIM interoperability.	Improves the information transfer and coordination between architectural and structural IFC. Suggests extending to other fields including cost estimation
Fazeli et al., 2020	Semi-automated BIM-based cost estimation system	Links object-oriented data in BIM to activity-based cost estimation standard through MasterFormat.
D'Amico et al., 2020	Implementing BIM for infrastructure, focusing on optimising the design process through 4D and 5D BIM.	Estimating model that dynamically updates the bill of quantities (BoQ) and the project timeline. Divide BoQ into two. Bills of Supplies linked to model quantities, Bills of Resources linked to time schedule. Updates with each change.
Cerezo-Narváez et al., 2020	Integrating Cost Breakdown Structures (CBS) and Work Breakdown Structures (WBS)	Use of standardized cost classification systems such as ISO 12006-2, ISO 81346-12 and OmniClass. Utilise CBS to generate project WBS.
Mamaeva et al., 2019	A regulatory framework for cost calculation within BIM systems	Proposes a structure for developing construction costs that align with LOD and information content of BIM models.

Not all the selected studies focused on BIM cost estimation, yet they all addressed it from different points of view. Blending the SLR findings with the extant knowledge, an Integrated BIM Cost Estimating Framework was synthesised. A graphical representation of the estimating process in this framework is shown in Figure 1.

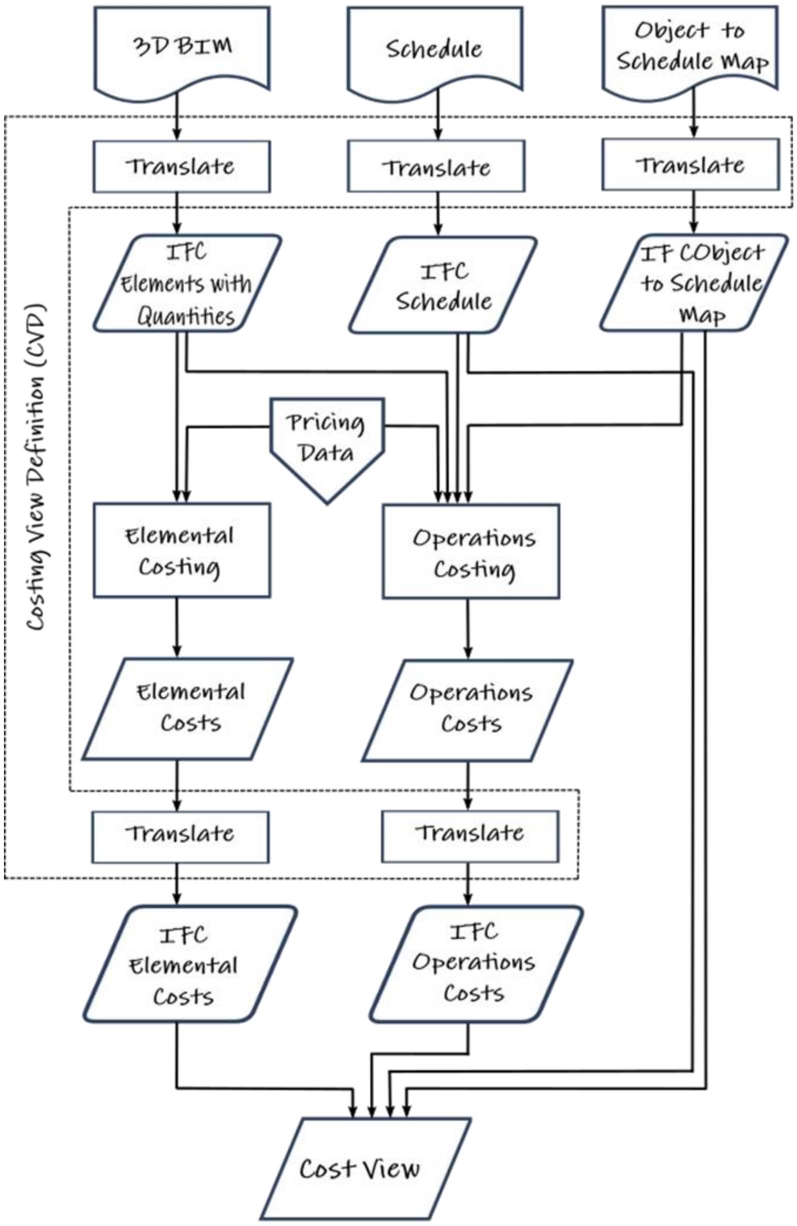


Figure 1: Integrated BIM cost estimating process framework

The cost estimation process is divided into two distinct but interlinked processes, i.e. (i) Elemental Costing, and (ii) Operations Costing. An Elemental Cost covers the cost of all the supplies that become part of a building element, while an Operations Cost covers the cost of all the resources required to build that building element. This is an efficient approach proposed by D'Amico et al. (2020) to improve the accuracy of estimates and allow complete dynamism to evolve the levels of information in BIM models.

The overall estimation process begins with information documents developed outside the estimation process. These are 3D-BIM models developed by other team members, construction schedules, and object-to-schedule maps. The object-to-schedule map procedure is followed to link BIM model objects to the Work Breakdown Structure (WBS) used in the construction schedule. Technically, the object to the schedule map is related to project time information, commonly referred to as 4D-BIM, to be established by planning engineers.

Fazeli et al. (2020) also presented a study that integrates the standards of MasterFormat and UniFormat with items of Iran's cost estimation standard: FehrestBaha. The structure of FehrestBaha is identified to be similar to MasterFormat, primarily because both are organised based on construction activities and materials. Further, similar to traditional estimating methods, FehrestBaha uses an activity-based approach to cost, instead of an object-based approach.

In Fazeli et al. (2020)'s workflow, UniFormat code is added to the building element Type Properties (as Assembly Code), while MasterFormat code is added to the material identity (as Keynote). There is a separate database to link FehrestBaha to MasterFormat and another to link UniFormat with MasterFormat. In this way, relevant UniFormat items are linked to FehrestBaha, enabling automation.

Taking a similar approach, Alzraiee Hani (2022) used Structured Query Language (SQL) to create a dynamic mapping to link the relevant work items, created by the Quantity Surveyor, to the corresponding BIM elements in a parametric environment. This method can be applied to link BIM objects to WBS items. Their method involves the creation of a relational database of work items by the estimator. Once created, they can be reused and appended when and where necessary. Dynamic mapping facilitates evolving cost estimates along with the evolving LOD of BIM data.

Cerezo-Narváez et al. (2020) analyse "whether the integration of a Cost Breakdown Structure (CBS) can lead to the generation of more robust WBSs in construction projects" (p.1). They primarily consider ISO 12006-2, ISO 81346-12, OmniClass, CoClass, CCS, and UniClass to affect the required integration. These studies will assist in developing a robust approach to integrating building elements with the work breakdown structures used in project schedules.

In the early stages of a project, construction schedules are generally not prepared. Consequently, it may become necessary for the Quantity Surveyors themselves to prepare both the schedules and object-to-schedule maps.

All three types of documents are required to begin the cost estimation process. To enable interoperability between different types of documents and cost-estimating software, data in those documents must be translated to IFC. To ensure that all relevant data are translated, and that no unnecessary data are translated, a specific Model View Definition (MVD) should be defined. For consistency, a single Costing View Definition (CVD) is recommended. As shown in Figure 1, it governs the translation of all BIM information relevant to cost estimation.

A similar approach was proposed by Ren and Zhang (2021) in their work, where they added extended material properties to the architectural model and used this material information and geometric information while generating the structural model. By doing this, they improve the information transfer and coordination between architectural and structural IFC. They suggest that this should be extended to other fields, including cost estimation. Their study highlights that, instead of a separate repository, key coordination information or data needed for coordination shall be included in the model itself. Translating the construction schedule and object-to-schedule map to IFC is therefore further justified.

The next step in the process is to perform cost estimation. As previously mentioned, this step is informed by the method used by D'Amico et al. (2020). Their method improves the estimation accuracy by separately estimating the material and resource costs. "4D BIM simulations can turn into 5D BIM simulations by incorporating information about the resource consumption. This can provide a better understanding of the utilisation of resources over time" (D'Amico et al., 2020, p. 2). This shows that their interpretation of 5D is different from common use. This, however, is more meaningful because as per this approach the 5th dimension of BIM (i.e. the cost) comes only after 3D and 4D BIM.

The material cost is proportional to the quantity of building elements. Therefore, the quantities were obtained from the element quantities of the IFC file. Prices may vary for bulk purchasing, and such adjustments can be made by the Quantity Surveyor. The resource cost (such as labour, machinery, and tools) depends on both the quantity of work and time allocated for them. Therefore, resource cost estimation requires the federation of three IFC files i.e. (i) elements with quantities, (ii) construction schedule, and (iii) object-to-schema map. Alternatively, if software can federate them in native formats and export them as one IFC, it would increase the accuracy and efficiency, as demonstrated by Ren and Zhang (2021), when they linked architectural and structural models.

Presenting their approach of two separate estimates, D'Amico et al. (2020) state that "a dynamic model is proposed that can integrate time and cost variables in a bi-directional model able to simultaneously update: (i) the parameters of the proper design model, (ii) the quantity surveying, and (iii) the timeline at any given modifications" (p. 3).

To perform the estimation, proprietary software is utilised. A price database comprising market prices of materials, building element costs, and resource costs should be a part of or linked to the proprietary software. Once the cost estimates are completed, they are exported to IFC as two separate files. The same view definition, CVD, is used to perform this translation to maintain consistency.

The exported IFC Elemental Costs and IFC Operations Costs will then be federated with IFC Schedule and IFC Object to Schedule Map in different software to generate cost views for the project stakeholder. The data richness of these documents and the full integration of data in them enables highly sophisticated views compared to conventional cost information, including yet not limited to, (i) Traditional Cost Plan view, (ii) Traditional BoQ-based view, (iii) Material costs and resource costs in project timeline view, (iv) Summary views costs and cashflows, and (v) Cost views as heatmaps in 3D models and 2D drawings.

The framework shown in Figure 1 depicts the cost estimation process in a waterfall manner. However, for the cost estimate to evolve with developing levels of information in the BIM workflow, an agile approach is required. Therefore, in evolutionary estimation, the estimation process presented in Figure 1 is only a single sprint in an agile workflow. Other papers identified in SLR contribute to identifying approaches to handle evolving levels of information in this workflow.

BIM LOD frameworks are used to define the progression or evolution of details in BIM models (Hussain et al., 2024). Rouhanizadeh et al. (2021) claim that their cost estimation mechanism *"operates in a continuous spectrum from the study phase to the construction phase" (p.1)* to cover cost estimation from LOD 100 through LOD 400. They achieve this by first mapping data between LOD, Uniformat, MasterFormat, and IFC to ensure that all necessary information is captured and accurately represented, and then developing an algorithm to find related cost items at each LOD level and extract the required information from the IFC format. Cost estimation is performed based on a cost database established on MasterFormat. Different estimation methods are implemented at different LOD. *"There are different cost items for a specific element in each LOD, and the framework must be consistent with LOD specifications. Therefore, the framework uses various cost estimation methods and implements different cost items based on the selected LODs"* (Rouhanizadeh et al., 2021, p. 6). Therefore, their cost estimation may not literally "operate in a continuous spectrum" (Rouhanizadeh et al., 2021, p. 1), yet operates at a specific evolving LOD, viz. LOD 100, LOD 200, LOD 300, LOD 350, and LOD 400.

Mamaeva et al. (2019) have developed an evolving cost estimate in parallel with the evolving LOD in BIM systems. In their approach, from the BIM model of a capital construction object, the types and scopes of works are formed for both the entire construction object and its structural elements. These data are then translated into cost estimates. The estimation is carried out using consolidated cost indices. The paper does not identify the specifics of the translation. However, the use of consolidated cost indices indicates that BIM models at generic (LOD 100) and approximate (LOD 200) levels are supported by this approach. This point is further confirmed by their statement "*LOD 400) it is required to make the minimum use of indices of the enlarged format and to make the maximum use of elemental indices with price information*" (Mamaeva et al., 2019, p. 5).

Hussain et al. (2023, 2024) proposed a conceptual governance framework to integrate BIM cost estimation with project governance. The framework assists in aligning the cost estimation process with the strategic objectives of the project and facilitates transparency and accountability. The developed framework was guided by ISO 19650. The AACE International Cost-Estimate Classification System was utilised to align the cost estimation with the evolving levels of information in BIM. This study presents an initial guidance for aligning the proposed cost-estimating workflow for societal acceptance.

5. CONCLUSIONS

Synthesising the extent of knowledge on various aspects of cost estimation with BIM, this study proposes an Object-Oriented Evolutionary Estimating (O_2E_2) framework and workflow that facilitates IFC-based data exchange and evolving estimates through the design and construction processes as BIM information evolves through different LOD. The estimation framework separates the estimation of elemental costs and construction operations costs for improved accuracy (refer to Figure 1). The integration of cost estimates with project schedules and Object-to-Schedule Maps offers comprehensive cost views through the BIM workflow. This framework relies on data exchange between cost-estimating software and other BIM tools by using IFC with a single MVD, agile workflow for cost estimation where cost estimation at a given LOD is one of its sprints. Logically developed from extant knowledge, the proposed framework and workflow provide a promising vision for integrating cost estimation with BIM workflow, enabling more informed decision-making through the design and construction process.

The study's findings point to several areas for future research. Importantly, this study is inductive, and the proposed framework needs to be tested in future research. Because the framework covers several facades, it is recommended that each of (a) object-to-schedule map, (b) concept of single Costing View Definition, (c) IFC data integration for operations costing, (d) different costing views, and (e) cost estimation at different LOD be studied individually. These may require many more exploratory studies to refine the proposed framework and workflow.

6. REFERENCES

Abdel-Hamid, M., & Abdelhaleem, H. M. (2023). Project cost control using five dimensions building information modelling. *International Journal of Construction Management, 23*(3), 405–409. doi:10.1080/15623599.2021.1880313

Alshorafa, R., & Ergen, E. (2019). Determining the level of development for BIM implementation in large-scale projects: A multi-case study. *Engineering, Construction and Architectural Management, 28*(1), 397–423. doi:10.1108/ECAM-08-2018-0352

Alzraiee, H. (2022). Cost estimate system using structured query language in BIM. *International Journal of Construction Management, 22*(14), 2731–2743. doi:10.1080/15623599.2020.1823061

Baas, J., Schotten, M., Plume, A., Côté, G., & Karimi, R. (2020). Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. *Quantitative Science Studies, 1*(1), 377–386. doi:10.1162/qss_a_00019

Babatunde, S. O., Perera, S., Ekundayo, D., & Adeleye, T. E. (2019). An investigation into BIM-based detailed cost estimating and drivers to the adoption of BIM in quantity surveying practices. *Journal of Financial Management of Property and Construction, 25*(1), 61–81. doi:10.1108/JFMPC-05-2019-0042

Barroga, E., & Matanguihan, G. J. (2022). A Practical Guide to Writing Quantitative and Qualitative Research Questions and Hypotheses in Scholarly Articles. *Journal of Korean Medical Science, 37*(16), 1-9. doi:10.3346/jkms.2022.37.e121

Brewster, C., Suutari, V., & Waxin, M.-F. (2021). Two decades of research into SIEs and what do we know? A systematic review of the most influential literature and a proposed research agenda. *Journal of Global Mobility, 9*(3), 311–337. doi:10.1108/JGM-05-2021-0054

British Standards Institution. (2019a). *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling—Part 1: Concepts and principle* (BE EN ISO 19650–1; Version 2018). BSI Standards Limited.

British Standards Institution. (2019b). *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling—Part 2: Delivery phase of the assets* (BS EN ISO 19650–2; Version 2018). BSI Standards Limited.

British Standards Institution. (2022). *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling—Part 4: Information Exchange* (BS EN ISO 19650–4; Version 2022). BSI Standards Limited.

Cerezo-Narváez, A., Pastor-Fernández, A., Otero-Mateo, M., & Ballesteros-Pérez, P. (2020). Integration of cost and work breakdown structures in the management of construction projects. *Applied Sciences, 10*(4), 1386. doi:10.3390/app10041386

Creswell, J. W., & Creswell, J. D. (2018). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (5th ed.). SAGE Publications, Inc.

D'Amico, F., D'Ascanio, L., De Falco, M. C., Ferrante, C., Presta, D., & Tosti, F. (2020). BIM for infrastructure: An efficient process to achieve 4D and 5D digital dimensions. *European Transport/Trasporti Europei, 77*, 10. doi:10.48295/ET.2020.77.10

Epasinghe, E. A. K., Jayasena, H. S., Kolugala, L. M. B. N., & Wijewickrama, M. K. C. S. (2018). Open BIM Adoption in Sri Lankan Construction Industry. *Proceedings of FOSS4G Asia 2018* (pp. 1-13). https://www.foss4g-asia.org/2018/wp-content/uploads/2018/12/Full-paper_ID_44.pdf

Fazeli, A., Dashti, M. S., Jalaei, F., & Khanzadi, M. (2020). An integrated BIM-based approach for cost estimation in construction projects. Engineering, *Construction and Architectural Management, 28*(9), 2828–2854. doi:10.1108/ECAM-01-2020-0027

Hasan, A. N., & Rasheed, S. M. (2019). The Benefits of and Challenges to Implement 5D BIM in Construction Industry. *Civil Engineering Journal, 5*(2), 412–421. doi:10.28991/cej-2019-03091255

Hussain, O. A. I., Moehler, R. C., & Walsh, S. D. C. (2023). A conceptual framework for 5d-bim cost control and management: A state-of-the-art review of mega rail projects in Victoria. *Computing* *in civil engineering 2023: visualization, information modelling, and simulation* (pp.613–621). ACSE. doi:10.1061/9780784485231.073

Hussain, O. A. I., Moehler, R. C., Walsh, S. D. C., & Ahiaga-Dagbui, D. D. (2024). Minimizing cost overrun in rail projects through 5d-bim: A conceptual governance framework. *Buildings, 14*(2), Article 478. doi:10.3390/buildings14020478

Jayasena, H. S., Thurairajah, N., Perera, B. A. K. S., & Siriwardena, M. (2023). Affordance-led framework of understanding of BIM adoption. *International Journal of Architectural Research, ahead-of-print*. doi:10.1108/ARCH-02-2023-0028

Jiang, S., Jiang, L., Han, Y., Wu, Z., & Wang, N. (2019). OpenBIM: An enabling solution for information interoperability. *Applied Sciences, 9*(24), 5358. doi:10.3390/app9245358

Laakso, M., & Kiviniemi, A. (2012). The IFC standard: A review of history, development, and standardization. *Journal of Information Technology in Construction (ITcon), 17*(9), 134–161. Retrieved from https://www.itcon.org/paper/2012/9

Lee, Y.-C., Eastman, C. M., & Solihin, W. (2021). Rules and validation processes for interoperable BIM data exchange. *Journal of Computational Design and Engineering, 8*(1), 97–114. doi:10.1093/jcde/qwaa064

Mamaeva, O. A., Burakov, S. M., & Savenkov, A. N. (2019). Establishing relevant regulatory framework for construction cost calculation in BIM-systems. *IOP Conference Series: Materials Science and Engineering* (775, pp. 1–7). IOP Science. doi:10.1088/1757-899X/775/1/012050

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of web of science and Scopus: A comparative analysis. *Scientometrics, 106*(1), 213–228. doi:10.1007/s11192-015-1765-5

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, 71. doi:10.1136/bmj.n71

Radzi, A. R., Azmi, N. F., Kamaruzzaman, S. N., Rahman, R. A., & Papadonikolaki, E. (2023). Relationship between digital twin and building information modelling: A systematic review and future directions. *Construction Innovation, 24*(3), 811–829. doi:10.1108/CI-07-2022-0183

Ren, R., & Zhang, J. (2021). A new framework to address BIM interoperability in the AEC domain from technical and process dimensions. *Advances in Civil Engineering, 2021*, 8824613. doi:10.1155/2021/8824613

Rouhanizadeh, B., Kermanshachi, S., Ramaji, I. J., & Shakerian, S. (2021). Development of an Automated Tool for Cost Estimation of Transportation Projects. *International conference on transportation and development 2021: Transportation planning and development* (pp.178–190). ACSE. doi:10.1061/9780784483541.017

Silva, R. D., & Jayasena, H. S. (2013). The need for an integrated cost modelling framework for building information modelling. In Y.G. Sandanayake & N.G Fernando (Eds.). *World construction symposium 2013: Socio-economic sustainability in construction: practice, policy and research* (pp. 427–434). CIOB. https://ciobwcs.com/downloads/WCS2013-Proceedings.pdf

Stanley, R., & Thurnell, D. P. (2014). The benefits of, and barriers to, implementation of 5D BIM for quantity surveying in New Zealand. *Construction Economics and Building, 14*(1), 105-117. doi:10.5130/AJCEB.v14i1.3786

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2020). BIM assisted building automation system information exchange using BACnet and IFC. *Automation in Construction, 110*, 103049. doi:10.1016/j.autcon.2019.103049

Won, J., Lee, G., Dossick, C., & Messner, J. (2013). Where to focus for successful adoption of building information modelling within organization. *Journal of Construction Engineering and Management, 139*(11), 04013014. doi:10.1061/(ASCE)CO.1943-7862.0000731

Yin, X., Liu, H., Chen, Y., & Al-Hussein, M. (2019). Building information modelling for off-site construction: Review and future directions. *Automation in Construction, 101*, 72-91. doi:10.1016/j.autcon.2019.01.010

Perera, S., Madushan, K.V.P. and De Silva, G.H.S.P., 2024. Pinpointing project pitfalls: A study of critical risk factors in building construction projects in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 815-826. DOI: https://doi.org/10.31705/WCS.2024.65. Available from: https://ciobwcs.com/papers/

PINPOINTING PROJECT PITFALLS: A STUDY OF CRITICAL RISK FACTORS IN BUILDING CONSTRUCTION PROJECTS IN SRI LANKA

Samindi Perera[1], K.V.P. Madushan[2] and G.H.S.P. De Silva[3]

ABSTRACT

The design phase of a construction project sets the layout for the entire endeavour but is prone to different risks. Identifying the impact of such risks may help manage them properly and achieve project objectives. The research aims to determine the effect of risk factors on the performance of building construction projects in Sri Lanka. Identification of risks and their impact was accomplished by administering a questionnaire survey and adopting the quantitative approach. The data analysis contained 42 professional insights based on experience in the design stage of building construction projects. Using a Likert scale analysis, the data was analysed employing descriptive statistical tools such as weighted averages, percentage counts, to name a few. The research findings revealed the existence of design, legal, construction, environmental, financial, management, and political risks during the design stage. The design team faces frequent legal and design risks, notably from insufficient drawings and insolvency issues. Most risks moderately affect time, cost, and quality, except for future budget considerations, which significantly impact cost parameters in Sri Lankan building projects. This study emphasises the need for a keen awareness of risks associated with the design stage to streamline the project with the set project parameters: time, cost, and quality. It sets a parameter for project practitioners engaged in the design stage of building construction projects in Sri Lanka, the level of attention they should pay to risk factors to be within the set parameters of the project.

Keywords: *Building Projects; Design Stag; Risk Factors; Sri Lanka.*

1. INTRODUCTION

Building and infrastructure construction, which serves as the nation's primary economic platform, are among the various duties the construction industry performs (Madushanka & Tilakasiri, 2020). In the construction industry, successful project completion requires meeting the three primary parameters: time, cost, and quality (Qazi et al., 2021). However, due to risks associated with these construction projects, the majority of construction projects fail to meet set objectives and miss targets (Yousri et al., 2023; Zou et al., 2007). According to Schwartz (2021), a risk is anything that might affect the project's budget, time, and quality. Risks can occur at any stage in the construction project

[1] Academic, Quantity Surveying, Kotelawala Defence University, Sri Lanka, samindi3d@gmail.com
[2] Student, Liverpool John Moores University, United Kingdom, kvpmadushan67@gmail.com
[3] Academic, Department of QS, SLIIT, Sri Lanka, priyanwadadesilva@gmail.com

life cycle, from project initiation to project closure (Qazi et al., 2021). Therefore, identifying risks is essential to managing a construction project (Yousri et al., 2023). As responsible professionals, project managers must monitor every event and know its impact on the project's success or outcome (Ghaleb et. al., 2022).

Construction requires a variety of activities, making construction projects complex (Bahamid et al., 2019). The construction industry mainly engages with unknown, unexpected, unpredictable, and undecided factors (Kishan et al., 2014). On the other hand, the unique nature associated with construction activities also makes the construction industry a risky trade (Abeysinghe & Jayathilaka, 2022) and makes risks a part of the day-to-day life of construction projects (Yousri et al., 2023; Zou et al., 2007). With such a nature, achieving the set project objectives is easier if the project is well-planned and managed (Yousri et al., 2023). These risks include design, logistics, environmental, management, finances, construction, and politics. Many scholars, such as Kishan et al. (2014), Zou et al. (2007), and Yousri et al. (2023), indicated that every project must adopt a systematic risk management process to implement an appropriate plan for construction projects. Moreover, most of these scholars agreed that the first step of this process would be identifying risks (Goral, 2007; Qazi et al., 2021; Yousri et al., 2023). Thus, it is factual that proper risk identification can help the attainment of the objectives of a project (Qazi et al., 2021).

Yousri et al. (2023) indicated that in the initial stage of a project, design errors and design integration errors bring high risks to the project's safety and performance, and the responsibility for these weaknesses directly falls on the consultants and clients with their design liability (Awuni, 2019). Thus, they are responsible for ensuring a well-coordinated and error-free design during the design stage (Goral, 2007). A construction project's design phase has systematic implications that impact the entire project from inception to completion (Wuni, 2023). It also dictates the methodology of construction and other related activities (Zou et al., 2007) and significantly affects the decisions taken during the latter part of the project, specifically in the construction stage (Wuni, 2023). Therefore, the risks and the risk factors during the design stage can extensively impact the entire project (Smith et al., 2014). However, these risk factors may vary depending on various influences, such as the composition of the design team, the approach to mitigate the risk, and demographic factors. A study conducted on Risk assessment by Eskander (2018) indicated the six types of risks influencing Arabian construction projects as acts of God: physical, economic, political, design, and job site-related risks. The risks in Egyptian construction projects are categorised into 35 risk factors under six types: planning and controlling, execution, regulation, project finance, communication, unforeseen conditions and resources (Yousri et al., 2023).

The building projects in Sri Lanka are not an exception but are also vulnerable to risks during the design stage for various reasons. According to a study conducted by Madushanka and Tilakasiri (2020), the possibility of risks during the tendering and designing stages is 11% and 18%. Though these percentages appear slightly trivial, they significantly impact overall project parameters. Therefore, identifying these risks related to the design stage can minimise the impact on the entire project. The literature on risk management in the Sri Lankan construction industry is more focused on the whole lifecycle of construction projects, and there is a lack of studies specifically focused on the design stage of building construction projects. Therefore, this research aims to investigate the impact of risk factors during the design stage on the objectives of building construction projects in Sri Lanka. Thus, the study's objectives include investigating the likelihood of occurrence of specific risk factors at the design stage and analysing their impact in terms of time, cost, and quality aspects of the building construction projects during the design stage.

2. LITERATURE REVIEW

Every construction project is unique and built once (Yousri et al., 2023). It involves several stakeholders with direct or indirect interests in its outcome. Scholars use different perspectives to define risk (Ghaleb et al., 2022). While financiers and developers examine a project's financial and economic aspects, engineers, designers, and contractors consider risk from a technological standpoint (Baloi & Price, 2003). According to Genc (2023), risk is the probability of negative incidences that impact the project goals. Ignoring risks creates disasters in the project (Genc, 2023; Yousri et al., 2023). Risks also compromise the project's goals, which include scope, budget, schedule, and quality (Genc, 2023). However, risk in the construction business is the existence of opportunities or dangers, whether real or hypothetical, that affect the goals of projects during the project construction. The risk level depends on the construction project's complexity (Ghaleb et al., 2022). When a project gets complex, the level of risks also escalates (Adedokun et al., 2023; Wuni et al., 2023). However, each risk can affect every phase of the construction project as it fills with liabilities and assets (Asaminew, 2021). Among these risks, the risks associated with the design stage can make a huge impact throughout the project lifecycle (Awuni, 2019; Yousri et al., 2023).

2.1 TYPES OF RISKS AND RISK FACTORS

The literature contains different classifications of risks depending on different aspects, such as the project's nature, causes of risks, building elements, to name a few (Awuni, 2019; Goral, 2007; Yousri et al., 2023). The literature identifies many scholars who attempted to classify different risks related to construction projects (Bahamid et al., 2019; Genc, 2023). Accordingly, in studying the Ghanaian construction industry, Awuni (2019) classified risks into eight types: financial, contractual, economic, environmental, political, technological, social, and force majeure. According to Awuni (2019), technological risks include the risks related to the operational and execution of technology in the project, and financial risks are the matters associated with financing the project. They further describe political risk as matters or concerns linked with the local, regional, and state political and governing conditions challenging the project, as well as economic risks as matters or concerns related to the macroeconomic influence of the project on the public and region. Moreover, they identify environmental risks as matters related to environmental problems. Construction risks involve design changes, labour issues, etc. (Mahendra et al., 2013). According to Zou et al. (2007), the design risk involves matters such as specifying requirements and estimating time and resources to complete the design. Legal risks relate to obtaining permits and the vagueness of work legislation. Management risks are related to works that require top management's consent before making decisions (Adedokun et al., 2023).

Studying the Turkish construction industry, Genc (2023) identified 33 principal risk factors and focused on critical ones in different construction contexts. Bahamid et al. (2019) identified 56 risk factors crucial for developing countries' construction industries. By deepening the study, Shen et al. (2001) classified time-related risks as cost, time overruns, and not meeting the targets as expected. Analysing these risks, they further stated that cost overruns force scope or quality reductions to stay within the baseline budget, and performance risk arises. Moreover, they described quality risk as the possibility of losses due to poor quality that exceeds the client's expectations. Similarly, Madushanka and Tilakasiri (2020) identified design, political, safety, and fault risks in the Sri Lankan construction industry. Moreover, they indicated that the local construction industry has significant financial and time risks. Another study on financial and economic risks associated with Sri Lankan high-rise apartment building construction projects revealed 17 risk factors. It indicated financial problems due to estimation errors as the most significant risk factor (Perera et al., 2020). Another study on critical factors affecting the performance of large construction projects in developing countries revealed 66 risk factors that impact the construction performance in the Sri Lankan context (Santoso & Gallage, 2020).

2.2 IMPACTS OF RISKS

Risks are inherent to construction projects, and no construction project is free of risks (Samarakkody & Perera, 2023). Productivity, performance, quality, and cost are the primary areas where risk can impact a construction project (Kangari, 1995). Studying the Ghanian construction project, Awuni (2019) expressed that the risk and uncertainty during the design phase can significantly impact the entire project in terms of time, cost and quality. According to Genc (2023), failure to identify risks may make it unable to achieve the completion date, keep the expenditure within the agreed cost estimate, and thereby fail to achieve the quality and the operational requirements of a construction project. Similarly, Shen et al. (2001) revealed that poor quality can lead to product recalls, client complaints, reduced durability, and cracks in the structure. Apart from the construction project being complex, the lack of coordination among the project team at the early stage will impact the project's performance (Awuni, 2019). Therefore, there is no doubt that the statement made by Andi (2006) stresses the importance of the recognition of risks and their appropriate assignment to contractual partners.

3. METHODOLOGY

The study employed the quantitative research approach, which collects numerical data and analyses it mathematically (Creswell & Creswell, 2017). Reviewing the risks and risk factors associated with the design stage of construction projects was conducted through a comprehensive literature survey using journal articles, conference papers, books, etc. Scholars of construction management commonly use questionnaire surveys to gather information on behaviours, opinions, and attitudes, and they consider them a cost-effective way of gathering data (Genc, 2023). The study explored several risks associated with the design stage of building construction projects in Sri Lanka and their impacts on project parameters: time, cost, and quality by administering a questionnaire survey among the construction project professionals engaged as design team members. The developed questionnaire survey gathered perceptions of 42 industry practitioners. Finally, the study employed descriptive statistical tools such as weighted averages and percentage counts through Likert scale analyses to analyse the data. The Likert scale is a popular technique that measures attitudes, concepts, and values. It is also a principal instrument in measuring general and emotional phenomena (Kusmaryono et al., 2022). Alabi and Jelili (2023) propose five to seven items on a Likert scale as acceptable for most constructs.

Kusmaryono et al. (2022) found that over 90% of research uses five-point Likert scales. The study adopted two 5-point- Likert scales, and Table 1 illustrates the Likert scales used to explain the frequency of occurrence and the level of impact of risk factors on time, cost, and quality of the building project.

Table 1: Likert scales

1a: Frequency of occurrence of risk factors during the design stage			**1b: Level of impact of risk factors against the quality, time, and cost parameters of the building project**		
Result	**Value**	**Range**	**Result**	**Value**	**Range**
Never	1	1.00 – 1.80	Very Low	1	1.00 – 1.80
Very Rare	2	1.81 – 2.60	Low	2	1.81 – 2.60
Rare	3	2.61 – 3.40	Moderate	3	2.61 – 3.40
Often	4	3.41 – 4.20	High	4	3.41 – 4.20
Very Often	5	4.21 – 5.00	Very high	5	4.21 – 5.00

The Likert scale, 1*a:* where “very low” = 1 and “very high” = 5 and *1b:* where “never” = 1 and “very often” = 5, to investigate the frequency of occurrence of risk factors during the design stage and to explore the level of impact of risk factors against the quality, time, and cost parameters of the building project respectively.

Moreover, the study made the following assumptions when using the two Likert scales: identifying risks and exploring their impacts. The distance between “very often” and “often”, “very high” and “high” is the same as “often” and “moderate” and “high” and “moderate” in 1a and 1b Likert scales, respectively. With this assumption, the distance between “never” and “very rare”, “very low” and “low” in 1a and 1b Likert scales is five times greater than the distance between “very often” and “often”, “very high” and “high” in 1a and 1b respectively. This study considers only limited risk factors under design, construction, environment, legal, financial, management and political risks.

Though different researchers identified many risk factors within the Sri Lankan context (Perera et al., 2020; Santoso & Gallage, 2020), the study examined only a limited number of risk factors under identified risks during the design stage of building construction projects in Sri Lanka. Accordingly, under the *design risks*, the study considered the lack of drawings and designs, lack of design team skills competencies, the durability of the building, suitability of structure (design) for climate conditions, misunderstanding site conditions, the complexity of the building, the orientation of the building, and consideration of the future maintained budget. *Legal risk:* insolvency litigation matters; *construction risk*: durability of the building; *environmental risk*: suitability of structure (design) for climate conditions, misunderstanding site conditions, health safety issues; financial risk*:* consideration of future maintained budget, *management risk:* an impermanent workforce and under *political risk:* only the country's economic situation considered for further studies.

4. DATA ANALYSIS AND DISCUSSION

4.1 DETAILS OF THE RESPONDENTS

According to the data collected, the majority of 52% of respondents were Quantity Surveyors while 21% were Engineers. The rest consist of 10% Architects, planning engineers, managerial level offices, Environmental and Safety Officers, and Technical Officers. Figure 1 shows the respondents' working experience during the design stage of building construction projects in Sri Lanka.

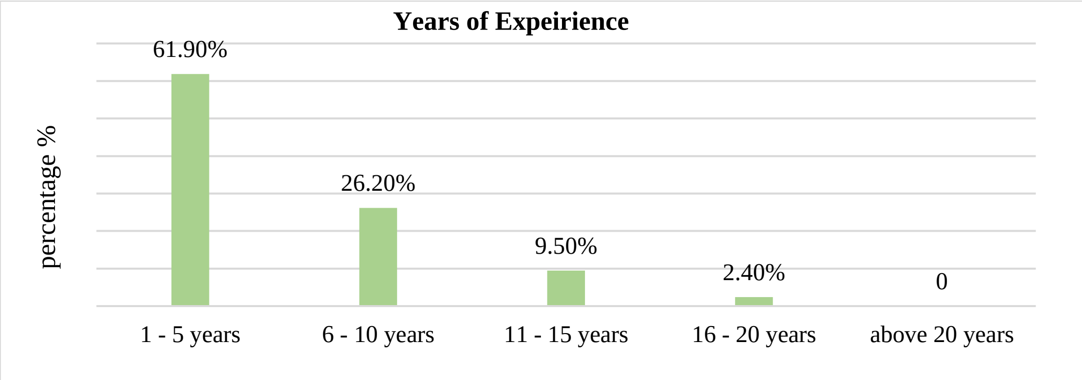


Figure 1: Working experience during the design stage in building construction projects

Table 2 provides the respondent's details of the questionnaire survey.

Table 2: Details of respondents

Profession	Usage
Quantity Surveyors	52%
Engineers	21%
Architects	10%
Project Managers	5%
Planning Engineer	2%
Deputy General Manager	2%
Quality Assurance Engineer	2%
Environmental and Safety Officer	2%
Technical Officer	2%

As per Figure 1, 61.9% of respondents who participated in the survey have 1-5 years of experience in building construction projects, while 26.2% have 6-10 years of experience, 9.5% have 11-15 years of experience, and 2.4% have 16-20 years of experience. However, in the sample, all respondents reported having less than 20 years of experience in building construction projects.

4.2 FREQUENCY OF OCCURRENCE OF RISK FACTORS DURING THE DESIGN STAGE IN BUILDING CONSTRUCTION PROJECTS

Figure 2 illustrates the frequency of occurrence of different risks during the design stage.

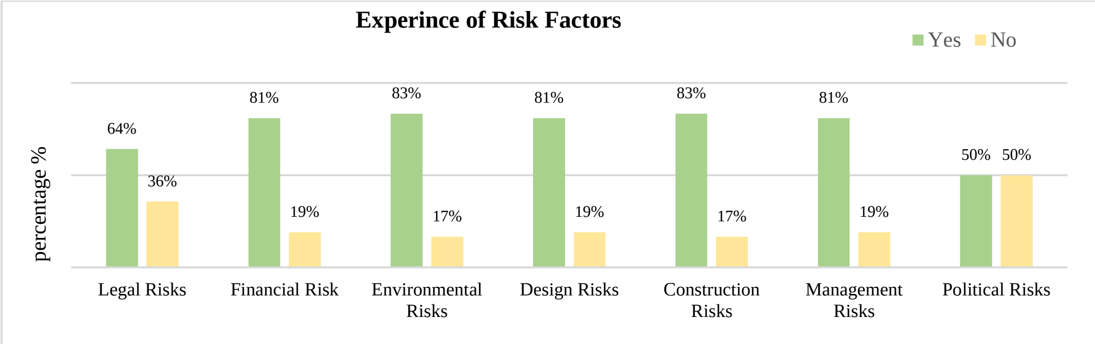


Figure 2: Frequency of occurrence of different risks during the design stage

According to the respondents, the majority confirmed the existence of all the listed risks in Figure 2 above during the design stage of building construction projects in Sri Lanka. Accordingly, 83% of the population confirmed they had experienced environmental and construction risk factors during the design stage of building construction projects in Sri Lanka. Similarly, 81% of respondents confirmed the existence of design risk factors and management risk factors. In contrast, only 50% indicated the presence of political risk factors during the design stage of building construction projects in Sri Lanka. Therefore, the review of responses confirms that Sri Lankan construction projects face all potential risk factors during the design phase. Table 3 indicates the frequency of different types of risks.

Table 3: Frequency of occurrence of different risks

Risk factors	Weighted average	Frequency of Occurrence
Design risk	3.619	Often
Construction risk	3.167	Rare
Environment risk	3.167	Rare
Legal risk	3.643	Often
Financial risk	3.333	Rare
Management risk.	3.071	Rare
Political risk	3.000	Rare

Moreover, the respondents indicated that design and legal risks occur often, while financial, construction, environmental, management, and political risks occur rarely during the design stage in building construction projects.

Table 4, indicates the frequency of occurrence of risk factors identified under different types of risks and their impact on project performance.

Table 4: Frequency of the occurrence of risk factors and their impacts

Risk	Risk Factors	Frequency	Time	Cost	Quality
Design risk	Lack of drawings and designs	Often (3.619)	Moderate (3.143)	Moderate (3.071)	Moderate (3.286)
	Lack of design team skills & competencies	Rare (3.119)	Moderate (2.952)	Moderate (3.143)	Moderate (3.262)
	Durability of building	Rare (3.167)	Moderate (3.071)	Moderate (3.095)	Moderate (3.286)

Risk	Risk Factors	Frequency	Time	Cost	Quality
	Suitability of structure (Design) for climate conditions	Rare (3.167)	Moderate (3.190)	Moderate (3.167)	Moderate (3.238)
	Misunderstanding site conditions	Rare (3.238)	Moderate (3.071)	Moderate (3.214)	Moderate (3.167)
	Complexity of building	Rare (3.262)	Moderate (2.833)	High (3.238)	Moderate (3.262)
	Orientation of building	Rare (3.095)	Moderate (3.024)	Moderate (3.167)	Moderate (3.310)
	Consideration of future maintained budget	Rare (3.333)	Moderate (3.119)	Moderate (3.357)	Moderate (3.310)
Legal risk	Insolvency & litigation matters	Often (3.643)	Moderate (2.833)	Moderate (2.952)	Moderate (3.143)
Construction risk	Durability of building	Rare (3.167)	Moderate (3.071)	Moderate (3.095)	Moderate (3.286)
Environment risk	Suitability of structure (Design) for climate conditions	Rare (3.167)	Moderate (3.190)	Moderate (3.167)	Moderate (3.238)
	Misunderstanding site conditions	Rare (3.238)	Moderate (3.071)	Moderate (3.214)	Moderate (3.167)
	Health & safety issues	Rare (3.095)	Moderate (3.000)	Moderate (3.071)	Moderate (3.000)
Financial risk	Consideration of future maintained budget	Rare (3.333)	Moderate (3.119)	High (3.357)	Moderate (3.310)
Management risk	An impermanent workforce	Rare (3.071)	Moderate (3.095)	Moderate (3.214)	Moderate (3.214)
Political risk	The country's economic situation	Rare (3.000)	Moderate (2.881)	Moderate (3.262)	Moderate (3.214)

According to Table 4, the respondents indicated that under the design risks, the frequency of lack of drawings is often whilst the other risk factors: lack of design team skills and competencies, durability of building, suitability of structure (design) for climate conditions, misunderstanding site conditions, complexity of building and orientation of building rarely appears during the design stage. The respondents recognised that insolvency and litigation matters under legal risks also appear often whilst the other risk factors under construction: durability of the building, environment, suitability of structure (design) for climate conditions, misunderstanding site conditions, health safety issues, financial: consideration of future maintained budget, management: an impermanent workforce and political risk: the country's economic situation rarely appear during the design stage of the building construction projects.

4.3 IMPACT OF THE RISK FACTORS ON TIME, COST, AND QUALITY ASPECTS OF THE BUILDING CONSTRUCTION PROJECTS

As illustrated in Table 4, the respondents confirmed that all the risk factors moderately impact the time and cost of building construction projects in Sri Lanka. Moreover, considering the cost, the data indicated that the factors except for considering future budget maintenance risk factors under financial risk and complexity of the building under design risk, all the other factors have a moderate impact on the project cost. In contrast, respondents confirmed that considering future budget maintenance risk factors under financial risk and complexity of the building under design risk make a high impact on the project cost.

4.4 DISCUSSION

The design stage is a crucial phase in a construction project as it sets the foundation for the entire endeavour (Goral, 2007; Madushanka & Tilakasiri, 2020; Wuni, 2023). Even though it sets the groundwork for the project's success, it also shows a high vulnerability to risks that can significantly impact the whole project and its outcomes. The design phase faces seven types of risks: design, legal, construction, environmental, financial, management, and political risks. These design stage risks have risk factors that contribute to the project's overall performance in different ways. The data analysis revealed the existence of all these six risks during the design stage of building construction projects in Sri Lanka. Among them, the most experienced risks by the design team professionals are the legal and design risks. Similarly, a study on the Ghanaian construction industry by Awuni (2019) revealed that contractual risks appear to be a significant type with a high impact on the project.

Under the design risk factor, while lack of drawings and design occur often, the other risk factors such as lack of design team skills and competencies, the durability of the building, suitability of structure (design) for climate conditions, misunderstanding site conditions, complexity of the building, orientation of building and consideration of future maintained budget reported a rare occurrence. Insolvency and litigation under legal risks also often occur during the design phase. In contrast, all the other risk factors under construction, environmental, financial, management, and political risks, rarely occur during the design stage. Similarly, MacMillan et al. (2002) revealed that lack of drawings, state law and economics, and misunderstanding related to site circumstances and weather are the most critical risk factors in the UK construction industry.

Overall, the risk factors under six types of risks associated with the design stage indicate a moderate impact on building projects' time and quality parameters. In support of research findings, Latham et al. (1994) pointed out that delays caused by subcontractors and consultants are significant in government projects and result in time and cost overruns. Furthermore, he stressed that this problem is common in traditional types of contracts, where they proceed with the lowest bid at all times in the projects carried out by the state in developing countries. In terms of the impact against the cost of the building construction projects in Sri Lanka, except for the risk factor: consideration of future budget, which comes both under design risk and financial risks, which showed a high impact, all t the other risk factors showed a moderate impact against the cost parameter. The research findings prove that considering risks during the design stage of a building construction project is not just about eliminating the uncertainty but also handling them proactively. Identifying the gravity of potential risks early during the design stage can facilitate planning actions for a smooth run and successful project completion within time, cost, and quality parameters.

5. CONCLUSIONS

Risks associated with the design stage of a construction project can have a domino effect, influencing every aspect of the project. Understanding these risks and risk factors is essential in every construction project to act on today's competitive business landscape. Therefore, identifying them to decide on mitigatory measures during the project's early stages can ensure its goals are successful. This study revealed that the design risk factors can considerably impact the project objectives (time, cost, and quality) of building construction projects in Sri Lanka. Therefore, every building construction project must consider identifying potential risks to integrate risk management practices during the design stage into practice. As a result, it seemed worthwhile to identify risks and risk factors in Sri Lankan building construction projects. Previous research has analysed individual risk factors, neglecting a broader view that identifies hazards and evaluates their potential impact on project parameters. The main focus of this study was to identify the impact of several design risk factors on the project parameters.

This study identified six categories that contributed to the issues in building construction projects: legal, financial, environmental, design, construction, and political risks. Among these risks associated with the design stage, the legal and design risks are the two types that often entangle with the design stage. However, considering risk factors associated with six kinds of risks of the design stage, it showed a moderate occurrence except for lack of drawings and designs under design risk and insolvency and litigation matters under legal risks. All the other risk factors show a rare occurrence during the design stage of building construction projects in Sri Lanka. However, in terms of their impact on the project parameters, time, cost, and quality, except two risk factors: consideration of future budget, which comes under design risk, and consideration of future maintained budget under financial risks, which showed a high impact against the cost parameter of the project, all the other risk factors showed moderate implications against time, cost and quality parameters.

The study revealed that the design stage is associated with risk factors that can impact the project parameters differently. Since the design stage sets the layout for the entire project, it is worth carefully identifying these risks to proactively handle them to minimise the impact on the set parameters of the project. Even though it is impossible to eliminate every risk and risk factor, the best solution would be to identify possible risks associated with the design stage and minimise the number of occurrences and their impact on the project's time, cost and quality.

5.1 LIMITATIONS

The study only focused on specific risk factors under six types of risks that exist in the design stage of building construction projects in Sri Lanka. Similarly, only the practitioners with experience working during the design stage of the building construction projects participated in the data collection.

5.2 FURTHER RESEARCH DIRECTIONS

This investigative study identifies the critical risk factors at the design stage in building construction, which allows the exploration of the impact of the same risk factors in infrastructure projects, including roads, bridges, and dam construction.

6. ACKNOWLEDGMENTS

The authors thank the Sri Lanka Institute of Information Technology (SLIIT) and Kotelawala Defence University for facilitating this timely research. Further, they acknowledge the time and effort of this study's respondents for their contribution

7. REFERENCES

Abeysinghe, N., & Jayathilaka, R. (2022). Factors influencing the timely completion of construction projects in Sri Lanka. *PLoS ONE, 17*(12), e0278318. Retrieved from https://doi.org/10.1371/journal.pone.0278318

Adedokun, O. A., Egbelakin, T., Adedokun, D. O., & Adafin, J. (2023). Success criteria-based impacts of risk factors on education building projects in southwestern Nigeria. *Journal of Engineering, Design and Technology, 21*(6), 1901–1924. Retrieved from https://doi.org/10.1108/JEDT-09-2021-0458

Alabi, A. T., & Jelili, M. O. (2023). Clarifying Likert scale misconceptions for improved application in urban studies. *Quality & Quantity, 57*(2), 1337–1350. Retrieved from https://doi.org/10.1007/s11135-022-01415-8

Andi. (2006). The importance and allocation of risks in Indonesian construction projects. *Construction Management and Economics, 24*(1), 69–80. Retrieved from https://doi.org/10.1080/01446190500310338

Asaminew, F. (2021). Assessing risk management in construction companies: Case study of real estate companies in Ethiopia [Master's thesis, St. Mary's University]. Retrieved from https://hdl.handle.net/123456789/1234

Awuni, M. A. (2019). Risk assessment at the design phase of construction projects in Ghana. *Journal of Building Construction and Planning Research, 7*(2), 39–58. Retrieved from https://doi.org/10.4236/jbcpr.2019.72004

Bahamid, R. A., Doh, S. I., & Al-Sharaf, M. A. (2019). Risk factors affecting the construction projects in the developing countries. *IOP Conference Series: Earth and Environmental Science, 244*(1), 012040. doi:10.1088/1755-1315/244/1/012040

Baloi, D., & Price, A. D. F. (2003). Modelling global risk factors affecting construction cost performance. *International Journal of Project Management, 21*(4), 261–269. Retrieved from https://doi.org/10.1016/S0263-7863(02)00017-0

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). Sage Publications.

Eskander, R. F. A. (2018). Risk assessment influencing factors for Arabian construction projects using analytic hierarchy process. *Alexandria Engineering Journal, 57*(4), 4207–4218. Retrieved from https://doi.org/10.1016/j.aej.2018.10.018

Genc, O. (2023). Identifying principal risk factors in Turkish construction sector according to their probability of occurrences: A relative importance index (RII) and exploratory factor analysis (EFA) approach. *International Journal of Construction Management, 23*(6), 979–987. Retrieved from https://doi.org/10.1080/15623599.2021.1946901

Ghaleb, H., Alhajlah, H. H., Abdullah, A. A., Kassem, M., & Al-Sharafi, M. (2022). A scientometric analysis and systematic literature review for construction project complexity. *Buildings, 12*(1), 482. Retrieved from https://doi.org/10.3390/buildings12050482

Goral, J. (2007). *Risk management in the conceptual design phase of building projects* (Master's thesis, Chalmers University of Technology). Chalmers University of Technology. Retrieved from https://odr.chalmers.se/server/api/core/bitstreams/50e88e0d-3a2a-4015-a188-dff696d9d6ee/content

Kangari, R. (1995). Risk management perceptions and trends of U.S. construction. *Journal of Construction Engineering and Management, 121*(4), 422–429. Retrieved from https://doi.org/10.1061/(ASCE)0733-9364(1995)121:4(422)

Kishan, P., Bhatt, R., & Bhavsar, J. J. (2014). A study of risk factors affecting building construction projects. *International Journal of Engineering Research & Technology, 3*(12), 831–835. doi: 10.17577/IJERTV3IS120480

Kusmaryono, I., Wijayanti, D., & Maharani, H. R. (2022). Number of response options, reliability, validity, and potential bias in the use of the Likert scale education and social science research: A literature review. *International Journal of Educational Methodology, 8*(4), 625–637. Retrieved from https://doi.org/10.12973/ijem.8.4.625

Latham, G. P., Winters, D. C., & Locke, E. A. (1994). Cognitive and motivational effects of participation: A mediator study. *Journal of Organizational Behavior, 15*(1), 49–63. Retrieved from https://doi.org/10.1002/job.4030150106

MacMillan, S., Steele, J., Kirby, P., Spence, R., & Austin, S. (2002). Mapping the design process during the conceptual phase of building projects. *Engineering, Construction and Architectural Management, 9*(3), 174–180. Retrieved from https://doi.org/10.1108/eb021213

Madushanka, H. K. P., & Tilakasiri, K. K. (2020). The identification and management of major risks in Sri Lankan construction industry. *IOSR Journal of Economics and Finance, 11*(1), 16–23. Retrieved from https://doi.org/10.9790/5933-1101071623

Mahendra, P. A., Pitroda, J. R., & Bhavsar, J. J. (2013). A study of risk management techniques for construction projects in developing countries. *International Journal of Innovative Technology and Exploring Engineering (IJITEE), 2*(3), 45–49. Retrieved from https://doi.org/10.35940/ijitee

Perera, B. A. K. S., Samarakkody, A. L., & Nandasena, S. R. (2020). Managing financial and economic risks associated with high-rise apartment building construction in Sri Lanka. *Journal of Financial Management of Property and Construction, 25*(1), 143-162. Retrieved from https://doi.org/10.1108/JFMPC-04-2019-0038

Qazi, A., Shamayleh, A., El-Sayegh, S., & Formaneck, S. (2021). Prioritizing risks in sustainable construction projects using a risk matrix-based Monte Carlo simulation approach. Sustainable Cities and Society, 65, Article 102576. Retrieved from https://doi.org/10.1016/j.scs.2020.102576

Samarakkody, A., & Perera, B. A. K. S. (2023). Application of Soft Landings concept in Sri Lanka to narrow the building performance gap, enablers and barriers. *Smart and Sustainable Built Environment, 12*(1), 156-180. Retrieved from https://doi.org/10.1108/SASBE-03-2021-0052

Santoso, D. S., & Gallage, P. G. M. P. (2020). Critical factors affecting the performance of large construction projects in developing countries: A case study of Sri Lanka. *Journal of Engineering, Design and Technology, 18*(3), 531-556. Retrieved from https://doi.org/10.1108/JEDT-05-2019-0130

Schwartz, B. (2021, February 26). Project manager. *The Risk Management Process in Project Management*. Retrieved July 16, 2024, from https://www.projectmanager.com/blog/risk-management-process-steps

Shen, L. Y., Wu, G. W., & Ng, C. S. (2001). Risk assessment for construction joint ventures in China. *Journal of Construction Engineering and Management, 127*(1), 76–81. Retrieved from https://doi.org/10.1061/(ASCE)0733-9364(2001)127:1(76)

Smith, N. J., Merna, T., & Jobling, P. (2014). *Managing risk in construction projects* (3rd ed.). John Wiley & Sons.

Wuni, I. Y. (2023). Drivers of circular economy adoption in the construction industry: A systematic review and conceptual model. *Building Research and Information, 51*(7), 816–833. Retrieved from https://doi.org/10.1080/09613218.2023.2211689

Yousri, E., Sayed, A. E., Farag, A. M., & Abdelalim, A. M. (2023). Risk identification of building construction projects in Egypt. *Buildings, 13*(4), Article 1084. Retrieved from https://doi.org/10.3390/buildings13041084

Zou, P. X., Zhang, G., & Wang, J. (2007). Understanding the key risks in construction projects in China. *International journal of project management, 25*(6), 601-614. Retrieved from https://doi.org/10.1016/j.ijproman.2007.03.001

Shahu, S.R., Iyer, A. and Tawalare, A.G., 2024. ‘Plan of action’ for organisational change: A case study of Indian public sector construction organisation. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 827-838. DOI: https://doi.org/10.31705/WCS.2024.66. Available from: https://ciobwcs.com/papers/

‘PLAN OF ACTION’ FOR ORGANISATIONAL CHANGE: A CASE STUDY OF INDIAN PUBLIC SECTOR CONSTRUCTION ORGANISATION

S.R. Shahu[1], A. Iyer[2] and A.G. Tawalare[3]

ABSTRACT

Recently, one of the Indian public sector construction organisations has adopted app-based work measurement and its billing system to reduce the cycle time in the “Procure to Pay” process. Though it could be a small technological change in the working process that has re-engineered the “As-is” processes, it changes the entire organisational dynamics thereby eliminating gaps in the system. Therefore, this paper provides insights into these change management practices in the public sector construction organisation in the context of implementing technological change in the work process. To develop the "Plan of Action," this study utilised a case study methodology. This ‘Plan of Action’ consists of the following strategies change initiative, formation of change management team, leadership support and involvement, research and benchmarking, stakeholder involvement and engagement, change resistance and persuasion, mandatory training integration, operational efficiency analysis and stabilisation phase. It is revealed that the organisation required commendable efforts in conceptualising, planning, and executing the change process along with special attention to enhancing leadership participation, increasing stakeholder engagement, and providing extensive instruction, training and support to all employees and stakeholders.

Keywords: *Construction Management; Indian Construction; Measurement and Billing Systems; Organisational Change; Public Sector.*

1. INTRODUCTION

The construction industry in India holds significant economic importance, contributing about 8% to the GDP and accounting for approximately 9% of total expenditure. The Indian construction industry is rapidly evolving towards digitalisation through the adoption of technological workflows such as e-Tendering, Building Information Modelling (BIM), Virtual Reality (VR). This transition towards digitalisation not only enhances productivity and efficiency yet encourages innovation and competitiveness within the Indian construction industry, positioning it for sustained growth and an

[1] M.Tech Student, Department of Civil Engineering, Visvesvarya National Institute of Technology, Nagpur, India, srushtishahu@gmail.com

[2] B.Tech Graduate, Department of Civil Engineering, Visvesvarya National Institute of Technology, Nagpur, India, avinash.rajsand@gmail.com

[3] Assistant Professor, Department of Civil Engineering, Visvesvarya National Institute of Technology, Nagpur, India, abhaytawalare@civ.vnit.ac.in

increased contribution to the country's GDP in the future. Nevertheless, the adoption of technology in the construction organisation is not an easy task, as it is crucial for the reassessment and restructuring of existing workflows and processes within organisations. It requires not only the adaptation of new technical skills and tools; however, it equally demands a fundamental change in mindset to embrace innovation and leverage technology for enhanced efficiency and competitiveness. The implementation of these new practices within an organisation can be seen as a form of organisational change. Organisational change is an inevitable aspect of organisational existence, driven by various factors such as technological advancements, market fluctuations, and internal initiatives (Buick et al., 2015). Within the construction industry, common organisational change initiatives encompass the adoption of digital technologies, the refinement of management processes, and the adjustment of business strategies. Studies by Rashed and Mutis (2023), Liao and Ai Lin Teo (2018), Wong et al. (2017), Xerri et al. (2015), and Sheng-Pao Shih et al. (2013) have been limited to the application of organisational change management strategies within a specific domain and a limited number of projects in the organisation.

Organisational change management encompasses various methodologies aimed at facilitating the successful integration of transformative endeavours (Kasana et al., 2023). Effective change management is essential for the success and adaptability of an organisation in today's dynamic business environment, as poorly executed change can adversely affect performance (Xerri et al., 2015). Managing organisational change involves systematically planning and implementing modifications within the organisation (Kasana et al., 2023). To overcome the persistent obstacles related to the industry's adoption of change, both practitioners and researchers have increasingly explored strategies for managing organisational change that have been linked to successful adoption outcomes (Maali et al., 2022). According to Liao and Ai Lin Teo (2018), the MIT90s framework provides a valuable tool for comprehending organisational transformation in the context of adopting new technologies. This framework encompasses various elements, including strategy, organisational structure, business processes and infrastructure, and culture. Similarly, Errida and Lotfi (2021), in their study of change implementation within a Moroccan construction company, examined two models of change i.e. (i) the Processual model and (ii) the Descriptive model. A processual model establishes the procedures for executing and supervising change. The primary variables and factors influencing organisational performance and the success of organisational change are outlined in a descriptive model. By employing strategies such as clear communication, stakeholder engagement, and skill development, the industry can enhance its capacity to manage change effectively among practitioners, thereby maximising its economic impact. Lines and Vardireddy (2017) have stated that effective change management strategies are skills that can be acquired because each practice involves specific steps that professionals in the industry can implement to enhance the likelihood of successful adoption of change. However, since public sector companies have intricate hierarchies, implementing these strategies into effect can be difficult.

The internal structures of these organisations are frequently imposed by governmental regulations and display resistance towards change and the delegation of authority. In the examination of the City Works Department of Rotterdam's case study on organisational change, a theoretical framework has been introduced by Van der Voet et al. (2016) that highlights important elements observed in public sector organisations, such as transformational leadership and a commitment to change. Abdulraheem et al. (2013) investigated planned organisational change in the Nigerian public sector and concluded that understanding the values of the society in which an organisation functions is necessary before developing change initiatives. In their study of change management in the public sector of New Zealand, Ahmed et al. (2015) have determined that external environmental pressures serve as the primary catalyst for reform within public sector organisations, alongside the influence of various stakeholders on organisational change. Furthermore, considering the distinct difficulties confronted by public sector entities in the Indian construction sector, such as administrative obstacles and aversion to modification, it becomes crucial to customise change management approaches to tackle these hindrances.

Recently, the Indian public sector construction organisation has adopted app-based work measurement and its billing system to reduce the cycle time in the "Procure to Pay" process. However, it is a small technological change in the working process that has re-engineered the "As-is" processes; also, it has changed the entire organisational dynamics thereby eliminating gaps in the system. The app-based measurement and billing system includes features such as automated cost calculation upon updating the measurement book, automated bill generation and processing, which eliminates the need for manual data entry in physical measurement books and reduces the likelihood of errors. The ERP integration of the system enables stakeholders to directly view and process bills within the system itself once forwarded, thereby enhancing transparency. It is a technological advancement of the traditional measurement and billing techniques that are prevailing in the industry. Therefore, this study seeks to explore the complexities of technological changes through the perspective of organisational change management. Therefore, this research aims to define standardised organisational change management processes i.e. 'plan of action' to implement technological change in the working of public sector construction organisations.

2. LITERATURE REVIEW

The literature review was performed to understand the processes of change management in various organisations. It was found that a systematic 'plan of action' is required for implementing change effectively. The 'plan of action' encompassed several steps, including identifying the need for change, developing a vision, providing clear communication to the team, involving stakeholders, managing resistance, and monitoring and tracking the change.

The literature focused on the necessity or need for change as the first step. To implement a planned change, leaders must provide evidence for why it is necessary and persuade influential external parties and employees of the organisation (Talim, 2012). In their study, Kasana et al. (2023) stated that the Facility Management professionals were tasked with rapid and extensive operational shifts that underscored the need for change in response to the pandemic's challenges. The theory of transformational leadership also emphasises the need for change (Van der Voet, 2014). After identifying the need for the change, the process of convincing people usually begins with developing an appealing vision of the change. Rashed and Mutis (2023) stated that clear communication of the organisation's goals of steering away from the traditional method and shifting towards new technologies gives a clear vision to employees and clarifies the confusion about the need for this change implementation. To meet schedules, budgets, and the needs and expectations of employees, project teams ought to try to create a clear and unified vision (Kim et al., 2017). Employees must comprehend the goals that need to be met and the direction of the change. A well-defined vision provides clarity and reduces uncertainty among employees, thereby securing their buy-in and support (Buick et al., 2015).

Leaders or powerful coalitions within organisations can serve as agents to develop a vision for change. Employees are more inclined to commit to the change and provide support when they witness their senior managers investing time and energy in implementing change (Jurisch et al., 2013). Top management involvement during the adoption process is frequently mentioned as a strategy to establish and sustain momentum for a change initiative (Maali et al., 2022). While there is a lot of emphasis on the role senior management plays in initiating change, direct supervisors are just as important in executing change in public sector organisations (Van der Voet, 2014).

A wide range of stakeholders, including common citizens, politicians, government agencies, and even government departments, are involved in many public projects. Identifying the stakeholders who are affected by the change is very important to understand the potential impacts of the change. Public projects are more prone to changes in expectations and the environment due to the scrutiny of public opinion (Jurisch et al., 2013). According to Errida and Lotfi (2021), assessing the readiness level of stakeholders requires understanding their perceptions of change. Hence, stakeholder engagement is a critical element that can influence the success of change management initiatives. After analysing the stakeholders, change processes must be tailored to the specifications or situations of specific organisations, with goals and plans that are contextually appropriate (Buick et al., 2015). Good planning highlights the significance of the plan's execution in addition to developing a well-structured plan. It is thought that the commitment of team members responsible for implementing the strategy is critical to its success. As a result, the quality of the planning process has an immediate effect on the effectiveness of the final plan (Talim, 2012). Consensus building is a crucial aspect in the face of resistance to change. Management must articulate a clear and comprehensive purpose to the appropriate audience (Wang et al., 2013). Individuals respond differently to organisational change.

Rashed and Mutis (2023) indicated that the organisations with the greatest chance of overcoming employee resistance to change are those that involve employees in the decision-making process for change or the implementation of novel processes and methods. Employee awareness of the change's goals and direction is necessary for its effective implementation. Employee support for the change is increased when there is clarity as it reduces uncertainty (Buick et al., 2015). Therefore, rather than employing a single approach that works for everyone, managers ought to speculate about various approaches, such as those related to communication, training, and support, for each stage of the process.

In addition to minimising resistance from employees, sustaining the process requires adequate resources, which are essential for effective change management. The impact of resources on meaningful planned change is formidable. The presence of resources enhances the influence of awareness, self-efficacy, planning quality, and leadership effectiveness (Talim, 2012). Almost all organisational changes result in changes in the behaviour of organisational members. Regular get-togethers and casual talks can be utilised to keep employees informed about any changes and allow them to modify their behaviour as necessary to encourage effective interaction between employees and managers (Buick et al., 2015). Effective and open communication lowers resistance to change and increases employee acceptance of deviations from the status quo, which improves the efficiency of the organisation (Rashed & Mutis, 2023). Meaningful changes can be measured by their ability to deliver benefits. Hence the last stage is proper monitoring, tracking, and measuring to ensure ongoing progress of the change. To track the progress of the change, it is important to develop and establish metrics, as well as utilise milestones and tools (Errida & Lotfi, 2021). Thus, the literature review provided various theoretical frameworks for organisational change management practices. This study aims to examine change management practices within public sector construction organisations, specifically in the context of implementing technological changes in work processes.

3. RESEARCH METHODOLOGY

This study's research methodology was primarily a case study approach. A case study approach provides rich insights and in-depth analysis by facilitating an in-depth examination of a specific phenomenon within its real-world context (Yin, 2018). The study focuses on the successful implementation of organisational change in a public sector organisation within the Indian construction industry. The complex nature of the Indian construction industry, particularly within the public sector, presents a unique set of challenges and dynamics that necessitates a detailed examination. A case study within the Indian public sector is crucial to illustrate how change can be practically observed and handled in a construction organisation. By concentrating on a public sector organisation, this study enhances the understanding of the complexities involved in implementing organisational change and addresses a critical gap in the literature concerning the applicability of change management principles within the construction sector in India.

Yin (2018) recommends selecting a single case for study when the case is unique, exhibiting characteristics not found in other cases, or when it is a typical case involving the implementation of a specific project. By selecting a single case organisation within the Indian construction industry, the researchers were able to identify the unique challenges, strategies, and outcomes associated with the change implementation. This approach allowed for a comprehensive examination of the entire change process, from strategic planning to frontline implementation, within a real-world setting. The selection criteria for the case study organization were primarily because it is a public sector entity that has recently introduced an app-based measurement and billing system. This development represents a significant step towards incorporating technology into the construction industry in India and involves the implementation of organisational change management practices. Additionally, gathering insights from the organisation facilitated a thorough exploration of the perspectives of various stakeholders involved in the change, providing rich insights that could inform broader understandings of change management practices. The major approach to collecting data was semi-structured interviews with key stakeholders involved in the organisational change process. The interviewees encompassed 22 individuals from various levels of the organisation, including five members from the leadership team, seven members from the change management team, and ten employees who are the end users of the change. The participants of these interviews were selected through the purposive sampling method. The interviews were conducted to gain in-depth insights into the procedures implied by the organisation while navigating through the change under study. The questionnaire starts by asking for a summary of a recent change initiative and the rationale behind it. It delves into how those in charge deal with resource constraints, cultural opposition, and the balance of short-term demands and long-term objectives. Employee-focused questions seek to identify the personal impact of changes, including initial reactions, day-to-day obstacles, assistance received, and chances for professional development. Finally, it requests suggestions on how to improve the transition process, communication, and support methods, emphasising the significance of considering work-life balance and team dynamics. The leadership team provided insights on the overall perspective and need for the adoption of an app-based work measurement and billing from the strategic point of view. The series of interviews was conducted with the employees who were a part of the software programming team to understand their strategies in designing software and the challenges faced while navigating through the change. In addition, interviews with end-user employees directly affected by changes in the workflow provided insights into how the change impacts them and how the system can better support their performance and adaptability. This primary data was corroborated with secondary data collected such as various orders issued by top management related to the implementation of an app-based system, minutes of meetings finalised in the meetings of top management and software programming team and actual demonstration by end user employees in the field. All the interviews were transcribed in Microsoft Word files. The interview data was analysed by content analysis in N Vivo software–version 11.0.

4. RESULTS AND DISCUSSION

The content analysis is presented in Table 1. This content analysis identified the major themes from the 'plan of action' results derived from the interview data, which are discussed in detail.

Table 1: Content Analysis of conducted interviews

Theme	Code	Description	Source	Reference	% of articles quoted
Change Initiative	CI	Developing a comprehensive change plan aligned with organizational goals.	10	25	45%
Formation of the Change management team	STF	Forming a diverse, skilled team for effective change.	12	29	55%
Leadership Support and Involvement	LSI	Ensuring top-down support and communication of vision	8	20	36%
Research and Benchmarking	RB	Best practices identification and lessons learned.	12	30	55%
Stakeholder Involvement and Engagement	SIE	Inclusive decision-making and collaboration.	9	20	41%

Theme	Code	Description	Source	Reference	% of articles quoted
Change Resistance & Persuasion	CRP	Proactive resistance identification and persuasion efforts.	18	32	82%
Mandatory Training Integration	MTI	Train-the-trainer approach for skill development.	10	26	45%
Operational Efficiency Analysis	OEA	Analysing performance metrics for operational optimization.	19	34	86%
Stabilisation Phase	SP	Ensuring smooth transition and adoption of new processes.	16	33	73%

4.1 CHANGE INITIATIVE

The enforcement of state government orders and guidelines played a substantial role in initiating the change. The Central (Federal) Government owns the case organisation. On one project, the organisation was working for another State Government Organisation. This client organisation wanted to reduce the paperwork in the billing of work-related constructions. For this purpose, the top management of the case organisation implemented the billing software throughout the organisation. The higher management representative emphasised in the interview that "*Electronic measurement book is like a new concept stepped ahead towards and it's the first transactional portal of one of its kind in the country.*" The objective of implementing an app-based measurement book and billing system was to decrease cycle times and enhance effectiveness. However, this was not an easy task. The case organisation initially needed to identify and streamline its processes, particularly in the procurement-to-payment cycle. The organisation developed a comprehensive plan outlining the scope, timeline, and resources required for successful implementation, providing a roadmap for the change process. Thus, the top management tried to examine the need for the change and this initiative exemplifies a forward-thinking, positioning the organisation to adapt to contemporary challenges and capitalise on emerging opportunities. The top management communicated the vision and objectives of the change initiative to all levels of the organisation. The organisation's change initiation aligns closely with the theoretical frameworks and practical insights provided in the literature review (Talim, 2012), setting a solid foundation for successful implementation.

4.2 FORMATION OF CHANGE MANAGEMENT TEAM

After deciding to adopt the app-based billing system, it was necessary to determine who would be responsible for its implementation. There are always two options: first, to have the work completed by an external agency, or second, to have it done by the internal team. The handing over of work to an external agency always burdens the financial resources of the organisations. In addition, the external agency requires considerable effort and time to understand the processes of another organisation. Hence, it was decided to trust the internal talent of the organisation. A proactive, cross-functional change management team was formed to spearhead the initiative, comprising individuals with relevant expertise and representation from key departments. Change agents were selected based on their talent, reputation, and proactive nature. The role of software engineers is to develop the software, which will impact the operations of both the Construction Department and the Finance and Accounts Department. Therefore, the change team consisted of Civil Engineers, Software Engineers and Finance and Account Department officers. The change team worked closely with senior management and other stakeholders to align the change initiative with the organisation's strategic objectives and priorities, ensuring that it was integrated into broader organisational plans. Change agents played a crucial role in facilitating dialogue and building consensus among stakeholders. The formation of a proactive, cross-functional change team comprising individuals with relevant expertise and representation from key departments was a commendable approach. Thus, the diverse composition of the change team ensured comprehensive support to key areas affected by the change initiative.

4.3 LEADERSHIP SUPPORT AND INVOLVEMENT

The leadership provided unwavering support to the change management team and completely trusted the talent of internal employees. The change management team prepared the schedule of the work inclusive of time-bound review meetings with top management. Regular updates and progress reports were provided by the change management team to leadership. In addition, leadership gave regular feedback and ideas to the change management team. This was successful in maintaining the momentum and accountability of the change process throughout the software development phase. Contingency plans were developed to address potential challenges or setbacks, ensuring that the change initiative remained on track despite any unforeseen obstacles. However, the top-down approach prioritised the direction and decisions of senior leadership, and potentially overlooked the valuable insights and perspectives of the internal and external stakeholders within the organisation. This led to resistance from employees during the implementation phase of the software, as many felt excluded from the decision-making process.

4.4 RESEARCH AND BENCHMARKING

The leadership had shown complete trust in talent of the internal change management team. This team had not left out any efforts to let down this trust. The members of the change team conducted extensive research to identify best practices and gather insights from similar initiatives in other organisations. The change management team in their interview specified that "T*he process which has been implemented and ongoing in other organisations acted as a motivation for the change team to move forward with the request of the described change*". These Research findings were shared across departments and functions, fostering a culture of learning and collaboration. This collaborative approach enhanced the organisation's readiness for change and fostered cross-functional alignment, ensuring that all stakeholders were aligned. By delving into existing literature and analysing scholarly articles, the organisation ensured a robust understanding of best practices and theoretical frameworks in change management thereby implementing them practically in their domain. The organisation's commitment to conducting extensive research and benchmarking reflects a commendable level of thoroughness.

4.5 STAKEHOLDER INVOLVEMENT AND ENGAGEMENT

The leadership team actively involved stakeholders and employees in designing and implementing the change initiative, recognising the importance of their input and support for its success. The organisation's leadership team actively engaged employees across various branches and regions, soliciting their opinions and feedback on the proposed changes. The leadership team justified the inclusion of stakeholders "T*he change involves a first transactional portal in the organisation which has the stakeholder access to the portal. Hence, digital acceptance of agreements can be done without getting the stakeholder physically in the process*". This inclusive approach ensured that diverse perspectives were considered in the decision-making process. External stakeholders, including suppliers, contractors, and regulatory bodies, were also consulted and engaged throughout the change process. The system has a separate login for the stakeholders to help them adapt and understand the significance of the change. The organisation's approach to engaging employees and external stakeholders appears commendable, particularly in soliciting diverse perspectives and fostering collaboration. However, it lacked specifics regarding the depth of engagement and the effectiveness of feedback mechanisms. Leadership and the change team need to move past mere consultation to genuinely empower both employees and external stakeholders in the decision-making process. The major drawback identified here was that the stakeholders were not given adequate training to use the portal effectively. Hence, organisations implementing similar changes must recognise that merely involving stakeholders in decision-making is insufficient. It is essential to focus on their training and active involvement in the change implementation process, which will enhance their adaptability and reduce resistance to the change.

4.6 CHANGE RESISTANCE AND PERSUASION

"*Reaction of the employees to change can be of different types, some have interest in learning new things and some people have irritation in adoption of new system so they try to behave in such a way that the change cannot be implemented*". To understand such reactions of the people, the RAMA Principle (Rejection, Annoyance, Mellow, and Acceptance) was utilised by the change team to proactively identify and resolve this resistance to change. Regular meetings, awareness weeks, and internal marketing strategies were employed to communicate the benefits of the change initiative and address concerns raised by employees. Individuals facing disadvantages with the existing system were convinced of the benefits of the change through targeted persuasion efforts, highlighting how the new processes would improve their work experience and outcomes. By employing various communication strategies, such as regular meetings and internal marketing efforts, the organisation effectively communicated the benefits of the change initiative and addressed concerns raised by employees. Targeted persuasion efforts were aimed at individuals facing disadvantages with the existing system to make them understand the positive aspects of the change.

4.7 MANDATORY TRAINING INTEGRATION

The change team strategically implemented a "train the trainer" approach to ensure that employees were adequately prepared for the change initiative. Mandatory training subjects were integrated into the organisation's learning and development programs, ensuring that all employees received the necessary training to effectively transition to the new processes. Ongoing training and skill development initiatives were implemented to ensure that employees remained up to date on the latest developments and best practices related to the change initiative. However, simply integrating mandatory training into existing programs was not found to be sufficient to address the evolving needs and challenges associated with the change. The users in their interview stated a concern that "*All the overshare in-charge should be given training so that the workload can be distributed. So, proper training should be given to all the users so that only one person who knows the software would not be facing heavy workload*". Hence, it was found that considering the diverse learning needs of employees, allocating resources effectively, addressing potential resistance, and continuously evaluating the training approach are essential to maximise the effectiveness of the change.

4.8 OPERATIONAL EFFICIENCY ANALYSIS

Key Performance Indicators (KPIs) such as number of purchase orders pushed into the portal, number of purchase orders for which the billing is done, and the time between entering and approval of measurements were established to measure the success of the change initiative, focusing on time savings and cost reduction. Statistical data was used to set performance benchmarks and track progress towards achieving organisational goals. The change team stated that "*The offline process used to take 56 days and online takes just ten days, so the change implementation can save a time of up to 46 days and time saved is money saved*." This data was analysed by the change team, and it was found that the change resulted in time savings and was subsequently translated to monetary savings. The users of the system in their interview highlighted the advantages of the system as "T*here is increased transparency of the process of billing and measurement. The manual calculations to be done are being reduced for the engineer in charge. The maintenance of a physical measurement book requires a lot of effort, but electronic measurement is easier to maintain, and clarity would be there*". Continuous monitoring of performance metrics allowed the change team to make data-driven decisions and adjust its strategies as needed to optimise operational efficiency. By tracking progress towards achieving organisational goals and making data-driven decisions, the organisation ensured accountability and continuous improvement.

4.9 STABILISATION PHASE

Phased implementation was executed to mitigate risks and ensure a smooth transition from the old processes to the new ones. The organisation facilitated the concurrent use of both the old and new systems during the transition period, providing a safety net to minimise downtime and maintain continuity of operations. Pilot testing of the system was performed, and the organisation believed that "*Younger generation members of the organisation were enthusiastic about the opportunity and were keen to learn new technologies*". Action-taken reports were generated to document and address any issues or challenges encountered during the stabilisation phase. Troubleshooting mechanisms were established to provide support to users encountering difficulties with the new processes. Teething issues that arose were resolved immediately without inordinate delay. This ongoing support contributed to the successful adoption and institutionalisation of the change initiative. The team stated that "A*llowing concurrent use of both old and new systems during the transition period is a pragmatic strategy. It provided a safety net for the organisation, minimising downtime and disruptions to critical processes*". This approach acknowledged the challenges inherent in change and offered flexibility to users as they adapt to new systems.

The major problems addressed through the identified practices include managing resource limitations and overcoming resistance to change through effective communication and leadership support. Additionally, balancing short-term project demands with long-term sustainability goals was crucial in ensuring the successful implementation of technological changes.

5. CONCLUSIONS

This study established the standardised organisational change management processes i.e. 'plan of action' to implement technological change in the working of public sector construction organisations. This study contributes significantly to the field of organisational change management by outlining a precise and practical framework for implementing technology changes in public sector organisations, particularly in the Indian construction industry. By employing a case study methodology coupled with in-depth content analysis of semi-structured interviews, the study provides decision-makers with a guide for navigating organisational change. The 'plan of action' for effective change management, including the change initiative, formation of a change management team, leadership support and involvement, research and benchmarking, stakeholder involvement and engagement, change resistance and persuasion, mandatory training integration, operational efficiency analysis and stabilisation phase. The identified themes presented as a systematic 'Plan of Action' indicate the standardised steps that an organisation can undertake to navigate through the change and on a preliminary basis, the organisation can understand the approach to facilitate effective change management in context to technological changes. The 'Plan of Action' provides authorities and public sector managers with actionable recommendations in the context of change management. While global literature on change management emphasises the importance of planned change, including clear communication, stakeholder engagement, and the development of a unified vision, this study's findings highlight unique practices specifically tailored to the public sector in India. Notably, the identified practices place a strong emphasis on in-house development of systems to manage financial resources efficiently, and the use of the RAMA Principle to address resistance to change, which diverges from the broader global focus on external validation and top-down enforcement. The research findings contribute to the existing body of knowledge on organisational change management and offer valuable insights into the practical aspects of managing change within the Indian construction sector, especially in public sector organisations. By bridging the gap between theory and practice, the study offers actionable recommendations for decision-makers and practitioners seeking to navigate the complexities of change management effectively.

6. REFERENCES

Abdulraheem, I., Mordi, C., Ojo, Y., & Ajonbadi, H. (2013). Outcomes of planned organisational change in the Nigerian public sector: Insights from the Nigerian higher education institutions. *Economic Insights-Trends and Challenges, 2*(1), 26–37. https://repository.uel.ac.uk/item/85xy1

Ahmed, H., Balzarova, M., & Cohen, D. A. (2015). Evolutionary change stimuli and moderators – evidence from New Zealand. *Journal of Organizational Change Management, 28*(4), 546–564. https://doi.org/10.1108/JOCM-11-2013-0226

Buick, F., Blackman, D. A., O'Donnell, M. E., O'Flynn, J. L., & West, D. (2015). Can enhanced performance management support public sector change? *Journal of Organizational Change Management, 28*(2), 271–289. https://doi.org/10.1108/JOCM-12-2013-0249

Errida, A., & Lotfi, B. (2021). The determinants of organizational change management success: Literature review and case study. *International Journal of Engineering Business Management, 13,* 1-15. https://doi.org/10.1177/18479790211016273

Jurisch, Ikas, Wolf, & Krcmar. (2013). Key differences of private and public sector business process change. *E-Service Journal, 9*(1), 3-27. https://doi.org/10.2979/eservicej.9.1.3

Kasana, D., Smithwick, J., Dodd, J., Cavalline, T. L., & Mayo, G. (2023). Successful change management strategies for unforeseen events: impact of COVID-19 on facility management. *Journal of Management in Engineering, 39*(4), 04023016. https://doi.org/10.1061/jmenea.meeng-4870

Kim, A. A., McCunn, L. J., & Lew, J. (2017). Successful facility change-management practices for retrofit projects: Case study in lighting. *Journal of Management in Engineering, 33*(4), 05017001. https://doi.org/10.1061/(asce)me.1943-5479.000051

Liao, L., & Ai Lin Teo, E. (2018). Organizational change perspective on people management in BIM implementation in building projects. *Journal of Management in Engineering, 34*(3), 04018008. https://doi.org/10.1061/(asce)me.1943-5479.0000604

Lines, B. C., & Reddy Vardireddy, P. K. (2017). Drivers of organizational change within the AEC industry: Linking change management practices with successful change adoption. *Journal of Management in Engineering, 33*(6), 04017031. https://doi.org/10.1061/(asce)me.1943-5479.0000548

Maali, O., Kepple, N., & Lines, B. (2022). Strategies to achieve high adoption of organizational change initiatives within the AEC industry. *Journal of Management in Engineering, 38*(4), 04022021. https://doi.org/10.1061/(asce)me.1943-5479.0001051

Rashed, A., & Mutis, I. (2023). Influence of internal factors in construction organizations on implementing integrated project delivery viewed from the organizational change theories. *Practice Periodical on Structural Design and Construction, 28*(4), 04023052. https://doi.org/10.1061/ppscfx.sceng-1322

Robert K. Yin. (2018). *Case study research and applications sixth edition* (6th ed.). Sage Publication, Inc.

Sheng-Pao Shih, Ruey-Shiang Shaw, Ta-Yu Fu, & Che-Pin Cheng. (2013). A systematic study of change management during CMMI implementation: A modified activity theory perspective. *Project Management Journal, 44*(4), 84-100. https://doi.org/10.1002/pmj

Talim, B. (2012). *Creating a Meaningful Planned Change*. Procedia Economics and Finance, *4*, 140–148. https://doi.org/10.1016/s2212-5671(12)00329-2

Van der Voet, J. (2014). The effectiveness and specificity of change management in a public organization: Transformational leadership and a bureaucratic organizational structure. *European Management Journal, 32*(3), 373–382. https://doi.org/10.1016/j.emj.2013.10.001

Van der Voet, J., Kuipers, B. S., & Groeneveld, S. (2016). Implementing change in public organizations: The relationship between leadership and affective commitment to change in a public sector context. *Public Management Review, 18*(6), 842–865. https://doi.org/10.1080/14719037.2015.1045020

Wang, Z., Lim, B. T. H., & Kamardeen, I. (2013). *Change management research in construction: A critical review.* Conference Proceedings of CIB World Building Congress 2013, Brisbane, Queensland, Australia.

Wong, P. S. P., Zwar, C., & Gharaie, E. (2017). Examining the Drivers and States of Organizational Change for Greater Use of Prefabrication in Construction Projects. *Journal of Construction Engineering and Management, 143*(7), 04017020. https://doi.org/10.1061/(asce)co.1943-7862.0001309

Xerri, M. J., Nelson, S. A., Brunetto, Y., & Reid, S. R. M. (2015). NPM and change management in asset management organisations. *Journal of Organizational Change Management, 28*(4), 641–655. https://doi.org/10.1108/JOCM-11-2013-0222

Silva, M., Chamari, A. and De Silva, C., 2024. Potential of Virtual Reality (VR) technology for safety training and accident prevention in construction. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 839-850. DOI: https://doi.org/10.31705/WCS.2024.67. Available from: https://ciobwcs.com/papers/

POTENTIAL OF VIRTUAL REALITY (VR) TECHNOLOGY FOR SAFETY TRAINING AND ACCIDENT PREVENTION IN CONSTRUCTION

Maheesha Silva[1], Chamari Allis[2], and Chanuth De Silva[3]

ABSTRACT

The construction industry is inherently risky, with accidents and injuries posing significant challenges to workers' safety and well-being. Traditional safety training methods, while valuable, may have limitations in effectively preparing workers for the complex and hazardous environments they encounter. This study investigates the potential of virtual reality (VR) technology as an innovative approach to safety training and accident prevention in construction. Using a combination of literature review and empirical research, this study examines the effectiveness and feasibility of VR technology in simulating real-life construction scenarios, providing immersive training experiences, and enhancing workers' safety skills. The research explores the current state of VR adoption in safety training programs, identifies barriers to implementation, and proposes strategies for overcoming challenges. Qualitative design was used as the methodology and six industry experts were interviewed under semi-structured interviews. Key findings highlight the promising role of VR technology in improving safety awareness, hazard recognition, and emergency response among construction workers. Additionally, the study underscores the need for comprehensive training programs that integrate VR simulations with traditional methods to maximise effectiveness and engagement. Implications for practice include recommendations for safety training institutes, construction companies, and policymakers to invest in VR technology, develop tailored training modules, and foster a culture of safety consciousness within the industry. The study suggests avenues for future research to explore the long-term impact of VR training on accident rates, worker behaviour, and organisational safety culture. Overall, this research contributes to advancing safety practices in the construction industry by harnessing the potential of VR technology to prevent accidents, mitigate risks, and protect the well-being of workers.

Keywords: *Construction; Safety Training; Simulator Base Training; Sri Lankan Safety Training Program; Virtual Reality.*

[1] Graduate, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, silvasachin584@gmail.com

[2] Senior Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, chamari.a@sliit.lk

[3] Undergraduate, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka,, qs22068064@my.sliit.lk

1. INTRODUCTION

The history of the construction industry can be traced back to the time of huts and shelters, where houses, tools, bridges, and other structures were constructed by hand using simple tools. The word "construction" originates from the Latin word "construccioun" (Thomson, 1984), which encompasses the art and science of creating objects, systems, or organisations, primarily through building. The construction industry plays a vital role in a country's social welfare, national economy, and job market (Baraka et al., 2019), with various professionals contributing, such as Engineers, Architects, Quantity Surveyors, Land Surveyors, Planners, and various types of labourers.

The construction industry is generally divided into four sectors i.e., (i) residential building construction, (ii) commercial construction, (iii) industrial construction, and (iv) heavy construction. Residential building construction includes individual houses or private dwellings, lodging or rooming houses, dormitories, apartments, and hotels. In the commercial construction sector, projects range from small-scale to medium-scale and large-scale commercial buildings. Heavy construction, known as civil engineering, encompasses infrastructure projects such as public works, bridges, waterways, dams, and all types of roads. Industrial construction involves the construction of various industrial works, plants, and power generation facilities (Anupoju, 2020).

The Sri Lankan construction industry holds significant importance for the country's Gross National Income (GNI) and Gross Domestic Product (GDP). Over the last decade, investments in the construction industry have had a substantial impact on the Sri Lankan economy. In the fourth quarter of 2016, the Sri Lankan construction industry achieved record-high GDP figures. The construction industry makes a considerable contribution to both global and local GDP and GNI (Yuen et al., 2005). Productivity is a key indicator of economic performance for any industry, including construction (Naismith et al., 2016). The strong correlation between the construction industry and GDP/GNI is evident in Sri Lanka, where the construction industry has significantly influenced the country's gross national income over the past three decades (Wedikkara & Devapriya, 2000).

According to global macroeconomic models and analysts, from 2010 to 2019, the construction industry in Sri Lanka generated an average GDP of 142,507.63 LKR million. The fourth quarter of 2017 saw a peak of 190,372 LKR million, while the second quarter of 2010 marked a low of 77,176 LKR million. Projections indicate that by the first quarter of 2020, the industry's value is predicted to reach 166,736.00 LKR million ("Sri Lanka GDP from construction", n.d.).

On the other hand, the construction industry is widely recognised as one of the most perilous fields to work in. Within this industry, certain roles, such as roofers, excavator drivers, steelworkers, and logging workers, are among the highest-risk occupations globally. Various factors contribute to the increasing rate of construction accidents. These include the inherently high-risk nature of construction tasks, limited safety knowledge among workers and professionals, lack of on-site safety awareness and technical education (Saleh & Pendley, 2012), the transient nature of the industry, inadequate resource management at construction sites, and the complexity of organisational structures within the industry (Rameezdeen et al., 2006). Unsafe working conditions, insufficient safety training, failure to follow safety protocols, negligence, and lack of adherence to safety regulations also play significant roles (Perera et al., 2017).

Effective recording systems for occupational accidents are crucial within the construction industry of any country. Such systems serve as valuable management tools for risk assessment, aiding in the prevention of fatalities, injuries, and health hazards, as well as minimising costs associated with accidental losses. However, the absence of robust reporting procedures can lead to shortcomings in accident management (Fu et al., 2018). Safety issues significantly impact construction industry productivity, resulting in waste, health problems, and safety hazards (Kenley, 2014). Moreover, construction worker injuries have broad adverse effects, including personal suffering, construction delays, productivity losses, reduced workforce morale, increased insurance premiums, and potential liability lawsuits (Rameezdeen et al., 2006).

A risk in the construction industry is defined as a probable event with identifiable causes and potential impacts (Baraka et al., 2019). The level of risk fluctuates throughout a construction project, influenced by various project circumstances. According to construction fatality statistics, falls account for 33.5% of accidents and injuries, followed by being struck by objects (11.1%), electrocutions (8.5%), and being caught in or between objects (5.5%) (Jones, 2020). Globally, approximately one in every five construction workers experiences accidents or fatalities. Poor training, failure to follow safety protocols, negligence, and carelessness are identified as significant factors contributing to construction accidents (International Labour Organization [ILO], 2019). The International Labour Organization (ILO) estimates that 2.3 million workers worldwide suffer work-related accidents annually, resulting in 6,000 deaths daily (ILO, 2019). In Sri Lanka, construction site accidents have increased between 2009 and 2012, with the ILO estimating that accidents cost approximately 4% of a country's Gross National Product (GNP) (Wijekoon, 2016).

Improving safety education in the construction industry is crucial. Safety training is paramount in reducing accidents and protecting workers. Several safety training institutions in Sri Lanka offer programs such as National Occupational Safety and Health, Advanced Construction Training Academy, Construction Industry Development Authority, Safety Global, Colombo International Nautical and Engineering College, OSHA Training Courses, and Occupation Safety and Health Management, among others. Utilising virtual reality (VR) technology for safety training offers advantages such as exposure to fewer real-world hazards, increased efficiency, and enhanced worker confidence. VR training can reduce training costs, accident rates, and associated expenses, while providing comprehensive knowledge of Personal Protective Equipment (PPE) and safety procedures (Sacks et al., 2013).

The construction industry in Sri Lanka, resembling many developing countries, faces challenges in safety education and management. Safety education is vital for reducing fatalities and enhancing construction productivity. Accidents in the Sri Lankan construction industry is commonly caused by factors such as vehicle and machinery use, slips, falls from heights, collapses, and exposure to hazardous materials (Spellman, 2020).

VR technology has evolved significantly since its inception in the 1960s, particularly in gaming and educational applications. VR simulations offer immersive experiences that can enhance learning and training in various industries, including construction. In the construction sector, VR training can simulate real-world scenarios, providing valuable experiential learning without the need for physical site visits.

Unplanned events in the construction industry are classified as accidents (Laufer & Ledbetter, 1986), highlighting the paramount importance of safety in construction projects. Work-related injuries result in significant productivity losses for construction companies worldwide, emphasising the necessity of prioritising safety training in every construction project (Jones, 2020). However, there is no evidence that VR has been adopted in the Sri Lankan construction industry. Hence, this research aims to identify the current state of VR adoption in safety training programs, identifies barriers to implementation, and proposes strategies for overcoming challenges to improve construction safety training and mitigate the adverse impacts of accidents on construction productivity.

2. LITERATURE REVIEW

2.1 OVERVIEW OF VIRTUAL REALITY

The concept of VR is one of the most successful simulator systems globally. The first VR/AR head-mounted display was founded by Ivan Sutherland and his student Bob Sproull in 1968 (Dom, 2018). Although the first head-mounted display was established in 1968, the VR concept traces back to the 19th century. VR concept originated from panoramic paintings, which aimed to create illusions of being somewhere we are not ("History of virtual reality", n.d.). Panoramic paintings, also known as 360-degree murals, provided viewers with a sense of immersion in historical events or scenes.

Following 1929, numerous companies began to explore VR technology, resulting in various innovations. For instance, in 1960, the first Head-Mounted Display (HMD) was introduced, followed by the first motion tracking HMD and video screens for each eye in 1961. Ivan Sutherland conceptualised the VR room in 1965, and in 1966, Thomas Furness developed a military engineer flight simulator. In 1968, Sutherland and his student created the first VR HMD with 3D models that changed with head movement. Myron Krueger introduced artificial reality in 1969, and General Electric built the first flight simulator with a 180-degree field of vision in 1972.

The 1970s and 1980s witnessed significant advancements, including the creation of the first interactive VR platform in 1977 (Aspen Movie Map), McDonnell-Douglas Corporation's VITAL helmet for military use in 1979, and stereo vision glasses in 1980. Sayre gloves were developed by Sandin and Defanti in 1982, followed by the introduction of VR goggles and gloves by Jaron Lanier and Thomas Zimmermen in 1985. The super cockpit, a flight simulator with 3D maps and real-time sound, was created in 1986. NASA integrated audio elements with the Power Glove in 1989, and in 1991, they developed Computer Simulated Teleportation, the first mass-produced VR entertainment system.

The 1990s saw the launch of the Virtual Boy, the first portable console to display 3D graphics in 1995, and the first PC-based cube room in 2001. Google introduced Street View with stereoscopic 3D mode in 2007 and 2010. Sony launched PlayStation 4 (PS4) in 2014, while Google introduced a low-cost and do-it-yourself stereoscopic system. Samsung developed a VR headset for Galaxy smartphones in 2014. In 2015, the Wall Street Journal launched a VR roller coaster, and BBC created a 360-degree video. HTC introduced the HTC VIVE Steam VR headset in 2016, allowing users to move freely in space. Since 2016, many companies have developed their own VR headsets, including HTC, Google, Apple, Amazon, Microsoft, Sony, Samsung, and Facebook.

2.2 TYPES OF SENSORS AND SOFTWIRES RELATED WITH VIRTUAL REALITY

All types of sensors contribute to providing real-time experiences for users (Teja, 2017). Electromagnetic sensors utilise electromagnetic fields and a source system. These sensors rely on the fixed position of the source and previously known items. Acoustic sensors function similarly to electromagnetic sensors, yet they differ in that they transmit high-frequency sound to the receiver. Optical sensors are crucial for VR and AR technology, aiding in motion tracking and optical motion capture. These sensors consist of various cameras, which track the position of markers in space by observing their positions in the field of view of each camera. These systems employ different monitoring principles, often utilising markers made of reflective material. Infrared-sensitive cameras monitor these markers or body movements in space. The cameras must be calibrated, meaning their overall position and orientation must be known. By combining the 2D tracking position of markers with information about the location and characteristics of each camera, the 3D position of markers can be accurately determined (Cvetković, 2021). Various sensor types are involved in Virtual Environments (VE).

VR development software includes paradigms such as Multigen, Perillith Industriell, VRML, Wild Tangent, 3Dstate, and 3D game engines (Thabet et al., 2002). Other notable software platforms include Unity, Amazon Sumerian, the Google VR developer portal, Unreal Engine 4 (UE4), CRYENGINE, Blender, 3Ds Max, SketchUp Studio, Maya, and Oculus Medium, among others (Davies, n.d.).

2.3 USAGE OF VIRTUAL REALITY IN THE INDUSTRIES

VR is evolving across various industries for different purposes (Shang et al., 2012). They further emphasised that the automotive industry uses VR technology for design and engineering reviews. Engineers and designers utilise VR technology to reduce the number of prototypes built per vehicle line (Korkut & Surer, 2023). The authors further mentioned that many vehicle manufacturing companies, such as BMW and Jaguar Land Rover, are adopting this technology at an early stage. In the healthcare industry, VR technology is being used in innovative ways (Qu et al., 2022). They further emphasised that health professionals nowadays use virtual human body parts for treatments. These virtual body parts are created to resemble real bodies and injuries closely. VR technology is known for its effectiveness in treating PTSD and anxiety.

The retail industry is using VR technology to enhance the shopping experience (Nantel, 2004). The author further mentioned that “in online shopping, we can’t try on clothes, shoes, etc., before buying them. This can lead to items not meeting requirements in terms of size, colour, etc”. With VR technology in the retail industry, customers can decide on clothes with body-scanning, providing different types and designs at one point. In the tourism industry, VR technology is used to create virtual maps for tourists (González-Rodríguez et al., 2020). They further emphasised that these maps include visiting places, hotels, restaurants, tourist landmarks, etc. In the real estate industry, VR helps reduce the time and money for clients (Ullah et al., 2018). The authors further mentioned that clients can look around properties virtually, mitigating the time spent visiting properties physically. In the construction industry, VR technology is used for various purposes, with architecture being the most common. VR helps visualise design models as real concepts before they are built. The advantage is that when a client needs to change some aspects of the building or home, it only affects the design (Guo et al., 2018). The Learning and Development (L&D) industry uses VR technology to provide training and soft skills for students. The sports and gaming industry allows viewers to watch their favourites and play games with 360 or 180-degree screens. Art can be created using VR painting tools, and it is also used for events and conference meetings. One of the popular industries using VR is law enforcement. Many countries now use VR and AR technology for military and police force training (Thompson, 2024). Rokooei et al. (2023), further mentioned that there is a high potential to use VR in safety training programme in the world.

3. RESEARCH METHODOLOGY

Every research study is based on a unique approach. During research, the primary goal is to find a method to address the study objectives. In making this decision, it is essential to first determine the type and availability of information needed to meet these objectives. The main strategies are typically qualitative and quantitative, with a combination of these two called mixed strategies. This research is based on the qualitative research strategy. in-depth interviews, questionnaires, focus groups, ethnographic research, content analysis, and case study research are examples of qualitative research methodologies commonly used.

The interview guideline comprised two parts; one to evaluate demographic factors, and the other to identify the potential of implementing VR technology in the construction field. The collected data is presented using both graphical and numerical methods.

Firstly, the data presentation focuses on the demographic composition of the respondents to provide insight into the sample distribution. Those demographic data are presented in pie charts, although the research design illustrates a qualitative approach. The data were collected from six respondents serving in safety academies and safety training centers. Each respondent held a different position: Senior HR Executive, Safety Manager, Training Manager, Managing Director, Deputy Health and Safety Manager, and Safety Officer. Regarding years of service, it was found that four members had five to ten years of experience in the safety training field, while the remaining two members had 20-25 years and over 25 years of exposure in the safety training field.

4. RESEARCH FINDINGS AND ANALYSIS

Data was collected from the six respondents using the semi structured interviews and their demographic data are as given in Table 1. These interviews were conducted to gather the opinions of industry experts, covering various aspects of the industry.

Table 1: Profiles of the interviewees

Code	CIDA Grading	Designation	Professional Experience (Years)
R1	C9 - Water Supply & Sewerage	Senior HR Executive	8
R2	C4 - Building Construction	Safety Manager	25
R3	C4 - Building Construction	Training Manager	7
R4	C5 - Building Construction	Managing Director	28
R5	C5 - Building Construction	Deputy Health and Safety Manager	10
R6	C6 - Building Construction	Safety Officer	6

For data analysis, both graphical and numerical methods were utilised. The analysis included examining the respondents' status, experience, education level, and more. Based on the data analysis and presentation, the respondents' names, safety institute or firm, and professional status were included in the personal profile and have not been taken into the research paper. The demographic composition of each individual response was then presented first to provide insight into their experience and sample distribution.

Based on Figure 1, most respondents had five to ten years of experience in the construction safety field, accounting for 66.67% of the total respondents. Additionally, an equal percentage of respondents, 16.67% each, had 20-25 years of experience and over 25 years of experience in the field.

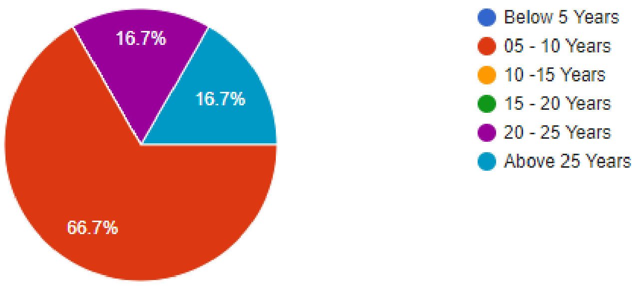


Figure 1: Experience in the safety field

In the Sri Lankan safety training field, there are main sources used for safety training programs. According to Figure 2, lectures and photographs/videos/presentations are mostly utilised, followed by team training and case studies. Game-based safety training methods are not widely used. Respondent R1 and R2 mentioned that; "in a country like Sri Lanka, traditional techniques are still popular since the non-availability of the hands-on experience".

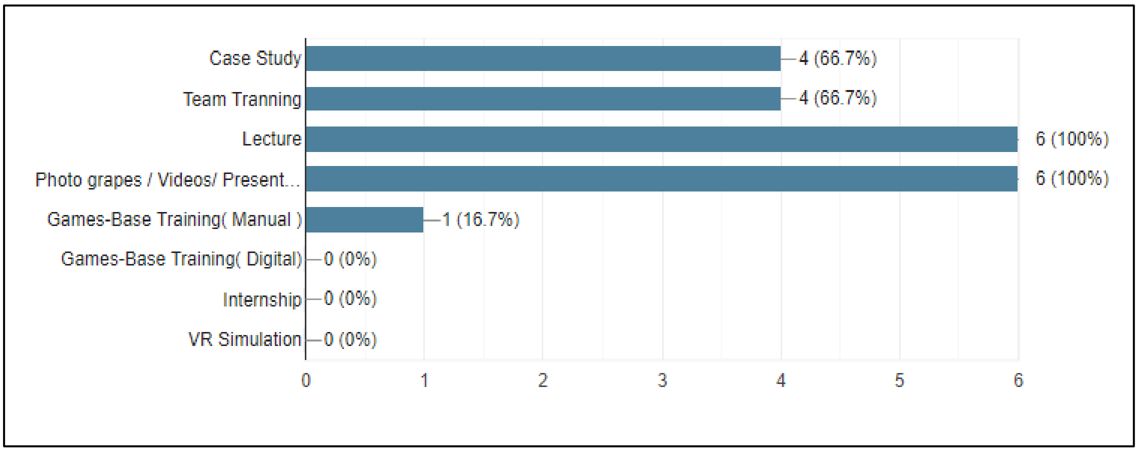


Figure 2: Sri Lankan safety training sources

According to Figures 3 and 4, VR technology is not being used in Sri Lanka for safety training.

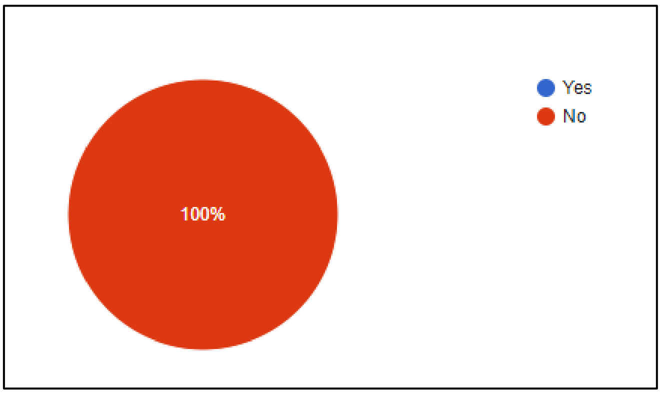


Figure 3: VR simulation safety training using in the construction field

In Sri Lanka, there are several reasons why VR technology has not been adopted in safety training programs, yet there is a potential for its expansion.

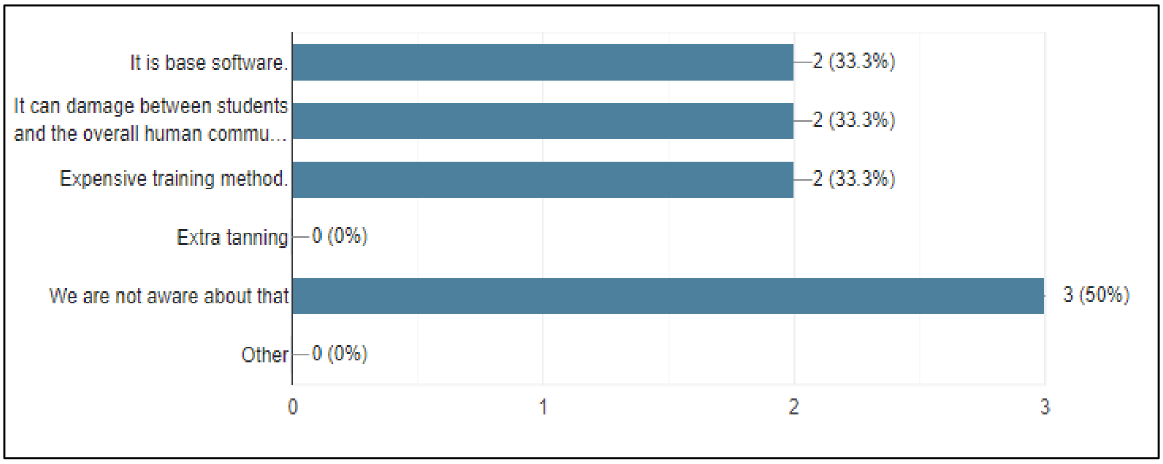


Figure 4: Reason for VR technology not involving the safety training program in Sri Lanka

As per the responses, 50% of the respondents were not aware of VR technology which is highlighted in Figure 5. Among the remaining respondents, 33.3% avoided using VR technology because they perceive it as an expensive training method, while another 33.3% avoided it due to concerns about potential damage to student interactions and overall human communication. Additionally, another 33.3% cited resistance to adoption due to its software nature.

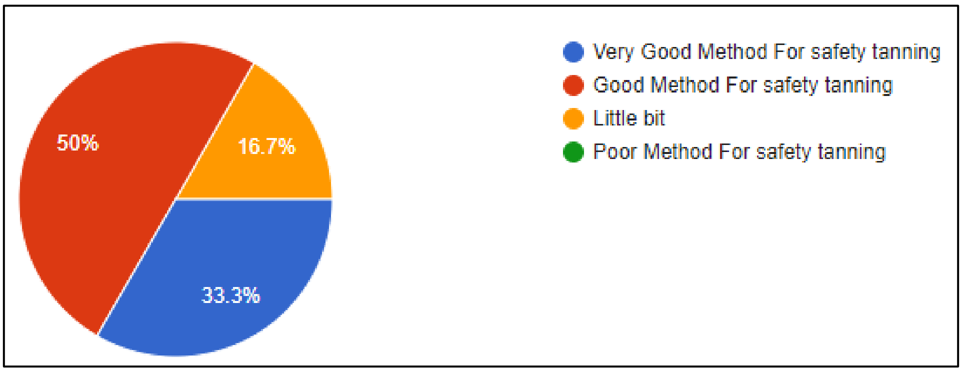


Figure 5: Respondent idea about VR technology

In accordance with the result, 33.3% of the respondents believed that VR simulator safety training is a very good method for safety training. However, the rest of the respondents had varying opinions, with 50% considering it as a good method and 16.7% viewing it as some kind of good software.

When using VR technology, workers can experience construction accident simulations in various situations. According to the responses represented in Figure 6, 33.3% strongly emphasised that VR simulation-based safety training can significantly improve safety skills in the workplace.

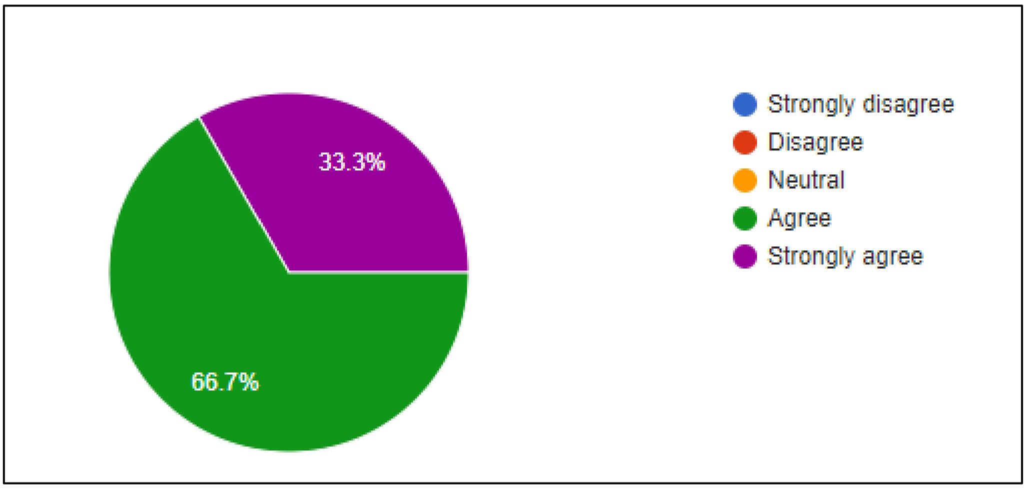


Figure 6: VR safety training improvement for the safety education

Responses strongly indicate that new trainees require virtual construction safety training before they begin their work. This sentiment is shared by 66.7% of respondents, with an additional 16.7% in agreement, as illustrated in Figure 7.

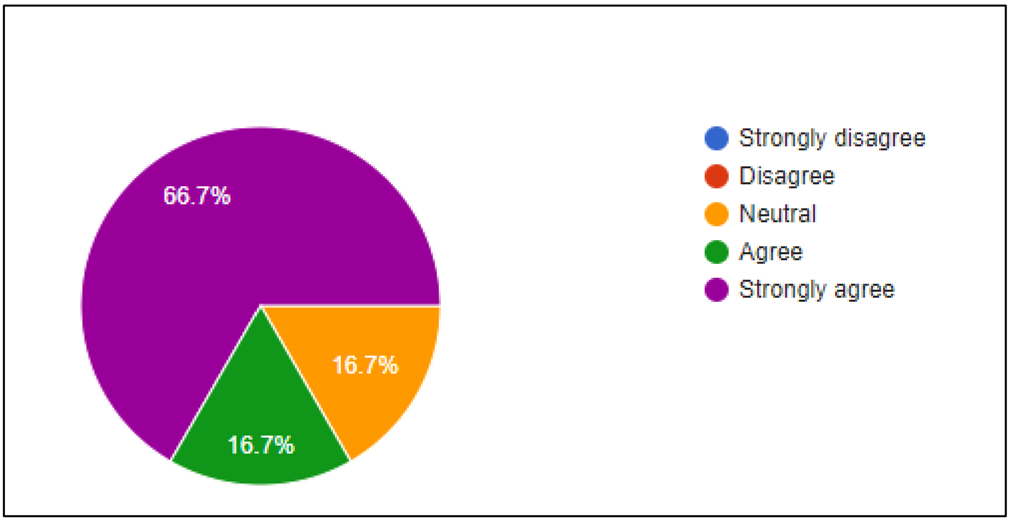


Figure 7: Important of the live-like safety training

In the construction industry, various types of accidents occur in day-to-day operations. Respondents believe that certain accidents need to be included in VR simulating construction safety training. According to the responses, 50% believe that VR safety training programs can effectively cover the construction accidents to mitigate unfair incidents. However, as shown in Figure 8, 16.7% of responses believed VR cannot be used for construction safety programs based on the mentioned accidents. Anyway, they have positive feedback regarding the use of VR as a tool for construction, particularly in the timely allocation of relevant resources.

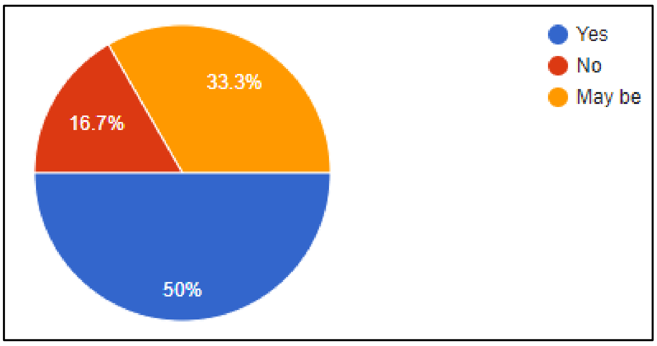


Figure 8: Response of the VR safety program.

5. CONCLUSIONS

The study investigated the potential of VR technology as a novel approach to safety training and accident prevention in the construction industry in Sri Lanka. The primary research objectives were to assess the effectiveness of VR in enhancing safety awareness and hazard recognition among construction workers, identify barriers preventing the adoption of VR technology in Sri Lanka, and propose strategies for integrating VR with traditional safety training methods.

Key findings from the empirical research and literature review revealed that VR technology offers significant advantages in safety training by providing immersive and realistic simulations of construction site scenarios. These simulations enhance workers' ability to recognise hazards and respond to emergencies effectively, which is not always achievable through traditional training methods. The qualitative data collected from interviews with industry experts highlighted that VR could significantly improve safety skills and emergency response preparedness among construction workers.

However, the study identified several barriers to the adoption of VR in Sri Lanka, including high costs, limited awareness and understanding of VR technology among stakeholders, and a lack of technical expertise and VR software developers. Additionally, concerns were raised about the potential negative impact of VR on interpersonal communication and interaction during training sessions. These barriers indicate a need for concerted efforts to promote and facilitate the adoption of VR technology in the construction industry.

To address these challenges, the study recommends increasing awareness and education about VR through workshops and seminars to educate stakeholders about the benefits and applications of VR technology in safety training. Financial investment and support from government bodies and private sector partnerships are crucial to subsidise the costs of VR equipment and software. Moreover, investing in the training of VR software developers and technicians is essential to build local expertise. Additionally, developing comprehensive training programs that combine VR simulations with traditional hands-on and classroom-based training can maximise engagement and effectiveness.

In conclusion, while VR technology presents promising opportunities for improving safety training in the Sri Lankan construction industry, its successful implementation requires overcoming significant barriers through targeted strategies. By addressing these challenges, the construction industry in Sri Lanka can harness the full potential of VR to enhance worker safety, reduce accidents, and improve overall productivity. The study solely focuses on the potential of VR implementation in the Sri Lankan construction industry. Therefore, it is recommended that future research explore the integration of VR technology with personal protective equipment. Additionally, investigating the effectiveness of VR technology implementation in other industries in Sri Lanka would be beneficial.

6. REFERENCES

Anupoju, S. (2020). *Types of residential buildings and their site selection*. The Constructor. https://theconstructor.org/building/types-site-selection-residential-building/5995/#

Baraka, H., Kotb, M. H., & Dief, M. I. A. (2019). Risk in the construction industry. *Current Trends in Civil & Structural Engineering-CTCSE*, *2*(4). https://doi.org/10.33552/ctcse.2019.02.000541

Cvetković, D. (2021). Introductory chapter: Virtual reality. *Virtual reality and its application in education*. IntechOpen. https://doi.org/10.5772/intechopen.91950

Davies, A. (n.d.). *Top 10 VR tools for software development.* DevTeam.Space. https://www.devteam.space/blog/10-great-tools-for-vr-development/

Dom, B. (2023, February 20). *History of VR - Timeline of events and tech development.* VirtualSpeech. https://virtualspeech.com/blog/history-of-vr

Fu, X., Liu, M., Wang, X., Yin, J., & Su, P. (2018). Construction technology and innovation research of municipal civil engineering. *Smart Construction Research, 2*(1), 1-5. https://doi.org/10.18063/scr.v0.393

González-Rodríguez, M. R., Díaz-Fernández, M. C. & Pino-Mejías, M. Á. (2020). The impact of virtual reality technology on tourists' experience: A textual data analysis. *Soft Computing*, *24*, 13879-13892. https://doi.org/10.1007/s00500-020-04883-y

Guo, Z., Zhou, D., Chen, J., Geng, J., Lv, C., & Zeng, S. (2018). Using virtual reality to support the product's maintainability design: Immersive maintainability verification and evaluation system. *Computers in Industry, 101*, 41-50. https://doi.org/10.1016/j.compind.2018.06.007

History of virtual reality. (n.d.). Virtual Reality Society. https://www.vrs.org.uk/virtual-reality/history.html

International Labour Organization (ILO). (2011, July 13). *World statistic*. https://www.ilo.org/moscow/areas-of-work/occupational-safety-and-health/WCMS_249278/lang--en/index.htm

Jones, K. (2020, January 03). Increase in number of fatal and nonfatal injuries for construction workers in 2018. *SBE Today E-Newsletter, 35*(84), pp. 1-8. https://www.sbeinc.com/files/PDFNewsletter/January%203,%20SBE%20Newsletter.pdf

Kenley, R. (2014). Productivity improvement in the construction process. *Construction Management and Economics, 32*(6), 489–494. https://doi.org/10.1080/01446193.2014.930500

Korkut, E. H., & Surer, E. (2023). Visualization in virtual reality: A systematic review. *Virtual Reality, 27*, 1447-1480. https://doi.org/10.1007/s10055-023-00753-8

Laufer, A., & Ledbetter, W. B. (1986). Assessment of safety performance measures at construction sites. *Journal of Construction Engineering and Management, 112*(4), 530–542. https://doi.org/10.1061/(ASCE)0733-9364(1986)112:4(530)

Naismith, N., Monaghan, B., Zhang, T., Doan, D., GhaffarianHoseini, A., & Tookey, J. (2016). Examining the productivity in the NZ construction industry. *The 2nd NZAAR International Event Series on Natural and Built Environment, Cities, Sustainability and Advanced Engineering, Kuala Lumpur*. https://www.researchgate.net/publication/323358720_EXAMINING_THE_PRODUCTIVITY_IN_THE_NZ_CONSTRUCTION_INDUSTRY

Nantel, J. (2004). My virtual model: Virtual reality comes into fashion. *Journal of Interactive Marketing, 18*(3), 73-86. https://doi.org/10.1002/dir.20012

Perera, H. N., Somachandra, V., & Samarasiri, N. C. (2017). Preventing accidents in building construction through safety management. *International Conference on Technology Management (INCOTEM) 2017, University of Moratuwa, Sri Lanka.* https://www.icbt.lk/wp-content/uploads/2018/08/Preventing-Accidents-in-Building-Construction-through-Study-of-Safety-Management.pdf

Qu, Z., Lau, C. W., Simoff, S. J., Kennedy, P. J., Nguyen, Q. V., & Catchpoole, D. R. (2022). Review of of innovative immersive technologies for healthcare applications. *Innovations in Digital Health, Diagnostics, and Biomarkers*, *2*(2002), 27-39. https://doi.org/10.36401/IDDB-21-04

Rameezdeen, R., Pathirage, C., & Weerasooriya, S. (2006). Study of construction accidents in Sri Lanka. *Built-Environment Sri Lanka*, *4*(1), 27-32. https://doi.org/10.4038/besl.v4i1.7650

Rokooei, S., Shojaei, A., Alvanchi, A., Azad, R., & Didehvar, N. (2023). Virtual reality application for construction safety training. *Safety Science*, *157*, 105925. https://doi.org/10.1016/j.ssci.2022.105925

Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality, *Construction Management and Economics*, *31*(9), 1005–1017. https://doi.org/10.1080/01446193.2013.828844

Saleh, J. H., & Pendley, C. C. (2012). From learning from accidents to teaching about accident causation and prevention: Multidisciplinary education and safety literacy for all engineering students. *Reliability Engineering and System Safety*, *99*, 105–113. https://doi.org/10.1016/j.ress.2011.10.016

Sri Lanka GDP from construction. (n.d.). Trading Economics. https://tradingeconomics.com/sri-lanka/gdp-from-construction?user=olexpb/forecast.

Spellman, F. R. (2020). Excavation safety. *Surviving an OSHA Audit* (2nd ed.). Taylor & Francis. https://doi.org/10.1201/9781003127734-14

Teja, R. (2024, June 26). *What is a sensor? 25 different types of sensors and their uses*. ElectronicsHub. https://www.electronicshub.org/different-types-sensors/

Thabet, W., Shiratuddin, M. F., & Bowman, D. (2002). Virtual reality in construction: A review. In B. H. V. Topping, & Z. Bittnar (Eds.), *Engineering Computational Technology*. (pp. 25-52). Saxe-Coburg Publications, Stirlingshire, UK. https://doi.org/10.4203/csets.8.2

Thomson, D., (1984). *An edition of the middle English grammatical texts* (1st ed.). Routledge. https://www.routledge.com/An-Edition-of-the-Middle-English-Grammatical-Texts/Thomson/p/book/9780367195489

Thompson, S. (2024, March 21). *VR Applications: Key industries already using virtual reality*. VirtualSpeech. https://virtualspeech.com/blog/vr-applications

Ullah, F., Sepasgozar, S. M. & Wang, C., (2018). A systematic review of smart real estate technology: Drivers of, and barriers to, the use of digital disruptive technologies and online platforms. *Sustainability*, *10*(9), 3142. https://doi.org/10.3390/su10093142

Weddikkara, C., & Devapriya, K. (2000, November). The Sri-Lankan construction industry in the new millennium. *2nd International conference on construction in developing countries. Challenges facing the construction industry in developing countries, Botswana* (pp. 15-17). https://www.irbnet.de/daten/iconda/CIB8976.pdf

Wijekoon, A. W. M. B. (2016) *Significant workplace injuries and diseases in Sri Lanka* [Masters monograph, University of Moratuwa]. http://dl.lib.mrt.ac.lk/bitstream/handle/123/12321/full-thesis.pdf?sequence=2&isAllowed.

Yuen, H., Corndorf, E., Barbosa, G., & Kumar, P. (2005). Barbosa et al. reply:. *Physical Review Letters*, *94*(4). https://doi.org/10.1103/physrevlett.94.048902

Weerasekara, K.M.K.D., Rathnayake, R.M.K.M., Mendis, M.S., Galabada, G.H., Jayasinghe, G.Y. and Halwatura, R.U., 2024. Prototyping a coating based on ancient technology: A case study in Sigiriya, Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 851-863. DOI: https://doi.org/10.31705/WCS.2024.68. Available from: https://ciobwcs.com/papers/

PROTOTYPING A COATING BASED ON ANCIENT TECHNOLOGY: A CASE STUDY IN SIGIRIYA, SRI LANKA

K.M.K.D. Weerasekara[1], R.M.K.M. Rathnayake[2], M.S. Mendis[3], H. Galabada[4], G.Y. Jayasinghe[5] and R.U. Halwatura[6]

ABSTRACT

This paper presents a study on prototyping a coating based on ancient technology, specifically focusing on the techniques used in Sigiriya, an ancient rock fortress located in Sri Lanka. Sigiriya stands out for its remarkable paintings and innovative hydraulic systems, emblematic of an advanced ancient civilisation. Through an interdisciplinary approach merging archaeology, materials science, and chemistry, this research seeks to understand and replicate the coatings found on the Sigiriya paintings. By analysing the composition and properties of these coatings, a modern prototype was developed that mirrors the characteristics of the ancient coatings, offering insights into their longevity and preservation methods. The experimental emphasis of the research is on the production of a natural surface coating utilising wood apple gum and other natural extracts. The methods included coating formulation, application, and testing. There were five treatments in the study, each with different ratios (20%,40%,50%,60%, and 80%) of wood apple (Limonia acidissima) gum, Dorana (Dipterocarpus glandulosus) oil, sesame (Sesamum indicum)oil and Haldummala (Trachylobium verrucosum) mixes. This investigation explored the basic performance properties of coatings, looking closely at water resistance, viscosity, adhesion, pH levels, and aesthetic appeal. However, in treatment T1, the ratio of 20:80 of water: Dorana oil exhibited exceptional adhesion properties and displayed the maximum hardness level (8H). Some treatments also showcased promising indications of water resistance. The findings of this study hold the potential to significantly impact various sectors by providing eco-friendly alternatives, fostering innovation, creating cultural business prospects, and upholding traditional values.

Keywords: *Ancient Coatings; Paintings; Sigiriya; Wood Apple Gum.*

---

[1] Undergraduate student, Department of Agriculture Engineering & Environmental Technology, University of Ruhuna, Mapalana, Kamburupitiya, Sri Lanka, dilshaweerasekara095@gmail.com
[2] Reseach scholar, Department of Civil Engineering, University of Moratuwa, Bandaranayake Mawatha, Moratuwa, Sri Lanka, kaarathnayake1@gmail.com
[3] Senior Lecturer, Department of Civil Engineering, NSBM Green University, Pitipana, Homagama, Sri Lanka, malsharesearch@gmail.com
[4] Researcher, Department of Civil Engineering, University of Moratuwa, Bandaranayake Mawatha, Moratuwa, Sri Lanka, hyasasiri@yahoo.com
[5] Professor, Department of Agriculture Engineering & Environmental Technology, University of Ruhuna, Mapalana, Kamburupitiya, Sri Lanka, jayasinghe@ageng.ruh.ac.lk
[6] Professor, Department of Civil Engineering, University of Moratuwa, Bandaranayake Mawatha, Moratuwa, Sri Lanka, rangikauh@gmail.com

1. INTRODUCTION

The ancient city of Sigiriya, located amidst the lush forests of Sri Lanka, stands as a testament to its creators' ingenuity and artistic prowess (Ranasinghe, 2023). Among its many wonders are the vibrant paintings adorning the rock face, showcasing the artistry of an ancient civilisation (Dissanayaka & Arachchi, 2018). These paintings, along with the complex hydraulic systems and architectural marvels, continue to intrigue researchers and historians alike (Davids,1875; Silva, 2002; Subasinghe & Karunaratne,2022).

The Sigiriya paintings exhibit similarities to the Gupta style of painting seen in the Ajanta Caves of India. This similarity is not surprising, considering the geographical proximity of the two regions and the shared Buddhist faith during the 5th century. Scholars have referenced works by Silvat (1975), Somathilake (2002), and Nishanthi (2021) in support of this observation. However, despite this influence, the Sigiriya paintings are distinguished by their pronounced vibrancy, fluidity, and lifelike qualities compared to the paintings found in the Ajanta Caves. These Sigiriya artworks provide a rare glimpse into the pinnacle of ancient Sinhala artistry, as noted by Somathilake (2007). Particularly striking is the bold portrayal of well-defined bodies, ample bosoms, and full lips, which carries an unusually provocative tone (Subasinghe & Karunarathna,2022). Notably, these paintings constitute the sole instance of non-hidden female sensuality depicted in Sri Lankan art, as opposed to the strictly stylised representations of female figures with religious themes that predominate. Therefore, the Sigiriya paintings possess a distinctly Sri Lankan character. Furthermore, Subasinghe and Karunarathna (2022) emphasise that these paintings are the only surviving examples of secular, non-religious art from antiquity found in Sri Lanka today.

The paintings of Sri Lanka are predominantly recognised as religious art; however, the Sigiriya paintings stand out as temporal, as noted by Coomaraswamy (1907). Although historical records mention 25 paintings, few remain in the primary painting area today. These paintings predominantly feature female figures depicted with fair (yellow, golden yellow) or dark (ruddy, greenish) complexions. The main cluster of frescoes appears on the western face of the Sigiriya rock, specifically in the two rock chambers known as A and B, located approximately fifteen yards above the gallery floor near the rock's southern end (Subasinghe & Karunarathna, 2022). Cave 67.6 feet long is divided into two sections, A (26 feet 3 inches) and B (41 feet 3 inches), by a narrow ledge. Cave A is relatively spacious, while Cave B is taller and offers enough room to stand upright, except towards the end. The techniques employed in the Sigiriya paintings have sparked conjecture and controversy. Mr. Dhanapala proposed that the paintings were executed using the Fresco Bueno technique, whereas Dr. O.P. Agrawal and Dr. Nanda Wickramasinghe suggest they represent the Fresco Lustro technique (Agrawal, 2002:122). Additionally, some scholars believe they were created using the tempera technique. R.H. De Silva introduced a different perspective, suggesting the Sigiriya paintings were made using an "oil emulsion tempera with gum" technique (Seneviratne, 2018).

Utilising contemporary scientific methodologies, precise data was obtained regarding the mixtures, pigment bindings, and the presence of organic and inorganic chemicals used in Sigiriya paintings (Seneviratne, 2018; Seneviratne, 2020). This data was further scrutinised in the study conducted by Rathnayake et al. (2024). Consequently, a comprehensive understanding of the knowledge disseminated by scholars, both documented and undocumented, from various painting generations was achieved.

Numerous local and international researchers have utilised these findings to discern the ancient techniques employed by past painters (Seneviratne, 2018; Seneviratne, 2020; Rathnayake et al., 2024). Above studies have led to a robust understanding of the knowledge and techniques from various generations of painters, both documented and undocumented.

Despite the detailed understanding of the composition and techniques of ancient Sigiriya paintings, there is a lack of practical application of this knowledge in creating modern prototypes that replicate these ancient coatings.

Specifically, there is a need to bridge the gap between historical knowledge and contemporary application by developing a modern prototype that not only replicates but also demonstrates the performance properties of the ancient coatings. This paper, therefore, explores the research and development undertaken to construct a modern prototype that replicates the attributes of ancient coatings. Additionally, it presents the performance properties of the developed prototype, which is the innovative product under discussion in this paper. The study goes beyond theoretical analysis by applying historical knowledge to develop a modern prototype of ancient Sigiriya coatings. This transition from understanding to application is novel as it demonstrates the practical feasibility and performance of ancient techniques in a contemporary setting.

2. LITERATURE REVIEW AND CONCEPT

The Sigiriya paintings depict celestial maidens in graceful poses, painted with a remarkable level of detail and vibrant colours. The durability of these paintings over centuries points to the advanced techniques employed by the ancient artisans. Central to their preservation is the protective coating applied over the paintings, shielding them from weathering, humidity, and other environmental factors (Subasinghe & Karunarathna, 2022).

As noted by Seneviratne (2018) and Seneviratne (2020), traditional artists in Sri Lanka historically utilised Wood apple gum (Feronia Elephantum) for safeguarding the Sigiriya paintings. The Wood apple tree, indigenous to the Indian subcontinent and Southeast Asia, produces a clear, bright, and brown-coloured gum as a byproduct of specific plant and tree metabolic processes (Hossain et al., 1994). Natural gums derived from plants are either soluble in water or absorb water to create a viscous solution (Rodrigues et al., 2018). Among the essential resins employed in Sri Lankan art, Wood apple resin holds significant importance. Feronia gum is regarded as equivalent to gum Arabic in the context of varnishes and paints (Hossain et al., 1994). It serves as a substitute or adulterant for gum Arabic and finds use in artistic endeavours (Rodrigues et al., 2018).

Moreover, the research findings indicate the presence of minute quantities of Wood apple gum, Sesame oil, and Dorana Oil in the Sigiriya painting samples (Seneviratne, 2020; Rathnayake et al., 2024). It is evident that the use of oil as a medium for outdoor work, as observed in the late medieval period paintings of Sri Lanka, was crucial for their preservation. Without it, their longevity would be difficult to comprehend. According to Rathnayake et al. (2024), the ancient Sigiriya painters employed a chemical crosslinking process. This process involved the use of Wood apple gum (a water-soluble resin) and Dorana oil (a vegetable oil), catalysed by heat, oxidizing agents, and/or driers. This specific technique endowed the coating with increased durability, making it resistant to water solubility post-application. Haldummala was used as a thickening agent.

3. METHODOLOGY

The methodology of this research adopts a two-step approach, encompassing prototype development based on existing literature and performance analysis. The process is primarily organised into the following steps:

1. Prototyping based on literature, and
2. Studying basic performance properties.

The formulation of coating compositions generally involves four essential components: binder, solvent, pigment, and additive (Streit-Berger & Goldschmidt, 2018). In the preliminary development phase, this study selected Haldummala, Dorana oil, Wood apple gum, and Sesame oil for the coating formulation. Previous studies by Rathnayake et al. (2024) and Seneviratne (2020) provided material clarification for coating purposes. In this study, the identification of materials was followed by their classification based on purpose. After that, performance criteria were experimentally analysed by varying two variables: the aqueous plant gum solution to oil ratio using the 2 oils, Dorana and Sesame.

3.1 DEVELOPMENT OF MODERN PROTOTYPE

Seneviratne (2018) identifies the coating layer of Sigiri paintings as containing a water-soluble compound that turns into a white, fluffy substance with excess ethanol, indicating the presence of vegetable gum. Additionally, the binding medium features a drying oil that is insoluble in water but dissolves in ethanol, carbon tetrachloride, and chloroform. Seneviratne (2018) also utilised Gas Chromatography-Mass Spectrometry (GCMS) to detect wood apple gum and Dorana oil in the protective layer, concluding that it mainly consists of Dorana oil. This finding suggests that the paint layer mixed with Dorana oil may have degraded over time.

Building upon the insights gained from the analysis of the ancient coatings, a modern prototype was developed in this study. This study selected the method adopted in the study of Rathnayake et al (2024). As per the above studies, Haldummala, Dorana oil, Sesame oil, and Wood apple gum is used for coating formulation. Further in this study, two oils; Dorana and Sesame were identified as the crosslinking binding additives. Meanwhile, water as the solvent, wood apple gum as the binder, and Haldummala as an additive.

The formulation of the modern prototype drew inspiration from the following key components identified in the ancient coating:

- **Natural Resins:** Extracts from Wood apple trees, known for their adhesive and protective properties.
- **Mineral additives:** Haldummala consists of minerals such as Silica and Magnesium Carbonate, providing thickening properties (Subasinghe et al,2019).
- **Organic crosslinking oils:** Sesame oil and Dorana oil, contributing to the cohesive structure of the coating.

In the experimental phase, a quantity of 20g of each type of plant gum was dissolved in 500 mL of water, following the methodology outlined by Rathnayake et al. (2024). The dispersion method was employed to dissolve an equivalent quantity of Dummala in

Dorana oil for comparative analysis, thereby maintaining uniform concentrations across both substances. Subsequently, the two prepared solutions were subjected to a temperature of 80°C to facilitate thorough mixing with the previously mentioned additives. This procedure was replicated for Sesame oil. The study incorporated nine treatments, each characterised by varying ratios (20%, 40%, 50%, 60%, and 80%) of Wood Apple Gum (WG), and Haldummala combined with Dorana oil and Sesame oil, respectively as shown in Tables 1 and 2.

Table 1: Solution ratios with Dorana oil

Treatment abbreviation	WG solution: Dorana oil (ml)
T1	40:160
T2	100:100
T3	120: 80
T4	160: 40

Table 2: Solution ratios with Sesame oil

Treatment abbreviation	WG solution: Sesame oil (ml)
T1	40:160
T2	80:120
T3	100:100
T4	120: 80
T5	160: 40

The objective was to create a coating that not only mimics the appearance of the original but also offers enhanced durability and protection for contemporary applications. In this study, planed specimens of Soil-based wall care putty developed from drinking water treatment plant waste alum (Patent no. 21020) were used to apply the developed coatings. This wall care putty is a novel sustainable material known mostly for its good workability, properties, and appearance similar to the Sigiriya mirror wall. A total of 9 samples were used for the experiment and they were grouped as presented in Tables 1 and 2. The prepared wall care putty samples were applied with 9 coating treatments as in Table 3. The specimens underwent a conditioning period of 7 days in an environment maintained at a temperature of 20 ± 2 ◦C and a relative humidity of 50% ± 5% before the execution of any tests.

Table 3: Experimental design of the prototype

	Experimental Design	
	Dorana oil as crosslinking additive	Seasme oil as crosslinking additive
No.of samples	4 samples	5 samples
Coating system	Brush application	Brush application
Coating formulae	10% binder with a 20% dilution with water during application	10% binder with a 20% dilution with water during application
Applied surface	Patent no. 21020 - soil-based wall care putty	Patent no. 21020, soil-based wall care putty

	Experimental Design	
	Dorana oil as crosslinking additive	**Seasme oil as crosslinking additive**
Coating application	2- coat application with a light 2000-grit sanding between	2- coat application with a light 2000-grit sanding between
Tested properties	1)Adhesion test 2)Water resistance test 3) Hardness test 4) Viscosity 5) pH value 6)Visual appearance	1)Adhesion test 2)Water resistance test 3) Hardness test 4) Viscosity 5) pH value 6)Visual appearance

3.2 TESTING OF PERFORMANCE PROPERTIES

The modern prototype underwent rigorous testing to assess its performance and characteristics:

- **Adhesion Tests:** ASTM D3359 represents the standard testing procedures for evaluating adhesion through a tape test. This examination measures the adherence of film coatings to metal substrates by applying and subsequently removing a pressure-sensitive tape over incisions made in the film. This testing methodology is commonly referred to as the Cross Hatch test.
- **Hardness Tests:** ASTM D3363 represents the standard procedure that involves assessing the surface aesthetics of a coating after trying to inflict a scratch on it using a pencil of a specific hardness, angled at 45 degrees, and applying a steady force.
- **Water resistance:** ASTM D870 testing procedure involves submerging coated samples in water within a container that resists corrosion. Observations are made and reported regarding any alterations in color, the formation of blisters, loss of adhesion, softening, or embrittlement.
- **Viscosity:** Krebs Stormer viscometer was used to measure the viscosity as described in ASTM D562.
- **pH Value:** pH value was measured using a laboratory pH meter.
- **Visual appearance:** The inspection area was set up with consistent lighting conditions, ideally utilising natural daylight. The inspection area was ensured to have a neutral background to eliminate potential visual distraction. Each coated sample was individually examined with care.

4. RESULTS

One way ANOVA was carried out to identify the significant difference between tested nine treatments considering their pH values, viscosity, adhesion properties, hardness and water resistance. Significance of difference was defined at p-value < 0.05. Minitab17 was used to perform the statistical analysis.

4.1 VARIATIONS ACCORDING TO THE ADHESION

The effectiveness of coatings adhering to surfaces is influenced by a multitude of factors. It includes the compatibility of the substrate, the preparation of the surface, the formulation of the coating, the methods of application, the conditions under which curing occurs, environmental factors, and the age of the coating (Chen et al., 2014). To ensure that coatings provide effective protection and maintain their aesthetic appeal over time, it is crucial to achieve consistent adhesion (Chen et al., 2014). The delivery of high-quality coatings that exhibit reliable and robust adhesion necessitates a comprehensive understanding of these variations and the implementation of appropriate testing, formulation, and application strategies. Zero to seven increase the adhesion ability. The highest adhesion level shows higher performance. Adhesion performance variations are shown in Figure 1. T1, T9, and T2 showed the best adhesion.

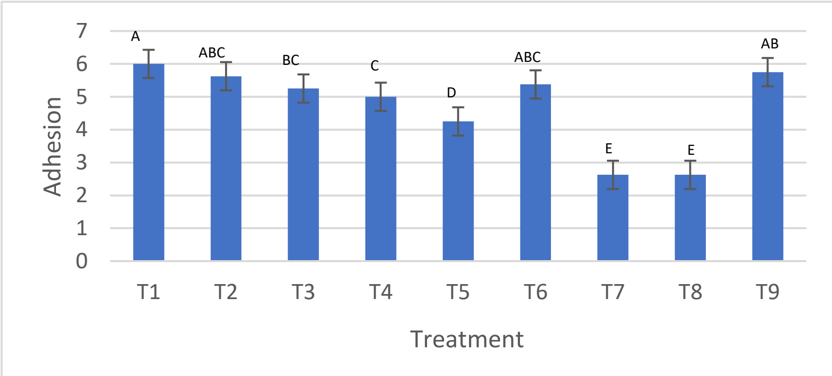


Figure 1: Adhesion vs Treatments

*(*Vertical bars indicate the standard errors of the mean adhesion (n = 3), Means that do not share a same letter are significantly different according to Ducan Multiple Range Test (DMRT))*

4.2 VARIATIONS ACCORDING TO THE HARDNESS

Several factors such as the composition of the coating, conditions under which curing is performed, thickness of application, adhesion, texture, dispersion of particles, flexibility, age, and the methodologies employed for testing, can potentially influence the outcomes of the pencil hardness test (Kim et al,2016). Gaining insights into these variations can aid in the development and optimisation of coatings for specific uses by shedding light on crucial aspects of the mechanical properties and longevity of the coatings. (Kim et al., 2016). Hardness performance variations are shown in Figure 2. T1, T3 and T2 shows the highest hardness value and there is a significant difference between other coatings.

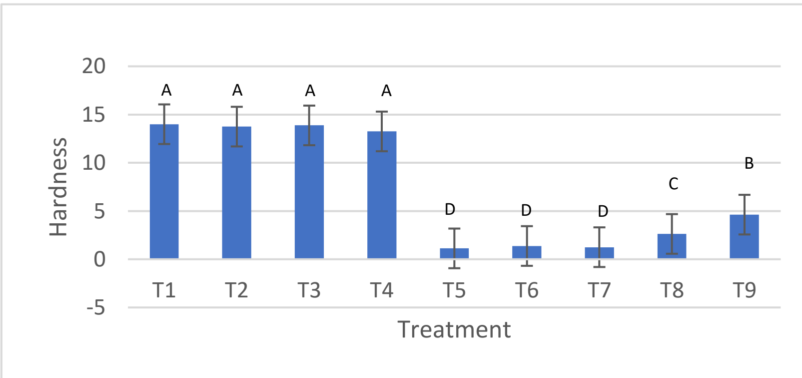


Figure 2: Hardness vs Treatments

*(*Vertical bars indicate the standard errors of the mean Hardness (n = 3), Means that do not share a same letter are significantly different according to Ducan Multiple Range Test (DMRT))*

4.3 VARIATIONS ACCORDING TO THE WATER RESISTANCE

The water immersion test serves as a vital method for evaluating the water resistance of a coating. Factors such as the formulation, thickness of the coating, conditions under which curing is performed, porosity, exposure to the environment, interaction with the substrate, methodologies employed for testing, and parameters all contribute to the variations observed in the results pertaining to water resistance (Zhang et al., 2021). Comprehending these variations empowers those formulating the coatings to develop coatings that maintain their structural integrity and functionality in the face of challenges related to water, thereby ensuring durability and reliability across a multitude of applications. Water resistance variations are shown in Figure 3. After water immersion, test hardness of coatings and again highest hardness coating become T1. T1 and T2 were not significantly differed from each other but they were significantly differed from other seven coatings.

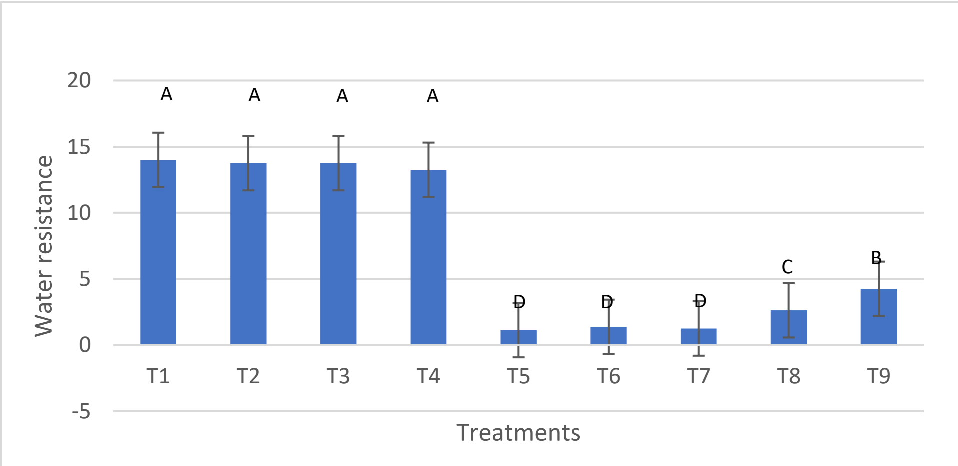


Figure 3: Water resistance vs Treatments

*(*Vertical bars indicate the standard errors of the mean water resistance (n = 3), Means that do not share a same letter are significantly different according to Ducan Multiple Range Test (DMRT))*

4.4 EVALUATION OF PH VALUES

The pH values of coatings significantly impact their formulation, application, adhesion, curing, and overall longevity. To ensure that coatings deliver uniform performance, robust adhesion, and enduring protection under diverse conditions, it is imperative to appropriately consider and regulate pH during both the formulation and application stages. A detailed grasp of how pH affects coatings can aid in the creation of coatings that satisfy certain performance criteria in a variety of applications. The best pH value for coating is 6.5-8.5 (ISO 19396- 2:2017). The pH values of the treatments are shown in Figure 4. Therefore, every treatment needs future developments because any of them not reach that range.

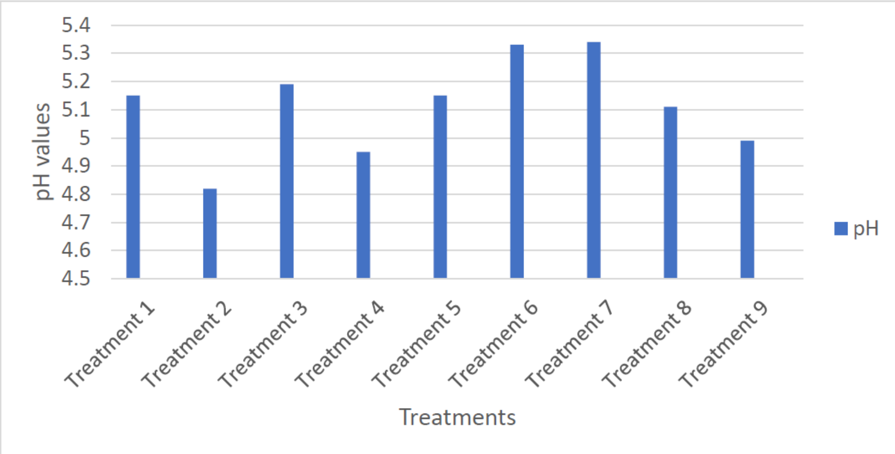


Figure 4: pH vs Treatments

4.5 EVALUATION OF VISCOSITY

The viscosity of wall coatings is a significant element that considerably influences their application, adhesion, film thickness, texture, and overall finish. To ensure uniform application, sufficient adhesion to vertical surfaces, and the desired appearance, it is essential to achieve the correct balance of viscosity (Yuan et al., 2013). Appropriate formulation, viscosity testing, and modifications are vital for wall coatings to meet performance and aesthetic standards across various application conditions. Accepted range viscosity for coatings is 25-35 maps (ISO 2884:1974). The viscosity values are shown in Figure 5. The T1, T2, T3 and T4 were between that range.

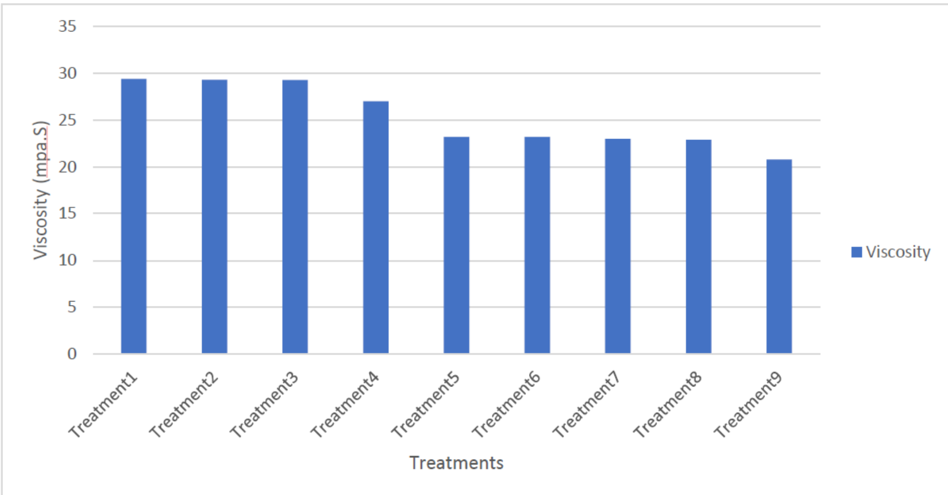


Figure 5: Viscosity vs Treatments

4.6 EVALUATION OF VISUAL APPEARANCE

Beyond basic aesthetics, the visual attractiveness of coatings plays a significant role in influencing product quality, consumer perception, and functional performance. This aspect is particularly pertinent in industries where coatings are crucial for enhancing the aesthetic appeal of various objects and surfaces. Numerous internal and external factors influence the perception of coatings in terms of their visual appearance, collectively impacting the overall impression they create. Color, gloss, and texture are fundamental components of these factors (Barletta et al., 2018). The selection of color serves as a medium for expressing brand identity, aesthetic appeal, and product uniqueness, in addition to personal preference. The final color is determined by additives and pigments, and it can be modified to evoke specific emotions or to fulfil practical requirements. Visual appearances are depicted in Figure 6. Smooth wall surfaces exhibit greater resistance to fungal growth (Udawattha & Halwatura, 2018). Further to the authors, smooth wall surfaces are more resistance to fungi growth. When consider these coatings T1 shows best visual appearance.

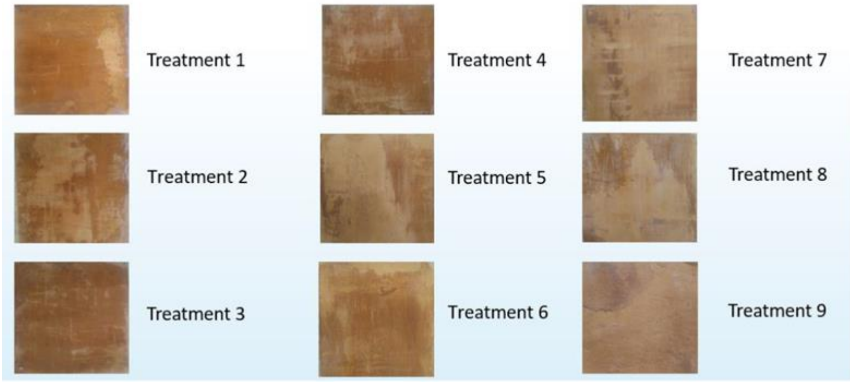


Figure 6: Visual appearance

5. DISCUSSION

This study comprehensively evaluates the multifaceted properties of coatings, emphasising both visual attractiveness and functional performance. Key findings include the significance of pH, viscosity, adhesion, hardness, and water resistance for identifying product performance. Optimal pH levels (6.5-8.5) are crucial for coating formulation, application, and durability, though adjustments were needed to maintain this range. Viscosity, within the standard 25-35 mPas, significantly affects application and adhesion, with T1, T2, T3, and T4 performing best. Adhesion, influenced by substrate, preparation, formulation, and environmental factors, was highest in T1, T2, T6, and T9. Pencil hardness tests identified T1, T2, T3, and T4 as having superior mechanical endurance. Water resistance, essential for coating longevity, showed T1, T2, T3, and T4 as the top performers, though further improvements are possible. Overall, the research underscores meticulous formulation and application methods to achieve high-performance, durable coatings, offering valuable insights for industry advancements and innovation.

Additionally, when comparing the Sigiriya paintings to the Ajanta cave paintings, a specific reason for using an oil medium in the Sri Lankan paintings becomes apparent (Seneviratne, 2020). The majority of Sigiriya paintings are located outdoors, where superior water resistance properties are crucial. This advantage of the oil medium was confirmed by the study's results.

Notably, the coating formulated with in the study demonstrated results that align with ASTM standard for wall coatings. This suggests that there is potential for the development of advanced coatings using methodologies derived from ancient coating technologies. Furthermore, this coating was developed entirely from natural materials, underscoring the feasibility of creating innovative coatings based on traditional practices. Therefore, this experimental study underscores the importance of preserving the intangible cultural heritage of Sri Lanka through the lens of scientific innovation. This endeavour draws inspiration from the rich heritage of Sri Lanka, where ancient artisans possessed profound insights into the chemical interactions within their coatings. Moreover, they ingeniously crafted paintings and coatings to withstand the country's diverse climatic conditions.

6. CONCLUSIONS

The exploration and prototyping of an ancient coating technology from Sigiriya represent an intriguing convergence of historical context and modern materials science. By decoding the composition of the initial coating and formulating a modern equivalent, this study has procured an invaluable understanding of the expertise of ancient craftsmen.

Theoretically, this research enriches the understanding of ancient coating technologies, offering insights into the materials and methods used by ancient Sri Lankan craftsmen. It contributes to the broader field of materials science by demonstrating how historical techniques can inform and enhance modern formulations. Practically, the findings suggest that the modern equivalent of the Sigiriya coating can be effectively used in heritage conservation. The resilience and protective qualities of prototype T1 make it a promising candidate for preserving not only cultural relics but also modern art pieces, ensuring their longevity and durability through further development.

The contemporary prototype T1 exhibits potential in terms of resilience and safeguarding, paving the way for its application in the conservation of cultural relics and modern art pieces. Subsequent research could probe further into the refinement of the formulation for distinct applications and investigate its viability in global heritage preservation initiatives. The heritage of Sigiriya persists not solely in its awe-inspiring paintings but also in the pioneering technologies utilised by its ancient residents. Through endeavours to comprehend and replicate these ancient coatings, this study honours the proficiency of Sri Lankan ancestors while preserving cultural assets for future generations.

The study faced several limitations, including the challenge of precisely replicating ancient materials and methods with available modern equivalents. Additionally, the testing conditions may not fully replicate the environmental factors that the original Sigiriya paintings endured over centuries. The study's scope was also limited to specific formulations and testing methods, which may not encompass all possible variables influencing the coatings' performance.

7. ACKNOWLEDGMENT

This research was supported by a Senate Research Grant (Grant Number: SRC/LT/2021/29) from the University of Moratuwa. I am sincerely grateful for the funding provided, which was essential for the successful completion of this study. I would also like to extend my appreciation to the University of Moratuwa and University of Ruhuna for its continuous support and encouragement.

8. REFERERNCES

Agrawal, O. P., & Wickramaslnghe, N.A. (2002). Materials and techniques of ancient wall paintings of Sri Lanka, India, Lucknow.

ASTM International - Standards Worldwide. (n.d.). Retrieved June 28, 2024, from https://www.astm.org/

Barletta, M., Aversa, C., Pizzi, E., Puopolo, M., & Vesco, S. (2018). Design, development and first validation of "biocide-free" anti-fouling coatings. *Progress in Organic Coatings*, *123*, 35–46. https://doi.org/10.1016/j.porgcoat.2018.06.007

Chen, Z., Zhou, K., Lu, X., & Lam, Y. C. (2013). A review on the mechanical methods for evaluating coating adhesion. *Acta Mechanica*, *225*(2), 431–452. https://doi.org/10.1007/s00707-013-0979-y

Coomaraswamy, A. K. (1907). Notes on painting, dyeing, lacwork, dumbara mats, and paper in ceylon. *The Journal of the Ceylon Branch of the Royal Asiatic Society of Great Britain & Ireland*, *19*(58), 103–121. http://www.jstor.org/stable/45385003

Davids, T. W. R. (1875). Art. X.—Sigiri, the Lion Rock, near Pulastipura, Ceylon; and the Thirty-ninth Chapter of the Mahâvaṁsa. Journal of the Royal Asiatic Society, 7(2), 191–220. https://doi.org/10.1017/s0035869x00016452

De Silva, R. H. (2002). Sigiriya and its significance: A Mahayana-Theravada buddhist monastery. Brecourt Academic.

Dissanayake, D. M. K. D., & Arachchi, R. S. S. W. (2018). Tourist attitudes of visitor management techniques in Sigiriya for the visitor experience quality. In *Proceedings of the third interdisciplinary conference of management researchers, Belihuloya*, 23 – 25 October 2018. (pp. 379-394). Sabaragamuwa University, Sri Lanka.

Hossain, M., Biswas, B. K., Karim, M. R., Rahman, S., Islam, R., & Joarder, O. I. (1994, December). In vitro organogenesis of elephant apple (Feronia limonia). *Plant Cell, Tissue and Organ Culture, 39(3)*, 265–268. https://doi.org/10.1007/bf00035980

ISO - International Organization for Standardization. (n.d.). ISO. Retrieved June 28, 2024, from https://www.iso.org/home.html

Kim, Y., Sung, A., Seo, Y., Hwang, S., & Kim, H. (2016). Measurement of hardness and friction properties of pencil leads for quantification of pencil hardness test. *Advances in Applied Ceramics, 115(8)*, 443–448. https://doi.org/10.1080/17436753.2016.1186364

Nishanthi, M. (2021). Plaster and colour technology of ancient Sri Lankan murals. *Journal of History, Art and Archaeology, 1(1)*, 91-100. Retrieved from http://www.arfjournals.com/

Ranasinghe, S. (2023). Archaeobotanical Perspective on the "Vetkol Flower" in Sigiri Graffiti, Sri Lanka. *Ancient Lanka*, 2. https://doi.org/10.29173/anlk737

Rathnayake, K., Halwatura, R., Mendis, M. S., & Galabada, H. (2024). Analyzing and Deciphering the Ancient Coating Technology Employed at Sigiriya, Sri Lanka. https://doi.org/10.2139/ssrn.4739140

Rodrigues, S., De Brito, E. S., & Silva, E. D. (2018). Wood Apple— Limonia acidissima. In S. Rodrigues, E. D. Silva, & E. S. de Britoeds.(Ed.), *Exotic Fruits* (pp. 443–446). Academic Press. https://doi.org/10.1016/b978-0-12-803138-4.00060-5

Seneviratne, J. N. (2018). Instrumental analysis of the plaster, pigment and preservative coatings in Sri Lanka: Techniques of paintings, conservation history and scientific analysis of the mural paintings in Sigiriya, Tiwanka Image House, Dambulla Cave Temple and Mirissa Samudragiri Viharaya. Department of Archaeology.

Seneviratne, J. N. (2020). Binding mediums, protective coatings and mural painting techniques were used by ancient painters. *Ancient Ceylon*. *27*, 87-110. Retrieved from https://archaeology.gov.lk/media/attachments/2022/09/07/ac27updated.pdf#page=87

Somathilake, M. (2002). *Ancient Buddhist mural painting of India and Sri Lanka*. Godage International Publishers. https://lccn.loc.gov/2003331287

Somathilake, M. (2007). Further analysis on fresco and tempera: an analysis of the technique of murals in South Asia. *Journal of the Royal Asiatic Society of Sri Lanka*, *53*, 109-132. Retrieved from https://www.jstor.org/stable/23731202

Subasinghe, W. T. I. M., & Karunarathna, H. H. A. (2022). Chronological Age Limit of Female Figures Portrayed In Sigiriya Fresco Pockets. *South Asian History, Culture and Archaeology*, *2*(1), 195–217. Retrieved from http://www.esijournals.com/sahca

Subasinghe, H. C. S., Bandara, T. G. T. A., Christopher, W. A. P. P., Hewathilake, H. P. T. S., & Pitawala, H. M. J. C. (2019). *Characterisation of "Dummala" Origin in Sri Lanka by XRF, XRD and FTIR*.

Uva Wellassa University, Sri Lanka, Retrieved from http://erepo.lib.uwu.ac.lk/bitstream/handle/123456789/675/477.pdf?sequence=1&isAllowed=y.

Udawattha, C., & Halwatura, R. (2018). Life cycle cost of different Walling material used for affordable housing in tropics. *Case Studies in Construction Materials*, *7*, 15–29. https://doi.org/10.1016/j.cscm.2017.04.005

Yuan, L., Weng, X., & Deng, L. (2013). Influence of binder viscosity on the control of infrared emissivity in low emissivity coating. *Infrared Physics and Technology*, *56*, 25–29. https://doi.org/10.1016/j.infrared.2012.09.004

Zhang, J., Cho, Y., Kim, J., Malikov, A. K. U., Kim, Y. H., Yi, J. H., & Li, W. (2021). Non-Destructive Evaluation of Coating Thickness Using Water Immersion Ultrasonic Testing. *Coatings*, *11*(11). https://doi.org/10.3390/COATINGS11111421

Ruwanpura, U.D.R.E., Perera, B.A.K.S. and Ranadewa, K.A.T.O., 2024. Revamping the land acquisition process for infrastructure projects in Sri Lanka: Strategies for streamlining the existing process. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 864-877. DOI: https://doi.org/10.31705/WCS.2024.69. Available from: https://ciobwcs.com/papers/

REVAMPING THE LAND ACQUISITION PROCESS FOR INFRASTRUCTURE PROJECTS IN SRI LANKA: STRATEGIES FOR STREAMLINING THE EXISTING PROCESS

U.D.R.E. Ruwanpura[1], B.A.K.S. Perera[2], and K.A.T.O. Ranadewa[3]

ABSTRACT

Land Acquisition (LA) is a process of acquiring lands before constructing infrastructure projects for public purposes. Infrastructure projects often experience delays attributed to prolonged land acquisition processes. Compulsory LA becomes necessary, requiring compensation for the affected parties to mitigate these delays. Hence, various laws and regulations are enacted in different countries including Sri Lanka to ensure the validity of the process. The prolonged LA process raises the grievances of project-affected parties and leads to project delays. This study aims to enhance the existing land acquisition process for Sri Lanka to acquire lands for infrastructure projects. In Sri Lanka Land Acquisition Act, no 9 of 1950 is currently used for LA. Delays in infrastructure projects in Sri Lanka are caused by the problems in LA and those problems were identified through three case studies. Here, expert interviews were conducted with six experts and nine semi-structured interviews with other stakeholders involved in the LA process. The main problem with extending the LA is the time wasted from Section 2 to Section 9. The study recommended that providing technological facilities and establishing grievance readdress committees are the key suggestions. This study contributes to theory by categorising different strategies into short-term, middle-term and long-term bases. It further emphasises the necessity of explicit discussions to change the LA law in Sri Lanka to meet the industry's needs. Further, this study recommends implementing the suggestions in an action plan to revamp the land acquisition process for infrastructure projects in Sri Lanka.

Keywords: *Infrastructure Projects; Land Acquisition Act; Land Acquisition.*

1. INTRODUCTION

Infrastructure development positively relates to the economic development of a country (Nguyen et al., 2020). Expanding the infrastructure facilities is one of the key functions of any government and becomes fundamental for any sustainable growth strategy (Fay et

[1] Research scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, ruwanpuraudre.22@uom.lk
[2] Ch. QS (Prof.), Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk
[3] Senior Lecturer, (Dr.) Department of Building Economics, University of Moratuwa, Sri Lanka, tharushar@uom.lk

al., 2017). Cook et al. (2017) linked the improvement of infrastructure with SDGs: 1, 2, 3, 4, 5, 6, and 8. Even though infrastructure projects are linked with sustainable development, delays in infrastructure projects have frequently occurred (Deep et al., 2022). This leads to time extension, cost overrun, disputes, arbitrations, litigations and adverse effects on national economic growth (Gardezi et al., 2014). Figure 1 visualises the severity of the occurrence of land acquisition issues among the other causative factors in delaying infrastructure projects. Elawi et al. (2016) discovered that the average delay in infrastructure projects in Mecca was 39% and the most severe cause of delay was found to be land acquisition. Consequently, 70% of delays in infrastructure projects in India are caused by land acquisition (Rao, 2018).

Figure 1: Word cloud of factors affecting delay the infrastructure projects

Land acquisition delays are categorised into owner-responsible delays (Elawi et al., 2016), technical delays (El-Sayegh & Mansour, 2015), socio-political delays (Dadhich, 2017) or external delays (Alfakhri et al., 2017). Hence, insight into the land acquisition process is crucial to reduce these delays in the existing land acquisition process. Acquisitions of land take place within a highly complicated land administration system and a politicised environment (Lay & Nolte, 2018). Hence, the length of the land acquisition process depends on the key influencing factors in the external environment. Wijekoon and Aththanayake (2012) identified issues in the land acquisition process as a key factor for delaying road construction projects in Sri Lanka. In addition, Silva (2016) emphasised that the Land Acquisition Act (LAA) is not friendly to the landowners. Therefore, a comparison of the LA process in different countries is required to propose an effective LA process. This paper aims to enhance the existing land acquisition process in Sri Lanka. The objectives are to identify the land acquisition processes used in different countries, to compare the land acquisition processes used in different countries with the Sri Lankan process, to investigate the problems in the existing land acquisition processes used in Sri Lanka and to propose suggestions to the land acquisition processes used in Sri Lanka to acquire lands for infrastructure projects.

2. LITERATURE REVIEW

2.1 LAND ACQUISITION

Land acquisition is the approach that governments use to acquire private properties to provide public facilities for the betterment of the public (Huggins, et al., 2013). The ultimate objective of the land acquisition process is to timely compensate the affected parties before the mobilisation of the contractor (Aditya et al., 2017). Further, it involves with a stipulated regulatory process involving with government institutes (Kumar, 2018) and hence, the land acquisition process needs to be prompt and transparent (Raghuram & Sunny, 2015). Land acquisition can be practised through voluntary purchase, land readjusting (consolidation) and compulsory acquisition (Belej & Walacik, 2008). Further, the authors expressed that voluntary purchase is the method of exchanging land while readjusting allows land assembly. Despite this, compulsory acquisition is predominantly practised in land acquisition for infrastructure development (Ghimire et al., 2017). Compulsory acquisition is a practice with eminent domain, which means without the consent of the landowner the required land can be acquired for public purposes (Adu-Gyamfi, 2012). Hence, this is empowered by separate rules and regulations to ensuring the method of compensation for the landowners and the affected parties (Wahi et al., 2017). However, various countries practice different land acquisition laws and practices to compensate affected parties for their loss (Rao et al., 2018). Despite, different laws imposed in different countries, delays in land acquisition are broadly dispersed (Elawi et al., 2016). Olanrele et al. (2017) declared that a fair approach to land acquisition is provided in different laws on the compulsory acquisition of land across countries and in the constitutions of different countries. Therefore, studying the land acquisition processes in different countries is vital to determine the efficient steps.

2.2 LAND ACQUISITION PROCESS IN SRI LANKA

The first legislative movement for land acquisition was initiated in 1876 as the Land Acquisition Ordinance of 1876. This was supplanted by the Land Acquisition Act No. 9 of 1950 (LAA). Currently, the provisions for land acquisition in Sri Lanka are governed by the above act. Initially, the applicant institute should apply to the respective ministry. Then Ministry of Land (MoL) issues a Section 2 order. Then Divisional Secretary (DS) acquires the respective land. Under Section 2 Ds request advanced tracing from the Survey department. The next step involves with calling objections from the PAPs. After conducting objection inquiries MoL issues Section 5 and performs the remaining duties by DS. Despite, more than 60 years have passed still no extensive amendments have been made to LAA (Silva, 2016). It implies that it is required to amend the act to ensure efficient and effective land acquisition. Therefore, a comparison of the LA process with other countries will facilitate to improvement of the existing process of LA in Sri Lanka.

3. METHODOLOGY

This research uses a qualitative method to achieve the aim of proposing modifications for the existing LA process in Sri Lanka. Polkinghorne (2005) stated that qualitative data can be gathered in either spoken or written forms from various sources, such as observations, interviews, document reviews, questionnaires, and drawings. The volume and richness of qualitative data can vary depending on the extent of different data collection methods used. Consequently, this study first employed a desk review. Topolewski (2020) explained that a desk review involves collecting data from secondary sources. Thus, in alignment with the first and second objectives, the review of LA processes in different countries was conducted through a desk review, referring to LA Acts in various countries, journals, conference papers, and websites.

Kumar (2014) noted that a case study provides an extensive, in-depth, and holistic exploration of the aspects that need to be investigated. Therefore, following the desk review, case studies were conducted to achieve the third and fourth objectives: identifying problems and proposing suitable solutions for the land acquisition process. The unit of analysis was the problems in the existing LA process, and the case boundary focused on infrastructure projects in Sri Lanka. Interviews are a commonly used method for collecting information from people (Kumar 2014). Hence, semi-structured interviews were conducted with two experts and three stakeholders involved in the LA process from each case. In total, 15 interviews, along with document reviews and observations, were conducted within the cases to ensure the robustness of the data collection. Findings were derived through manual content analysis within the case analysis. The findings and analysis will be discussed in subsequent sections.

4. RESULTS AND DISCUSSION

4.1 INTERVIEWEE PROFILE

The 15 interviewees including six experts and nine other interviewees were interviewed to explore problems in each step in LA which affected to delay of the LA process in Sri Lanka and solutions were identified for mitigating identified problems in the LA process. The data saturation was achieved at the 13th interview. The methods of qualitative data collection are mentioned in Table 1.

Table 1: Methods of data collection

Case 1-highway project				Case 2- irrigation project		Case 3- irrigation project	
Project value: LKR 445.30 billion				Project value: LKR 8000 million		Project value: LKR 16000 million	
Desk review	LAA, Land manual, LA progress review meeting minutes, Annual report, Newsletter						
Observations	Project meetings, Workshops						
Expert interviews				Semi-structured interviews			
Code	Designation	Profession	Experience (years)	Code	Designation	Profession	Experience (years)
I1	Social and Resettlement Safeguards Specialist (National)	Retired Secretary	47	I7	Project Director	Chartered Engineer	21
I2	Programme Director	Chartered Engineer	42	I8	Senior Superintend of Surveying	Surveyor	30
I3	Consultant Land acquisition and resettlement	Retired Additional Secretary	37	I9	Divisional Secretary	Land acquisition	6
I4	Acquiring officer	Land acquisition	15	I10	Project Director	Chartered Engineer	15
I5	Deputy project director	Land acquisition and resettlement	27	I11	District Valuer	Valuation of acquired land	25
I6	Inquiring officer (Acquisition)	Land acquisition	12	I12	Divisional Secretary	Land acquisition	8
				I13	Project Director	Chartered Engineer	18
				I14	Superintend of Surveying	Surveyor	12
				I15	Divisional Secretary	Land acquisition	5

According to Table 1, expert interviews were conducted with the professionals who are experienced in LA process while semi-structured interviews were conducted with the stakeholders who are engaged in LA process at different levels. Moreover, selected experts gained experience in LA at least two infrastructure projects. Since DS are frequently involved in LA they were selected in each case. Further, data obtained through document review and observations in each case were subjected to data analysis and presented in subsequent sections.

4.2 LAND ACQUISITION PROCESS IN DIFFERENT COUNTRIES

Land acquisition is executed in different countries by using different laws and statutes (Olanrele et al., 2017). In **India,** the land acquisition process is regulated by the Land Acquisition Act enacted in 1894 with a variety of processes (Wahi, 2017). Recently, this act was amended as Land Acquisition, Rehabilitation and Resettlement Act, 2013 (LARR) by resolving some of the issues in the compensation process in LA. By reviewing LARR representatives of the state collector held inquiries to the objections after declaring a land acquisition for a particular project. After hearing to objections, the government will decide what will be declared to the requested party. After that the collector proceeds with notifying the notices to survey the land and subsequently conduct the valuation process and its objections and the compensation will be paid. LA in **Malaysia** is governed by Article 13 of the federal constitution 1957 and Land Acquisition Act [LAA] 1960 (Alias et al., 2011). As mentioned in LAA, the LA process in Malaysia comprises with major six steps i.e. issuance of notice, entry and survey, gazetting, investigation and awarding the compensation. There are laws and regulations related to the land acquisition process in **Indonesia** and Law No. 2 of 2012 on Land Acquisition for Development for Public Interest, Law No. 11 of 2021. Yasuhiro (2015) mentioned the two methods of land acquisition in Japan i.e. (i) land purchase by an agreement, and (ii) land expropriation for compulsory land acquisition. The land acquisition process for public purposes is termed land expropriation and is regulated under the Land Expropriation Law of 1951 Article 29 Paragraph 3 (Boro, 2022).

In the **USA** land acquisition is divided into four types i.e. (i) donation, (ii) condemnation, (iii) exchange, and (iv) purchase. According to Section 7 of the Reclamation's Act of 1902, the Secretary of the interior is authorised to acquire the land for the state under judicial process and payment will be made from the reclamation fund. In **Australia** initially minister gives the consent to acquire a particular land plot through pre-declaration and the people who will be affected are informed within 14 days after publication by forwarding the following documents: a) a copy of the declaration, (b) a notice, (c) a compensation claim form. Under Section 47 (1) (a) the entry to the possession is vested to the acquiring authority in a compulsory acquisition.

Table 2: Comparison of the LA process in different countries

General information								
	1	2	3	4	5	6	7	8
LA provision embedded into constitution (a)/special act (b)	special act	special act	constitution	special act	constitution	special act	constitution	special act
Authorizing officials for LA (a)- Delegated central government officer, (b)- Local authorities, (c)- Delegated officials in State and federal states	Delegated central government officer	Delegated central government officer	Delegated officials in State and federal states	Local authorities	Delegated central government officer	Local authorities	Delegated officials in State and federal states	Delegated officials in State and federal states
Used term for land acquisition (a)- Expropriation, (b)- compulsory purchase, (c)- compulsory acquisition, (d)- resumption (e)- Eminent domain	compulsory acquisition	compulsory acquisition	compulsory acquisition	Expropriation, compulsory acquisition	Expropriation, compulsory acquisition, Eminent domain	Expropriation, compulsory acquisition, compulsory purchase, resumption	Eminent domain	Expropriation, compulsory acquisition, compulsory purchase, resumption
Other form of land acquisition (a)-Voluntary exchange, (b)- Compulsory acquisition (c)- Purchase by agreement (d)- The sale and purchase, (e)- Public expropriation (f)- Trust law	Voluntary exchange, Compulsory acquisition	Voluntary exchange, Public expropriation, Trust law	Voluntary exchange, Compulsory acquisition, Purchase by agreement	Compulsory acquisition	Compulsory acquisition, Purchase by agreement, Trust law	Compulsory acquisition	Compulsory acquisition	Compulsory acquisition, Purchase by agreement
Frequently used method of LA (a)-Voluntary exchange, (b)- Compulsory acquisition (c)- Purchase by agreement (d)- The sale and purchase, (e)- Public expropriation	Compulsory acquisition	Voluntary exchange, Compulsory acquisition	Purchase by agreement	Compulsory acquisition	Compulsory acquisition	Compulsory acquisition	Compulsory acquisition	Compulsory acquisition
Presence of stipulated period (a)- Yes (b)- No	No	No	No	Yes	No	Yes	Yes	Yes

Country- 1-Sri Lanka, 2-India, 3-Malaysia, 4-Indonesia, 5-Japan, 6-UK, 7-USA, 8-Australia

Table 3: Comparison of the LA process in different countries

Process step	1	2	3	4	5	6	7	8
Submit the acquisition proposal by the requiring agency	√	√	√	√	√	√	√	√
Acquire for public purpose	√	√	√	√	√	√	√	√
Provide resettlement plan	√	√	√	√	√	√	√	√
Acquire for private companies	*	√	√	√	√	√	√	√
Acquiring order is given by the minister to land/ infrastructure	√	√	√	*	*	√	*	√
Initially gazette the acquiring notice	*	√	√	√	*	√	*	√
Gazette the notices more than one time	√	*	*	*	*	*	*	*
Surveying respective land lots	√	√	√	√	√	√	√	√
Calling for objections	√	√	√	√	*	√	√	√
Emergency clause	√	√	√	√	*	√	√	√
Conduct inquiries to determine land ownership	√	√	√	√	*	√	√	*
Compensation procedures	√	√	√	√	√	√	√	√
Compensation is based on market value of the land and other acquired assets	√	√	√	√	√	√	√	√
Appeal committee	√	√	√	√	*	√	√	√
Create a land pool for procuring lands when it requires	*	√	*	*	√	*	*	*

Country- 1-Sri Lanka, 2-India, 3-Malaysia, 4-Indonesia, 5-Japan, 6-UK, 7-USA, 8-Australia Yes: √ No:*

4.3 COMPARISON OF LA PROCESS IN DIFFERENT COUNTRIES

By reviewing LAAs in different countries identified similarities and dissimilarities are mentioned in Table 3. Accordingly, LA is embedded into the constitutions of some countries such as Japan, Malaysia and the USA. Further, some of the country's LA process is centralised to the government and others are delegated to the federal states. Initially, LA in India was governed by the Land Acquisition Act, 1894 and it was replaced by Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation and Resettlement Act, 2013 (RFCT LAR&R 2013). Further, LA in the UK is legislated by the Acquisition of Land Act 1981. Moreover, the LA process in Australia is governed by commonwealth legislature while federal states are embedded with separate laws for land acquisition. This is comparable to LA laws in the USA. Land acquisition for development in Public Interest No. 2 of 2012 is applied in Indonesia while Land Acquisition Act 1960 was enacted in Malaysia. In addition, the law for land expropriation in Japan is governed by Law of 1951 Article 29 Paragraph 3 as a law of land's compulsory expropriation for public purposes. Apart from that India and Japan adhere to the Land Trust Act which creates a pool of land which provides suitable land for the infrastructure development projects conducted by private companies. Eventhough, LA is done for the public purposes provisions for acquiring land for private companies are also legally established in India. Further, different officials are devolved with LA authority such as in India, district collector or deputy collector (Tehsildar), in USA Secretary of the Interior and the Secretary of Agriculture General Services Administration Regional realty officers (RROs) in Sri Lanka divisional secretaries are the authorised officials for acquiring lands for infrastructure development.

The land acquisition process in most of the countries is started by submitting a proposal to the government. Except for India, Malaysia, and Indonesia land acquisition is done for public purposes and the above countries can acquire land for private companies. Further, the acquiring order must be given by the minister. Then it is published for the general public through a gazette notification. The order of acquiring the land is given by the minister to the land. In Sri Lanka, a gazette is published after conducting objection inquiries. LA processes in the UK, the USA and Australia are comprised of stipulated period for the steps in LA. Compared with Malaysia, the USA and Japan, the LA process in SL has been described as a special act. Further, In Sri Lanka, the term for land acquisition is used as compulsory acquisition. Although, voluntary acquisition is applicable in Sri Lanka compulsory acquisition is a highly used method for the LA in SL. The stipulated period for some steps is demarcated in LA laws there is no period for each step in LA act of SL. Although, LA provisions are applicable to acquire land for private companies in India, LA provisions in Sri Lanka are formulated for acquiring land for only public purposes. Moreover, the resettlement of affected parties from LA is considered in India in the recently enacted law Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation and Resettlement Act, 2013 (RFCT LAR&R 2013). However, in Sri Lanka, a separate policy as National Involuntary Resettlement Policy (NIRP) for the project-affected parties through LA was established in 2009 under the purview of the Asian Development Bank. Comparable to India, Malaysia and Indonesia, an emergency clause for urgency acquisition is mentioned in LAA. Therefore, land can be acquired instead of objections from the affected parties.

4.4 PROBLEMS IN THE LA PROCESS IN SRI LANKA

As per Table 4, the main problems in the LA process in Sri Lanka identified through interviews are: Unnecessary time-consuming for proceeding with some steps, Lack of coordination between organisations, Improper progress monitoring, Lack of training, Transfers of experienced officers, Insufficient physical resources, Insufficient human resources and not given the priority for LA process. Further, each problem is further described with examples in the LA process steps. I1 stated, ***"lack of timely coordination between stakeholders who engage with LA process is the main obstruction for the effective LA"***. The acquiring officer stated that since the LA Act is not compatible with the present-day context and time taken to proceed steps 2 to 7 was extended. For instance, a survey plan is requested in two steps. If it reduces into one step time and cost will be saved. Further, I2 and I4 agreed with the suggestions to amend the LA law and I4 mentioned that it should be an extensive discussion with all the stakeholders who are engaged with the LA process. Extending the time allocation for conducting Section 9 inquiries for deciding the land ownership for acquired land plots is common in the LA process for implementing infrastructure projects. Certain inquiries are not completed due to the absence of all the parties who are entitled to land ownership. Further, submitting incomplete documents especially, land records on land registration is not compatible with proving the ownership of the affected person. Hence, inquiries must be conducted for more than one time. In addition, I4, I5 and I6 agreed that the lack of physical resources such as space, and office equipment is one of the main barriers to the timely implementation of the LA process. Identified problems and proposed solutions are tabulated in Table 4.

4.5 SUGGESTIONS FOR IDENTIFIED PROBLEMS IN THE LA PROCESS IN SRI LANKA

As Table 4 visualises most of the suggestions can implemented in the short term. For instance, use other sources for sending documents except the manual method, involvement of client organisation for supporting to perform LA processes by Divisional Secretaries and Ministry of Land. In addition, simplifying the applications, and charts by introducing checklists and simple formats will improve the clarity of the documents.

Table 4: Problems and solutions for the LA process in Sri Lanka

Problem	Example of related step		Suggestion	Short term	Middle term	Long term
	Step	Example				
Unnecessary time consuming to proceed with some steps	Section 2	Delaying in sending documents to the Ministry of Lands	Use other sources except to the manual method	√		
			Appoint Grievance readdress committee (GRC) Through GRC solve the disputes of PAP time effectively		√	
		Extending the time for preparing advanced tracing	Involvement of client organization	√		
			Policy decision on review the step and amalgamate with section 5 and 7 step			√
	Section 4	Extending the time for conducting inquiries for objections	Provide more facilities for conducting more inquiries		√	
		Delaying in decision-making for respective objections given by PAP	Involvement of client organization	√		
			Policy decision on conduct objection inquiries as much as earlier before issuing section 2 order			√
	Section 5	Delaying for translation	Involvement of client organization	√		
		Delaying receiving documents	Involvement of client organization	√		
		Errors in submitted documents	Conduct an awareness programme for PAP	√		
			Use of formats	√		
	Section 6	Delays in receiving preliminary plan	Provide facilities for the Survey department		√	
			Involvement of client organization	√		
	Section 7	Delaying for translation	Hired a service from translators		√	
		Delaying receiving documents	Use other sources for sending and receiving documents (Handover, email, WhatsApp)	√		
		Errors in submitted documents	Early check	√		
			Conduct awareness programmes for submitting documents for inquiries	√		
	Section 9	Delaying conducting inquiries for determining ownership of lands	Provide additional staff for conducting inquiries	√		
		Delaying submitting documents related to land ownership	Conduct awareness programmes for submitting documents for inquiries	√		
		Incomplete documents	Conduct awareness programmes for submitting documents for inquiries	√		
		Errors in supplied documents	Conduct awareness programmes for submitting documents for inquiries	√		
		Higher rate of absenteeism for the inquiries	Use different methods of meetings (online meetings)	√		
		Delaying in decision-making	Delegate powers to nearby Divisional Secretaries			√
			Set a time-bound action plan		√	
	Section 10	Delaying issuing the decision-making	Delegate powers to nearby Divisional Secretaries			√
		Delays in valuation	Coordination of the Valuation department	√		
			Coordinate intra-departmental progress by the Ministry of Land	√		
Lack of coordination	Section 2	Poor coordination between Client organisations: The survey department and the DS office	Coordinate intra-departmental progress by the Ministry of Land	√		

Problem	Example of related step		Suggestion	Short term	Middle term	Long term
	Step	Example				
between organizations	Section 4	Poor coordination between Client organisations. Ministry to Lands and DS office		√		
	Section 5	Poor coordination between Client organization. survey department and DS office		√		
	Section 7	Lack of coordination between, Client organization, Government print		√		
Improper progress monitoring	Section 2	Lack of progress monitoring for publishing section 2 notices	Delegate authority to monitor the progress of the LA process in the district by the District Secretary		√	
	Section 4	Lack of progress monitoring for conducting inquiries	Ministry-level progress monitoring with District Secretaries	√		
			Maintain a pool of inquiring officers and provide their services where necessary		√	
	Section 9	Poor monitoring the progress of conducting inquiries	Delegate authority to monitor the progress of the LA process in the district by the District Secretary	√		
			Ministry-level progress monitoring with District Secretaries		√	
			Develop key performance indicators (KPI)		√	
	Valuation	Poor coordination between the valuation department and the Ministry of Lands	Coordinate intra-departmental progress by the Ministry of Land	√		
Lack of training		Lack of experience in land acquisition law and LA process	Conduct training programme by the Ministry of Lands, Project organization	√		
			Conduct capacity-building programme for government officers	√		
		Lack of expertise in examining titles and effectively deciding on land ownership	Conduct training programme by the Ministry of Lands, Project organization	√		
Transfers of officers		Discontinue the progress up to some period	Maintain a pool of inquiring officers and provide their services where necessary	√		
Insufficient physical resources		Insufficient resources for field inspections, space, equipment	Provide resources when it requires			√
			maintain a pool of resources and shift when the acquisition process is completed		√	
Insufficient human resources		Insufficient competent staff, Turnover of project staff	Maintain a pool of inquiring officers and provide their services where it necessary		√	
			Recruit temporary staff when necessary		√	
			Monetary/ nonmonetary incentives for the extra efforts of the officers engaged in LA		√	
			Appoint supportive staff temporary for external government institutes such as divisional secretaries		√	
Not given the priority for LA process		Lack of experience in land acquisition law and LA process	Conduct capacity-building programmes for government officers	√		
		Lack of experience in land acquisition law and LA process	Delegate powers to conduct inquiries for nearby divisional secretaries	√		

As per the perspective of I5 LA may delay due to objections. If a proper grievance redress mechanism is established prior to initiating LA, most of the objections can be resolved at the early stage. Hence, I5 suggested that Grievance Redress Committees (GRC) must be established before receiving Section 2 orders. Further, I1 stated that since Electronic Transaction Act No. 19 of 2006 was enacted Section 9 inquiries can be conducted online with the landowners who are not physically participating. By reviewing the above comments, the acquisition process can be improved by following existing rules and regulations. Moreover, I3 explained that comparing the LA process with Malaysia, the LA Act is comprised of certain period to complete the process steps. If unable to complete within the timeframe, the LA process will be cancelled. Further, I3 mentioned that such type of time frame can be applied to Sri Lanka by improving the facilities such as computers, undisrupted internet facilities, scanners, and networking of involved government institutions. Further, I7 proposed that due to the viability of the suggestions it can be implemented on either short-term, middle-term or long-term basis. Accordingly, most interviewees agreed to demarcate the short term as the suggestion will be implemented within a year, middle term as within 3 years long term as or more than three years.

As mentioned in Table 4, establishing GRC to manage the grievances raised by PAP can be implemented on a middle-term basis. Providing facilities to institutions involved in the LA process offers a capacity-building programme for the officers involved in the LA process and can be considered into middle-term plan due to allocating funds to organise those events. As per the perspectives of interviewees policy decisions on prevailing LA act must be taken and it requires extensive review with different stakeholders involved in LA as well as from the PAPs. Thus, it can be accomplished on a long-term basis. Ultimately, to reduce the barriers to implementing the LA process solutions must be categorised on a time basis and implemented through an action plan is vital.

5. CONCLUSIONS

LA is one of the main causative factors for delaying infrastructure projects there is no exception for Sri Lanka. Through the interviews, unnecessary time extension, lack of coordination, improper progress meetings, Lack of training, Insufficient physical and human resources are the main barriers in the LA process. Those issues can be substituted with possible solutions such as providing facilities to relevant institutions involved in the LA process and providing training programme. This study contributes to the theory by comparing the LA process in different countries by underlining its similarities and dissimilarities. Consequently, this study contributes to the industry of the current LA process in Sri Lanka and proposes suggestions on a time basis. In fact, the above solutions need to be implemented in an action plan.

6. REFERENCES

Aditya, A.K., Douglass, D.A. & Bhattacharya, M. Urban infrastructure development works in India: Delay and difficulties in implementation with reference to a water supply project. *Journal of the Institution of Engineers (India): Series A*, *98*(3), 349-354. https://doi.org/10.1007/s40030-017-0214-2.

Adu-Gyamfi, A. (2012). An overview of compulsory land acquisition in Ghana: Examining its applicability and effects. *Environmental Management and Sustainable Development*, *1*(2), 187-203. http://dx.doi.org/10.5296/emsd.v1i2.2519.

Alfakhri, A., Ismail, A., Khoiry, M. A., Arhad, I., & Irtema, H. I. M. (2017). A conceptual model of delay factors affecting road construction projects in Libya. *Journal of Engineering Science and Technology, 12*(12), 3286-3298. Retrieved from https://jestec.taylors.edu.my/Vol%2012%20issue%2012%20December%202017/12_12_12.pdf

Alias, A., Yanning, P., & Hanif, N. R. (2011). Land acquisition problems in China adopting land acquisition act 1960 of Malaysia as an alternative procedure. *Journal of Design and Built Environment, 8*(1), 1-22. Retrieved from https://ejournal.um.edu.my/index.php/jdbe/article/view/5309

Belej, M., & Walacik, M. (2008). *Land acquisition for public purpose in Poland on example of public roads construction*. FIG Working Week 2008. Retrieved from ts04b_03_belej_walacik_ppt_2849.pdf (fig.net)

Boro, V. (2022). Policies Land Expropriation System and The Compensation Rule in Japan Country. *Acitya Wisesa* (*Journal of Multidisciplinary Research), 1*(3). 17-27. Retrieved from https://journal.jfpublisher.com/index.php/jmr/article/view/125/125

Cook, J., Huizenga, C., Petts, R., Visser, C., & Yiu, A. (2017). *The contribution of rural transport to achieve the sustainable development goals*. Research for Community Access Partnership. Retrieved from http://research4cap.org/_layouts/15/start.aspx#//SitePages/Rural%20access%20library.asp

Dadhich, A., & Kar, S. (2017). *Risk management in highway projects*. [Unpublished master's theses]. Jaypee University of Information Technology.

Deep, S., Banerjee, S., Dixit, S., & Vatin, N. I. (2022). Critical factors influencing the performance of highway projects: An empirical evaluation. *Buildings, 12*(6), 849. https://doi.org/10.3390/buildings12060849.

Elawi, G. S. A., Algahtany, M., & Kashiwagi, D. (2016). Owners' perspective of factors contributing to project delay: Case studies of road and bridge projects in Saudi Arabia. *Procedia Engineering, 145*, 1402-1409. doi: 10.1016/j.proeng.2016.04.176.

El-Sayegh, S. M., & Mansour, M. H. (2015). Risk assessment and allocation in highway construction projects in the UAE. *Journal of management in Engineering, 31*(6), 04015004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000365.

Fay, M., Andres, L. A., Fox, C., Narloch, U., & Slawson, M. (2017). *Rethinking infrastructure in Latin America and the Caribbean: Spending better to achieve more*. World Bank Publications. http://dx.doi.org/10.1596/978-1-4648-1101-2.

Gardezi, S. S. S., Manarvi, I. A., & Gardezi, S. J. S. (2014). Time extension factors in construction industry of Pakistan. *Procedia Engineering, 77*, 196-204. https://doi.org/10.1016/j.proeng.2014.07.022.

Ghimire, S., Tuladhar, A., & Sharma, S. R. (2017). Governance in land acquisition and compensation for infrastructure development. *American Journal of Civil Engineering*, *5*(3), 169-178. https://doi.org/10.11648/j.ajce.20170503.17.

Huggins, E., Roach, K., & Jessemy, G. (2013). *Land acquisition in the context of institutional problems in the legal and administrative framework in Trinidad and Tobago*. Ministry of Food Production, Land and Marine Affairs Land Management Division, Trinidad and Tobago. Retrieved from https://sta.uwi.edu/conferences/11/landtenure/documents/EsricHugginskRoachGJessemyLandacquisitionprocess.pdf

Kumar, R. (2014) *Research methodology: A step-by-step guide for beginners*. (4th ed.). SAGE Publications Ltd., London.

Kumar, S. (2018). Dominant factors behind delay in commissioning of infrastructure projects and the extent of delay along with cost overrun: An analysis of infrastructure projects commissioned during last five years. *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, *6*(11), 79-92. Retrieved from https://www.ijraset.com/fileserve.php?FID=19033

Lay, J., & Nolte, K. (2018). Determinants of foreign land acquisitions in low-and middle-income countries. *Journal of Economic Geography, 18*(1), 59-86. https://doi.org/10.1093/jeg/lbx011.

Nguyen, P. T., Likhitruangsilp, V., & Onishi, M. (2020). Success factors for public-private partnership infrastructure projects in Vietnam. *International Journal on Advanced Science, Engineering and Information Technology, 10*(2), 858-865. Retrieved from https://mpra.ub.uni-muenchen.de/id/eprint/103508.

Olanrele, O. O., Alias, A., Said, R., & Bello, N. A. (2017). Towards global uniformity and sustainable compensation valuation for compulsory land acquisition. *Journal of Design and Built Environment*, (Special Issue: Livable Built Environment), *17*, 27-37. http://dx.doi.org/10.22452/jdbe.sp2017no1.3.

Polkinghorne, D. E. (2005). Language and meaning: Data collection in qualitative research. *Journal of counseling psychology*, *52*(2), 137-145. https://psycnet.apa.org/doi/10.1037/0022-0167.52.2.137.

Raghuram, G., & Sunny, S. (2015). *Right to fair compensation and transparency in land acquisition, rehabilitation and resettlement ordinance 2014: A process perspective*. IIMA Working Papers WP2015-07-03, Indian Institute of Management Ahmedabad, Research and Publication Department. Retrieved from https://www.im4change.org/siteadmin/tinymce/uploaded/IIMA.pdf.

Rao, J., Tiwari, P., & Hutchison, N. (2018). No way to say "no" stakeholder analysis for compulsory purchase for public infrastructure project in Australia. *Property Management, 36*(1), 37-66. https://doi.org/10.1108/PM-09-2016-0050.

Silva, D. L. M. (2016). Are they set to lose out in others' gains? an analysis of livelihood security in acquisition of lands in Sri Lanka. *Proceedings of 9th International Research Conference of KDU* (pp. 57-61). General Sir John Kotelawala Defence University, Sri Lanka. Retrieved from http://ir.kdu.ac.lk/handle/345/1213.

Topolewski, S., Górnikiewicz, M., & Stawarz, P. (2020). *The literature review and the "desk research" methods in studies conducted in social sciences with particular emphasis on security, political, and international relations studies*. Literature review & desk research report Retrieved from https://ec.europa.eu/programmes/erasmus-plus/project-result-content/811e6ec5-

Wahi, N. (2017, February 27). Land acquisition in India: A review of supreme court cases from 1950 to 2016. *SSRN Electronic Journal*. http://dx.doi.org/10.2139/ssrn.3915345.

Wijekoon, S.B., Attanayake, A. M., (2012, December) *Study on the cost overruns in road construction projects in Sri Lanka*. Proceedings of the 2nd International Conference on Sustainable Built Environment, Kandy, Sri Lanka, pp. 111–121.

Yasuhiro, Y. (2015). *Land acquisition & compensation for public use in Japan*. General Incorporated Foundation Japan Organization for Land Acquisition and Compensation. Retrieved from https://www.hosyoukikou.jp/business/pdf/201502Jica1.pdf.

Perera, W.S.D., Kulatunga, U., De Silva, M.C.K. and Dias, N., 2024. Revisiting the notion of 'public spaces': Professional and community perspectives. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 878-890. DOI: https://doi.org/10.31705/WCS.2024.70. Available from: https://ciobwcs.com/papers/

REVISITING THE NOTION OF 'PUBLIC SPACES': PROFESSIONAL AND COMMUNITY PERSPECTIVES

W.S.D. Perera[1], U. Kulatunga[2], M.C.K. De Silva[3], and N. Dias[4]

ABSTRACT

Public spaces serve as vital components of urban landscapes, facilitating social interaction, community cohesion, and individual well-being. However, differences exist between the perspectives of urban planning professionals and the broader community regarding the conceptualisation, design, and management of these spaces, with professionals focusing on sustainability and urban planning principles, while community members prioritise immediate concerns such as safety and accessibility. This paper conducts a comprehensive narrative literature review to delve into this divide and propose strategies for bridging it. The literature highlights the multifaceted nature of public spaces, emphasising their role as venues for social engagement, cultural expression, and community identity formation. This approach synthesises various themes and perspectives, capturing the nuanced evolution of public spaces in response to contemporary challenges. One key theme from the literature is the divergent priorities between urban planning professionals and the general community. While professionals prioritise inclusivity, sustainability, and community impact, the public focuses on immediate issues such as safety, accessibility, and environmental quality. This disconnect underscores the need for a more nuanced and inclusive approach to public space design and management. To bridge this gap, the paper suggests adopting context-sensitive approaches that integrate localised narratives, identities, and placemaking practices. By prioritising equity-focused and accessible design strategies, public spaces can become truly inclusive environments that foster a sense of belonging for all. As societies evolve in response to technological advancements, cultural shifts, and changing demographics, the notion of public space must adapt, requiring ongoing re-evaluation to promote social cohesion, community empowerment, and well-being.

Keywords: *Community Perspectives; Placemaking; Public Spaces; Social Cohesion; Urban Planning.*

[1] Research Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, wsdarshanaperera@gmail.com
[2] Professor in Building Economics, Department, University or Company, Country, ukulatunga@uom.lk
[3] Senior lecturer, Department of Town and Country Planning, University of Moratuwa, Sri Lanka, chathurads@uom.lk
[4] Lecturer in Disaster Management, The University of Manchester, United Kingdom, Nuwan.dias@manchester.ac.uk

1. INTRODUCTION

Public spaces serve vital functions for community building, inclusion, health, and urban liveability (Andersson, 2021). They facilitate social interaction, promote social life, and contribute to the quality of urban social communities (Malik et al., 2018; Ferwati et al., 2021). Public spaces play a role in defining the character of a city and are valuable assets for urban sociology, contributing to economic, social, and environmental value-added (Malik et al., 2018). As benefits, public spaces provide comfort and satisfaction to visitors, enriching everyday urban life and serving as indicators of the quality of life (Kim et al., 2021). Nevertheless, there are economic advantages of public places such as business opportunities through public markets, informal selling, and locations for festivals and celebrations, promoting economic development and community revitalisation (Low, 2023). However, the concept of "public" has evolved and changed over time, initially referring to the theatre audience and later expanding to encompass a variety of people in public spaces (Özbayraktar et al., 2017). Therefore, even though the conventional meaning and perspective of public places are as described above, those perspectives may change, or the notion of public places may be challenged due to various factors. This study primarily examines urban public spaces while acknowledging the broader geographical and cultural variations.

Perspectives and usage of public spaces can differ across geographical and cultural contexts. Public spaces are influenced by cultural and geographical contexts, leading to different perspectives and usage patterns (Ewertowski, 2023; İnce Güney, 2014; Karuppannan & Sivam, 2013). Thus, cultural conditions can have an impact on how urban space is created, perceived, and used (Ewertowski, 2023). Climate, gender norms, and local values influence how urban spaces are perceived and utilised across neighbourhoods (Karuppannan & Sivam, 2013). Understanding the nuanced socio-cultural meanings attached to public realms by diverse community groups is critical for responsive urban planning (Mehta, 2014). However, there is often a disconnect between professional public space planning/design aims and the localised needs and priorities of residents. This can be attributed to various factors such as professional disagreements (El-Kholei & Yassein, 2022), lack of community participation (El-Kholei & Yassein, 2022; Malá et al., 2022), and challenges in small cities (Malá et al., 2022).

Nevertheless, technology has an impact on the challenge for the notion as the integration of technology, such as wireless networks and surveillance cameras, in public spaces is reshaping the first amendment implications, affecting privacy, public forum issues, and the nature of public versus private expression (Zick, 2006). Location-aware technologies and social media platforms contribute to altering the perception and practice of public spaces through the provisioning of location-specific digital information, which transforms social and spatial interactions (Zimmerman et al., 2014).

Moreover, perspectives on public space priorities likely differ across groups. Urban planning professionals emphasise strategic design for community impact and sustainability of public places (El-Kholei & Yassein, 2022). The research emphasises the importance of an integrated approach to urban planning that considers the interplay between buildings, public spaces, and the broader urban context. Sustainable urban design requires attention to environmental efficiency, social connectivity, and economic viability, with a strong emphasis on local characteristics and the health and well-being of residents (Grierson, 2009; Santi et al., 2019). The strategic design of public places is crucial for achieving long-term sustainability and positive community impact (Wheeler, 2016). In contrast, residents judge public spaces based on personalised needs and experiences related to safety, belonging, and accessibility (Şenol, 2022). Residents evaluate public spaces based on personalised needs and experiences, with a focus on safety, belonging, and accessibility (Cao et al., 2022; Weidemann et al., 1982). Quality green spaces and well-maintained public areas contribute to a sense of safety and community, which are essential for residents' well-being and mental health (Błaszczyk et al., 2020). These differing viewpoints highlight the complexity of creating inclusive public places suited to diverse users.

The implications of this disconnect on community well-being are significant, affecting health, well-being, and social cohesion (Fallanca & Stagno, 2022; Aelbrecht et al., 2022). The disconnect between professional and community perspectives could negatively impact public space planning/its functionality. For example, the disconnect negatively affects the ability of public spaces to accommodate and encourage social interaction, which is crucial for community well-being (Brain, 2019). Bridging this gap by aligning the viewpoints of urban planners and communities is important so that the maximum benefits of public spaces/ addressing the expectations of community needs can be achieved.

Hence, there is a need for a re-examination of the notion of public places. Accordingly, this study aims to redefine the notion of public spaces from a global perspective, considering diverse geographical, cultural, and social contexts. This study primarily focuses on urban public spaces, reflecting the varying expectations of professionals and community members. While geographical differences are acknowledged, the emphasis remains on the urban context due to its unique challenges and opportunities. The paper is structured as follows. It begins with an introduction highlighting the importance of public spaces and the evolving perspectives surrounding them. The literature review section explores various definitions and typologies of public spaces, along with the needs, and expectations of professionals as well as the general community, and challenges associated with them. Following this, the methodology section outlines the approach used for the narrative literature review. The discussion section delves into key themes such as professional perspectives, community expectations, and challenges in meeting these expectations. Finally, the conclusion offers insights into the implications of the research findings and suggests avenues for future research on redefining public spaces.

2. METHODOLOGY

This study employs a narrative literature review to explore the gap between professional and community perspectives on public spaces. Unlike Systematic Literature Reviews (SLRs) or meta-analyses, which focus on quantitative synthesis, a narrative review allows for the integration of diverse perspectives and the exploration of theoretical nuances (Green et al., 2006). This method was chosen to capture the complex changes in public spaces influenced by recent global events and technological progress.

The choice of a narrative review is justified by the need to establish a theoretical foundation, integrate diverse perspectives, and provide a detailed thematic analysis that surveys alone cannot achieve. This method allows for a nuanced understanding of public spaces, bridging theoretical constructs with practical applications. In summary, the narrative literature review method provides a comprehensive and nuanced understanding of public spaces, addressing the theoretical and practical dimensions of the research.

3. LITERATURE REVIEW

3.1 WHAT ARE PUBLIC PLACES?

In Ray Oldenburg's conceptualisation of social spaces, public spaces have been identified with three distinct spheres: the intimate domain of the home, the structured environment of the workplace, and the dynamic realm of third places, which encompass public spaces such as cafes, parks, and libraries (Hummon & Oldenburg, 1991). Oldenburg contends that these third places play a crucial role in fostering community cohesion and facilitating public engagement (Hummon & Oldenburg, 1991).

When it comes to the term "public spaces or places" it suggests an image of accessible urban, suburban, rural, and wilderness landscapes. The term "public" connotes the idea that these settings are accessible to everyone—people of a community, State, or nation, regardless of age, gender, ethnicity, physical handicap, or other characteristics. In this context, however, "public" does not necessarily relate to ownership, but rather to use. Some privately owned places and spaces are accessible to the public and some publicly owned areas are not (Altman & Zube, 1989). According to Holland et al., (2007), public spaces allow people to meet on ostensibly neutral ground in planned and unplanned ways, to interact with others within the context of the whole community. Carr (1992) defines public space as "*the common ground where people carry out the functional and ritual activities that bind a community, whether in the normal routines of daily life or in periodic festivities…[it] is the stage where the drama of communal life unfolds"*. This is in line with social cohesion which is defined as the willingness of members of a society to cooperate with each other in order to survive and prosper (Stanley, 2003). Well-designed public spaces can contribute to social cohesion and the quality of life of residents (Aelbrecht et al., 2022).

3.2 TYPES OF PUBLIC SPACES

Public spaces can be public, private, inside, outside, restrictive, free, democratic, and inclusive, with changing everyday uses to accommodate recreational activities (Gehl & Matan, 2009). Further, types of public spaces include fully public, semi-public, and private sector-operated spaces, organised by criteria such as intended users, time limits, control, intended functions, and visual characteristics (Mantey & Kępkowicz, 2018). As public spaces, it can be identified different types of places. Carr, (1992) classified eleven different types of public spaces, based on how people use the space: public parks, squares and plazas, memorials, markets, streets, playgrounds, community open spaces, greenways and parkways, atrium/indoor marketplace, found/neighbourhood spaces, and waterfronts. Going beyond that, these types of public spaces are identified in older literature. For example, classic texts of Whyte (1980) examined how plazas, squares, and other open public areas function as gathering places. Cranz and Boland (2004) has influential research outlining the history and evolution of park ideals including recreational, picturesque, reform, recreational and sustainable park types. Furthermore, the seminal research of (Searns, 1995) analysed greenways through history advancing them as a distinct sustainable public linear space type. The United Nations' report on public spaces addresses six groups, including intensely used spaces, green open public spaces, public activity spaces, public sector realm, city as a public space, and cyberspace (Özbayraktar et al., 2017). Thus, it can be identified that public places can be classified based on their function, purpose, accessibility, and usage, with various categories in urban planning and design. As a whole, a good public space is responsive, democratic, and meaningful, evaluating factors like inclusiveness, meaningfulness, safety, comfort, and pleasurable (Mehta, 2014).

3.3 NEED FOR PUBLIC SPACES

The need for public spaces from the perspective of people living in different areas must be properly studied. Because the meaning and the need for public spaces may be different from their view. Several researchers highlight humans' innate need for social interaction and connection and public spaces as venues for interactions, relationships, and a sense of community (Andersson, 2021; Kim et al., 2021; Olwig, 1989; Peters et al., 2010). The lack of public spaces limits these opportunities. Furthermore, Peters et al. (2010) say people from all ethnic backgrounds spend some of their leisure time in green areas. Kaźmierczak (2013) found that urban parks are more inclusive green places than non-urban green areas that are agricultural and green infrastructures that provide ecosystem services (La Greca et al., 2011) and that urban parks can promote social cohesion. The influence of green space on the community attachment of urban and suburban residents was highly discussed by Arnberger and Eder (2012) in their research. Nevertheless, studies show public spaces such as parks, gardens, trails etc provide psychological benefits including stress relief, attention restoration, improved mood and cognitive functioning (Kaplan, 1995; Ulrich et al., 1991). They are needed for psychological health. Further, public spaces promote exercise through walkability and recreation facilities. They facilitate social connection and a sense of belonging which contribute to wellness and longevity (Frumkin, 2003). When considering urban liveability and placemaking, public spaces such as libraries, plazas, and parks enhance the quality of life and attachments to place. They act as 'living rooms' and give character to neighbourhoods (Spaces, 2015).

The functionality of public spaces can be mapped with the fundamental human needs at different levels in Maslow's hierarchy of needs. Maslow's hierarchy of needs is a well-known psychological theory that explains the motivation and expression of personality. It consists of five need categories: physiological, safety, belonging, esteem, and self-actualisation (Omodan & Abejide, 2022).

- When considering physiological needs, public rest areas, shelters, sidewalks and shaded spaces are supporting basic needs like rest, sleep, and warmth (Mehta, 2014).
- Safety needs: Well-designed public spaces with proper lighting, surveillance, and clear pathways can enhance feelings of safety and security (Kim et al., 2021).
- Belonging and love needs: Public spaces serve as gathering places where people can connect, socialize, and form relationships with others in their community (Andersson, 2021).
- Esteem needs: Public spaces that promote inclusivity, diversity, and equal access can contribute to individuals' sense of self-worth and respect (Andersson, 2021)
- Self-actualisation needs: Public spaces that offer opportunities for personal growth, creativity, and self-expression, such as art installations, community

gardens, or performance spaces, can contribute to individuals' pursuit of self-actualisation (Andersson, 2021)

3.4 PROFESSIONALS' PERSPECTIVES - EXPECTATIONS OF PUBLIC SPACES

Professionals, such as planners and urban designers, prioritise creating inclusive public spaces where everyone feels a sense of belonging. The design and management of public spaces are perceived as crucial for the well-being of city residents, with professionals understanding the challenges of creating spaces that positively impact communities (El-Kholei & Yassein, 2022). A mixed research methodology identified eight design principles, with professionals prioritising four core design principles aligned with sustainable development (El-Kholei & Yassein, 2022). The Analytical Hierarchy Process (AHP) was used to determine professionals' priorities, revealing disagreements on the rank of the design principles, possibly influenced by specialisation, gender, and experience (El-Kholei & Yassein, 2022).

Professionals prioritise factors such as inclusiveness, desirable activities, comfort, safety, and pleasurable to ensure that public spaces are inclusive, safe, and comfortable for diverse communities. However, these professional priorities may sometimes overlook or conflict with community needs. For example, urban renewal projects aimed at improving infrastructure and aesthetics can lead to gentrification, displacing long-term residents and altering the socio-economic fabric of neighbourhoods (Ha, 2004). Similarly, design choices focused on high-end amenities can create spaces perceived as exclusive or inaccessible to certain community groups (Pampillln, 2017). These conflicting objectives can manifest in the form of limited access to improved spaces for marginalised populations, as seen in the redevelopment of public spaces in San Francisco (Marche, 2015). This highlights the need for careful consideration and alignment of professional and community perspectives to create truly inclusive public spaces.

The COVID-19 pandemic has introduced new challenges and priorities for urban planners. Professionals have had to adapt designs to accommodate social distancing measures, increase sanitation protocols, and enhance the functionality of outdoor spaces to support physical and mental health (Honey-Rosés et al., 2021). The pandemic underscored the need for flexible and adaptive public spaces that can quickly respond to public health crises (Honey-Rosés et al., 2021).

Technological advancements have further influenced the expectations and design principles of professionals. The integration of smart technologies, such as sensors for monitoring air quality and crowd density, has become increasingly important. These technologies help create safer and more responsive public spaces by providing real-time data to manage and maintain these areas (Chitrakar et al., 2022). Moreover, the rise of digital public spaces, such as virtual meeting places and online community forums, has expanded the definition of public spaces and how they are used (Foth et al., 2016).

However, professionals face challenges in meeting these expectations, including the need to balance various design principles, the impact of specialisation and experience on prioritisation, and the lack of comprehensive tools for assessing public space quality (Askari & Soltani, 2019; El-Kholei & Yassein, 2022; Ferwati et al., 2021).

3.5 GENERAL COMMUNITY'S PERSPECTIVES - EXPECTATIONS

The general public's perceptions of safety in public spaces are influenced by gendered and place-based preconditions, with different safety strategies for women and men, especially when alone (Şenol, 2022). For example, a third of all crimes in official statistics were committed in public places, with their structure dominated by theft, plunder, and illegal drug trade (Afanasyeva et al., 2020). The feeling of safety in public spaces is connected to a wider positive evaluation of the quality of space and feeling at home, suggesting that concerns about safety are linked to the overall quality and comfort of the environment (Brands et al., 2021).

When broadly assessing the general community's expectations of public spaces, they are multifaceted and include various aspects such as transparency of information, environmental management, personal safety, and health protection (Jean-Baptiste et al., 2017). Mostly, government-owned public spaces were preferred by users due to easy access and freedom for activities (Peiris & Fayas, 2022). There are some economic Implications of Meeting Community Expectations from Public Spaces. The community expects public spaces to provide business opportunities through public markets and informal selling, and locations for festivals and celebrations that promote a sense of belonging and place attachment as well as transmit cultural practices (Low, 2023). Not only that, during disasters, public spaces become locations of social solidarity and support, and they can be realigned to highlight their importance for socially just cities (Low, 2023). Moreover, public safety concerns, such as well-lit and well-maintained spaces, are paramount for community members, whereas professionals may focus on broader environmental health perspectives (Maas et al., 2009). The emphasis on health protection by the community includes immediate health benefits from public spaces, such as mental health improvements and opportunities for physical activities, which professionals also recognize but often within a wider strategic framework (Francis et al., 2012).

3.6 CHALLENGES IN MEETING COMMUNITY'S EXPECTATIONS OF PUBLIC SPACES

The organisation of public space commonly reflects the priorities of dominant socioeconomic groups, who exercise disproportionate influence over its provision, governance, and material form, potentially undermining the inclusionary character of public space (Collins & Stadler, 2019). Excessive control of public space by community groups can be problematic as it diminishes a user's ability to access open spaces, compromising the public realm (Chitrakar et al., 2022). Additionally, there is often a disconnect between the priorities of urban planning professionals and the localised needs of residents. Professionals may emphasise long-term sustainability and aesthetic considerations, while community members focus on immediate concerns such as safety, accessibility, and practical utility (El-Kholei & Yassein, 2022; Şenol, 2022).

Gentrification is a prime example of this conflict, where urban renewal projects designed to improve public spaces often lead to the displacement of long-standing community members, thereby creating no-access spaces for certain groups (Collins & Stadler, 2019). This can result in the exclusion of marginalised communities from areas intended to serve the public, highlighting the disparity between professional planning goals and community needs (Chitrakar et al., 2022).

Technological advancements pose challenges in meeting community expectations. While smart technologies can enhance safety and convenience, they can raise concerns about privacy and surveillance (Kitchin, 2016). Balancing the benefits of technology with the need to protect individual freedoms and ensure equitable access is a significant challenge for urban planners.

Moreover, the lack of comprehensive instruments to measure the quality of public space poses a challenge in assessing and meeting the diverse expectations of the community from public spaces (Mehta, 2014). Older people's experiences of public places are challenged by physical, social, and legal constraints, leading to specific considerations and disincentivises to be in public places at certain times and in certain ways (Holland, 2015). Moreover, women's experience in public places is challenged by factors such as normalised distaste, fear of crime, and difficulty managing street remarks, requiring gender-conscious appraisal (Gardner, 1989). Hence, there is a need for a redefinition of the notion of public spaces.

4. DISCUSSION

The literature underscores the multifaceted divide between urban planning professionals' emphasis on universal design principles aligned with sustainable development goals and community groups context-specific perceptions rooted in geographical, cultural, and social realities. For instance, while professionals may prioritise creating aesthetically pleasing and sustainable public spaces, community members might focus more on immediate issues such as personal safety and accessibility. Real-world examples, such as gentrification resulting from urban renewal projects and the creation of no-access spaces for certain community groups, illustrate these potential conflicts.

Bridging this disconnect necessitates context-sensitive approaches that integrate localised narratives, identities and placemaking practices rather than imposing universalising paradigms. Crucially, aligning professional expertise with fundamental community expectations around personal safety, accessibility, comfort and fostering a sense of belonging is vital for cultivating ownership and attachment to public spaces. Inclusive, participatory and community-driven processes that centre resident voices through stakeholder engagement, co-design and empowered decision-making are imperative for socially sustainable public realm development responsive to lived experiences. Accommodating the diverse needs and intersectional experiences of different community members based on gender, age, ability and socioeconomic status through equity-focused and accessible design is essential for achieving true inclusivity. Moreover, as societies rapidly evolve alongside technological advancements, cultural shifts and changing societal dynamics, the malleable notion of public space must adapt by re-evaluating how these realms are defined, designed and experienced. Ultimately, revisiting and redefining public spaces should create resonant environments that foster social cohesion, community empowerment and a deep sense of belonging while contributing to sustainability goals by profoundly aligning with the multifaceted identities, values and aspirations of the residents they aim to serve. Based on the above discussion, the conceptual framework shown in Figure 1 has been prepared.

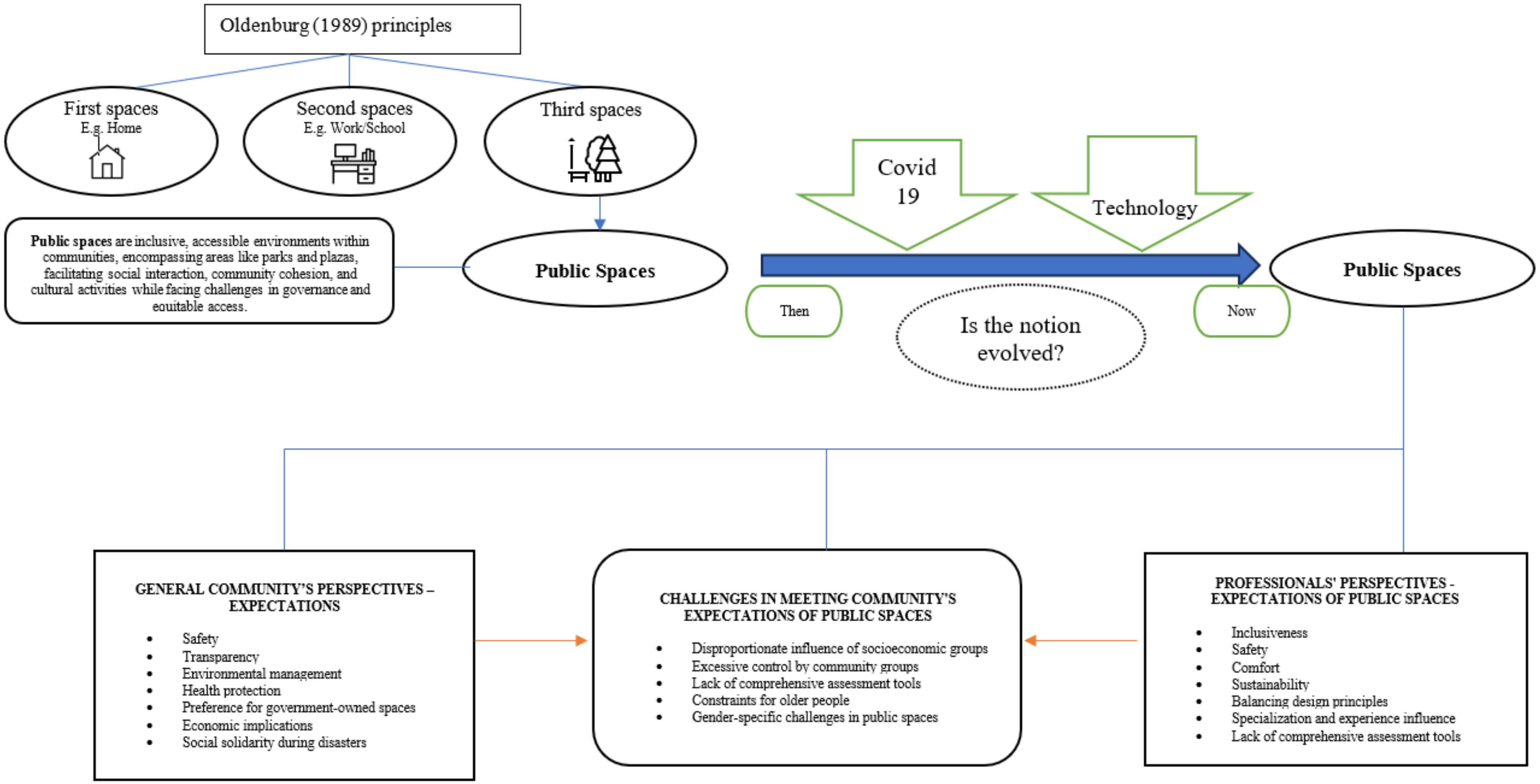


Figure 1: Conceptual framework

5. CONCLUSIONS

This study explored the differences between urban planning professionals' and community members' perspectives on public spaces, emphasising the need for inclusivity, sustainability, and community impact in public place design and management. The narrative literature review highlighted the multifaceted roles of public spaces in fostering social interaction, cultural expression, and community identity.

The findings underscore the importance of adopting context-sensitive and inclusive design principles that address both professional and community concerns. Urban planners should integrate localised narratives and participatory processes to bridge the gap between professional goals and community needs. This approach will enhance the functionality, safety, and accessibility of public spaces, promoting a sense of belonging and well-being for all community members.

Future research should focus on empirical studies that gather data from diverse communities to validate the findings of this narrative review. Investigating the impact of technological advancements on public space usage and exploring strategies for mitigating the effects of gentrification on marginalised communities are crucial areas for further study. Additionally, longitudinal studies examining the long-term outcomes of inclusive and participatory public space design initiatives would provide valuable insights for urban planners.

6. ACKNOWLEDGMENT

The authors greatly acknowledge the financial support provided by the ENSEMBLE Project in Collaboration with Canada.

7. REFERENCES

Afanasyeva, O., Goncharova, M., & Shiyan, V. (2020). The condition and trends of crimes committed in public places. *Russian Journal of Criminology, 13*(6), 895–908. https://doi.org/10.17150/2500-4255.2019.13(6).895-908

Altman, I., & Zube, E. H. (1989). Publictransformation, nostalgia, and illusion in public life and public place places and spaces. In M. Brill (Ed.), *Public Places and Spaces* (Vol. 10, pp. 7–29). Springer US. https://doi.org/10.1007/978-1-4684-5601-1

Andersson, C. (2021). Public space and the new urban agenda. In *Public Space Reader* (pp. 420–425). Routledge. https://doi.org/10.4324/9781351202558-62

Arnberger, A., & Eder, R. (2012). The influence of green space on community attachment of urban and suburban residents. *Urban Forestry & Urban Greening, 11*(1), 41–49. https://doi.org/10.1016/j.ufug.2011.11.003

Askari, A. H., & Soltani, S. (2019). Determinants of a successful public open space: the case of Dataran Merdeka in the city centre of Kuala Lumpur, Malaysia. *Landscape Research, 44*(2), 162–173. https://doi.org/10.1080/01426397.2018.1427221

Błaszczyk, M., Suchocka, M., Wojnowska-Heciak, M., & Muszyńska, M. (2020). Quality of urban parks in the perception of city residents with mobility difficulties. *PeerJ, 8*, e10570. https://doi.org/10.7717/peerj.10570

Brain, D. (2019). Reconstituting the urban commons: public space, social capital and the project of urbanism. *Urban Planning, 4*(2), 169–182. https://doi.org/10.17645/up.v4i2.2018

Brands, J., Doorn, J. van, & Spithoven, R. (2021). Supplemental safety? exploring experienced safety in relation to other qualities of successful public spaces. *Journal of Urban Design, 26*(1), 59–74. https://doi.org/10.1080/13574809.2020.1819781

Cao, Q., Yang, X., Li, S., & Cai, W. (2022). *A Study on the Perception of Public Space in Displaced Relocation*. https://doi.org/10.2991/assehr.k.220109.057

Carr, S. (2014). Public spaces. In *Authentic Learning for the Digital Generation* (pp. 39–50). Routledge. https://doi.org/10.4324/9781315794808-4

Chitrakar, R. M., Baker, D. C., & Guaralda, M. (2022). How accessible are neighbourhood open spaces? Control of public space and its management in contemporary cities. *Cities*, *131*. https://doi.org/10.1016/j.cities.2022.103948

Collins, D., & Stadler, S. L. (2019). Public spaces, Urban. In *International Encyclopedia of Human Geography* (2nd ed., pp. 103–111). https://doi.org/10.1016/B978-0-08-102295-5.10212-4

Cranz, G., & Boland, M. (2004). Defining the sustainable park: A fifth model for urban parks. *Landscape Journal*, *23*(2), 102–120. https://doi.org/10.3368/lj.23.2.102

El-Kholei, A. O., & Yassein, G. (2022). Professionals' perceptions for designing vibrant public spaces: Theory and praxis. *Ain Shams Engineering Journal*, *13*(5), 101727. https://doi.org/10.1016/j.asej.2022.101727

Ewertowski, W. (2023). Public space in different cultural conditions: The cases of Glasgow and Poznań. *Quaestiones Geographicae*, *42*(2), 115–129. https://doi.org/10.14746/quageo-2023-0019

Fallanca, C., & Stagno, E. (2022). Toward the development of a planning protocol for public space for improving health and wellbeing of communities. In F. Calabrò, L. Della Spina, & M. J. Piñeira Mantiñán (Eds.), *Lecture Notes in Networks and Systems* (Vol. 482, pp. 549–558). Springer International Publishing. https://doi.org/10.1007/978-3-031-06825-6_52

Foth, M., Hudson-Smith, A., & Gifford, D. (2016). Smart cities, social capital, and citizens at play: a critique and a way forward. In *Research Handbook on Digital Transformations*. Edward Elgar Publishing. https://doi.org/10.4337/9781784717766.00017

Francis, J., Wood, L. J., Knuiman, M., & Giles-Corti, B. (2012). Quality or quantity? exploring the relationship between public open space attributes and mental health in Perth, Western Australia. *Social Science & Medicine*, *74*(10), 1570–1577. https://doi.org/10.1016/j.socscimed.2012.01.032

Frumkin, H. (2003). Healthy places: Exploring the evidence. *American Journal of Public Health*, *93*(9), 1451–1456. https://doi.org/10.2105/AJPH.93.9.1451

Gardner, C. B. (1989). Analyzing gender in public places: Rethinking Goffman's vision of everyday life. *The American Sociologist*, *20*(1), 42–56. https://doi.org/10.1007/BF02697786

Gehl, J., & Matan, A. (2009). Two perspectives on public spaces. *Building Research & Information*, *37*(1), 106–109. https://doi.org/10.1080/09613210802519293

Gonzzlez Pampillln, N. (2017). Can urban renewal policies reverse neighborhood ethnic dynamics? *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2919283

Green, B. N., Johnson, C. D., & Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: secrets of the trade. *Journal of Chiropractic Medicine*, *5*(3), 101–117. https://doi.org/10.1016/S0899-3467(07)60142-6

Grierson, D. (2009). Towards sustainable building design. *Design Principles and Practices: An International Journal—Annual Review*, *3*(3), 143–152. https://doi.org/10.18848/1833-1874/CGP/v03i03/37682

Ha, S.-K. (2004). Housing renewal and neighborhood change as a gentrification process in Seoul. *Cities*, *21*(5), 381–389. https://doi.org/10.1016/j.cities.2004.07.005

Holland, C. (2015). Public places and age. In J. Twigg & W. Martin (Eds.), *Routledge Handbook of Cultural Gerontology* (pp. 477–484). Routledge. https://lccn.loc.gov/2008353259

Holland, C., Clark, A., Katz, J., & Peace, S. (2007). *Social interactions in urban public places*. Policy Press. http://oro.open.ac.uk/7445

Honey-Rosés, J., Anguelovski, I., Chireh, V. K., Daher, C., Konijnendijk van den Bosch, C., Litt, J. S., Mawani, V., McCall, M. K., Orellana, A., Oscilowicz, E., Sánchez, U., Senbel, M., Tan, X., Villagomez, E., Zapata, O., & Nieuwenhuijsen, M. J. (2021). The impact of COVID-19 on public space: an early review of the emerging questions – design, perceptions and inequities. *Cities & Health*, *5*(sup1), S263–S279. https://doi.org/10.1080/23748834.2020.1780074

Hummon, D. M., & Oldenburg, R. (1991). The Great Good Place: Cafes, Coffee Shops, Community Centers, Beauty Parlors, General Stores, Bars, Hangouts, and How They Get You Through the Day. *Social Forces*, *69*(3), 931. https://doi.org/10.2307/2579492

İnce Güney, Y. (2014). Gender and urban space: An examination of a small anatolian city | Toplumsal cinsiyet ve kamusal mekan: Bir Anadolu kenti incelemesi. *A/Z ITU Journal of the Faculty of Architecture*, *11*(2), 153–172. Retrieved July 1, 2024, from https://www.az.itu.edu.tr/index.php/jfa/article/view/460

Jean-Baptiste, M., Daniau, C., & Perrey, C. (2017). What the local community and an environmental organization expect of the public authorities about the Salindres industrial site: A comparative analysis. *Environnement, Risques et Sante*, *16*(3), 247–258. https://doi.org/10.1684/ers.2017.1018

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Karuppannan, S., & Sivam, A. (2013). Comparative analysis of utilisation of open space at neighbourhood level in three Asian cities: Singapore, Delhi and Kuala Lumpur. *URBAN DESIGN International*, *18*(2), 145–164. https://doi.org/10.1057/udi.2012.34

Kim, W., Lee, S., Chang, Y., Lee, T., Hwang, I., & Song, J. (2021). Facilitating in-situ shared use of IoT actuators in public spaces. *Proceedings of the 19th Annual International Conference on Mobile Systems, Applications, and Services*, 497–498. https://doi.org/10.1145/3458864.3468444

Kitchin, R. (2016). The ethics of smart cities and urban science. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2083), 20160115. https://doi.org/10.1098/rsta.2016.0115

La Greca, P., La Rosa, D., Martinico, F., & Privitera, R. (2011). Agricultural and green infrastructures: The role of non-urbanised areas for eco-sustainable planning in a metropolitan region. *Environmental Pollution*, *159*(8–9), 2193–2202. https://doi.org/10.1016/j.envpol.2010.11.017

Low, S. (2023). Why public space matters. In *Why Public Space Matters*. https://doi.org/10.1093/oso/9780197543733.001.0001

Maas, J., Spreeuwenberg, P., van Winsum-Westra, M., Verheij, R. A., Vries, S., & Groenewegen, P. P. (2009). Is green space in the living environment associated with people's feelings of social safety? *Environment and Planning A: Economy and Space*, *41*(7), 1763–1777. https://doi.org/10.1068/a4196

Malá, M., Sýkorová, M., & Felicioni, L. (2022). How municipalities should approach the transformation of public spaces. *Acta Polytechnica CTU Proceedings*, *38*, 635–641. https://doi.org/10.14311/APP.2022.38.0635

Malik, A., Akbar, R., Maryati, S., & Natalivan, P. (2018). Spatial analysis related to the location characteristics of park supply. Case study: Music Park and Pendawa Park, Bandung City, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *158*(1). https://doi.org/10.1088/1755-1315/158/1/012028

Mantey, D., & Kępkowicz, A. (2018). Types of Public Spaces: The Polish contribution to the discussion of suburban public space. *The Professional Geographer*, *70*(4), 633–654. https://doi.org/10.1080/00330124.2018.1443475

Marche, G. (2015). What can urban gardening really do about gentrification? A case-study of three San Francisco community gardens. *European Journal of American Studies*, *10*(3). https://doi.org/10.4000/ejas.11316

Mehta, V. (2014). Evaluating public space. *Journal of Urban Design*, *19*(1), 53–88. https://doi.org/10.1080/13574809.2013.854698

Olwig, K. R. (1989). Life between buildings: Using public space. *Landscape Journal*, *8*(1), 54–55. https://doi.org/10.3368/lj.8.1.54

Omodan, B. I., & Abejide, S. O. (2022). Reconstructing Abraham Maslow's hierarchy of needs towards inclusive infrastructure development needs assessment. *Journal of Infrastructure, Policy and Development*, *6*(2), 1483. https://doi.org/10.24294/jipd.v6i2.1483

Özbayraktar, M., Pekdemir, M., & Mirzaliyeva, G. (2017). Spatial character analysis of streets as public spaces: The case of Izmit Hurriyet and Cumhuriyet Street, Turkey. *IOP Conference Series: Materials Science and Engineering*, *245*(7). https://doi.org/10.1088/1757-899X/245/7/072019

Peiris, M. T. O. V., & Fayas, M. (2022). Assessment of user perception on public and private spaces within urban context. *International Journal of Built Environment and Sustainability*, *9*(2), 47–59. https://doi.org/10.11113/ijbes.v9.n2.938

Peters, K., Elands, B., & Buijs, A. (2010). Social interactions in urban parks: Stimulating social cohesion? *Urban Forestry & Urban Greening*, *9*(2), 93–100. https://doi.org/10.1016/j.ufug.2009.11.003

Salim Ferwati, M., Keyvanfar, A., Shafaghat, A., & Ferwati, O. (2021). A quality assessment directory for evaluating multi-functional public spaces. *Architecture and Urban Planning*, *17*(1), 136–151. https://doi.org/10.2478/aup-2021-0013

Santi, G., Leporelli, E., & Di Sivo, M. (2019). Improving sustainability in architectural research: Biopsychosocial requirements in the design of urban spaces. *Sustainability*, *11*(6), 1585. https://doi.org/10.3390/su11061585

Searns, R. M. (1995). The evolution of greenways as an adaptive urban landscape form. *Landscape and Urban Planning*, *33*(1–3), 65–80. https://doi.org/10.1016/0169-2046(94)02014-7

Şenol, F. (2022). Gendered sense of safety and coping strategies in public places: A study in Atatürk Meydanı of Izmir. *Archnet-IJAR: International Journal of Architectural Research*, *16*(3), 554–574. https://doi.org/10.1108/ARCH-08-2021-0213

Simões Aelbrecht, P., Stevens, Q., & Kumar, S. (2022). European public space projects with social cohesion in mind: symbolic, programmatic and minimalist approaches. *European Planning Studies*, *30*(6), 1093–1123. https://doi.org/10.1080/09654313.2021.1959902

Spaces, P. for P. (2015). Placemaking and the future of cities. In 6th (Ed.), *The City Reader* (Issue United Nations Human Settlements Programme (UN-Habitat), pp. 673–684). Routledge. https://doi.org/10.4324/9781315748504-83

Stanley, D. (2003). What do we know about social cohesion: The research perspective of the federal government's social cohesion research network. *Canadian Journal of Sociology / Cahiers Canadiens de Sociologie*, *28*(1), 5. https://doi.org/10.2307/3341872

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, *11*(3), 201–230. https://doi.org/10.1016/S0272-4944(05)80184-7

Weidemann, S., Anderson, J. R., Butterfield, D. I., & O'Donnell, P. M. (1982). Residents' perceptions of satisfaction and safety. *Environment and Behavior*, *14*(6), 695–724. https://doi.org/10.1177/0013916582146004

Wheeler, S. M. (2016). Response to Nico Larco's sustainable urban design framework. *Journal of Urban Design*, *21*(1), 47–49. https://doi.org/10.1080/13574809.2016.1114381

Whyte, W. H. (2009). The social life of small urban spaces. In *Common Ground?* (pp. 42–49). Routledge. https://doi.org/10.4324/9780203873960-9

Zick, T. (2006). Clouds, cameras, and computers: The first amendment and networked public places. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.924614

Zimmerman, C., Hansen, K., & Vatrapu, R. (2014). A theoretical model for digital reverberations of city spaces and public places. *International Journal of Electronic Government Research*, *10*(1), 46–62. https://doi.org/10.4018/ijegr.2014010104

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

RISK MANAGEMENT IN SRI LANKAN SME CONSTRUCTION SECTOR: IDENTIFYING BARRIERS AND ENABLERS

B.B. Bandaranaike[1], S.D. Gallage[2] and S. Sivanraj[3]

ABSTRACT

This study investigates risk management practices in the SME construction sector in Sri Lanka, aiming to identify critical issues, enablers, and barriers. Through a mixed-method approach comprising expert interviews and a questionnaire survey, the research highlights significant risk management (RM) challenges unique to the Sri Lankan context. Key findings indicate that economic instability, lack of education in organisational management, and reliance on experience-based practices are major obstacles to effective RM. The study identifies "unawareness of available practices" and "keeping outdated procedures" as the most severe barriers to RM implementation. Unlike global literature, which often emphasizes financial constraints and time limitations, this research underscores the critical role of awareness and procedural updates in Sri Lanka's small and medium enterprise (SME) sector. The findings have implications for industry practitioners, academics, and policymakers, emphasising the need for targeted RM training, supportive regulations, and localised RM strategies. Limitations of the study include a small sample size and a focus on SME contractors in Sri Lanka, suggesting the need for further research in different contexts.

Keywords: *Construction Risk; Risk Management; Small and Medium Enterprises (SME); SME Construction.*

1. INTRODUCTION

The construction industry faces inherent complexities due to numerous random processes and external factors, necessitating effective risk management (RM) strategies (Abourizk & Mohamed, 2002). The Project Management Institute's Project Management Body of Knowledge (PMBOK) highlights RM as crucial for mitigating hazards and reducing losses (Raz & Michael, 2001). Ineffective RM can significantly impede project outcomes, particularly in an industry marked by unpredictability (Bajo et al., 2012; Serpell et al., 2015).

Small and medium enterprises (SMEs) in the construction sector are pivotal for job creation and economic growth but face unique challenges like skills shortages and limited delivery capability (Ranadewa et al., 2018). These challenges are amplified in developing countries where SMEs handle less profitable projects in remote areas (Eyiah & Cook,

[1] Quantity Surveyor, VFORM Consultants Pvt Ltd, Sri Lanka, Buwaneka1105@gmail.com
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sasankag@uom.lk
[3] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, sivanrajs.19@uom.lk

2010). While RM's importance is well-documented, the literature mainly focuses on large organizations, leaving a gap in understanding RM practices in SMEs (Ferreira de Araújo Lima et al., 2021). SMEs often lack the resources to implement sophisticated RM tools used by larger companies (Perera et al., 2014; Virglerova et al., 2016).

Thus, addressing RM effectively is crucial for SMEs to thrive in the construction industry and ensure project success. This research aims to explore the feasibility of implementing RM practices among SME contractors in Sri Lanka. It will identify issues related to SME contractors, identify factors enabling the adoption of RM practices, and review barriers to implementing these practices. Understanding these elements will help bridge the gap in the literature and provide actionable insights for improving RM in the SME construction sector.

2. LITERATURE REVIEW

2.1 CONSTRUCTION INDUSTRY AND RISK MANAGEMENT

RM in the construction industry is essential for identifying, analysing, and responding to project risks, ensuring project objectives like cost, time, and quality are met (Bahamid et al., 2019; Perera et al., 2014). Key risk factors include technical, construction, physical, organizational, financial, socio-political, and environmental risks (Mok et al., 2015). For example, technical risks involve not meeting specifications, and financial risks involve budget overruns.

Effective RM increases the likelihood of project success by proactively addressing risks, involving activities like risk identification, analysis, response planning, and monitoring (Wang & Yuan, 2011). This approach minimises the impact of negative events and maximises opportunities, reducing the chances of project failures and saving time and money (Xia et al., 2018). The construction sector's inherent complexities and uncertainties make RM crucial for ensuring projects achieve their goals despite unpredictable conditions (Zou et al., 2007).

A comprehensive RM strategy, tailored to the specific risk thresholds and tolerance levels of the organization and stakeholders, significantly enhances project performance and success (Lyons & Skitmore, 2004). This proactive RM approach not only prevents costly delays and rework but also contributes to overall project efficiency and effectiveness.

2.2 CHALLENGES FACED BY SMES IN THE CONSTRUCTION SECTOR

SMEs are vital to the construction industry, significantly contributing to employment and economic growth (Ranadewa et al., 2018). In Sri Lanka, a substantial number of construction firms are SMEs, highlighting their economic importance (Senevirathna et al., 2015). However, these businesses face unique challenges, such as difficulty securing financing from banks, intense competition from larger firms, and a shortage of skilled workers (Eyiah & Cook, 2010).

Cash flow management and compliance with regulations are also significant concerns, as SMEs often lack the resources to hire specialised staff (Rahman & Omar, 2006). Limited access to the latest technology further hampers their competitiveness and efficiency (Egbu, 2000). For instance, Ranadewa et al. (2018) found that Sri Lankan SMEs struggle with funding, affecting their ability to upgrade machinery and maintain project timelines and quality. Similarly, Eyiah and Cook (2010) highlight Ghanaian SMEs' challenges in competing with larger firms, leading to market share loss and financial difficulties. These challenges underscore the need for targeted support and policies to enhance SME growth and sustainability in the construction sector.

2.3 RISK MANAGEMENT PRACTICES IN CONSTRUCTION

RM in the construction industry involves systematic identification, assessment, and response to risks to achieve project objectives (Bahamid et al., 2019). Common RM practices include risk identification, assessment, mitigation, and continuous monitoring (Nieto-Morote & Ruz-Vila, 2011). Large organisations typically use sophisticated RM frameworks and tools, like quantitative risk analysis and specialised software, to manage complex projects (Kamau & Mohamed, 2015). They also have dedicated RM teams and resources, enabling comprehensive strategies and contingency plans (Szymański, 2017).

In contrast, SMEs face distinct RM challenges due to limited resources and capacity (Falkner & Hiebl, 2015). SME RM practices are often informal and reactive, relying more on managers' experience and intuition than structured processes (Ranadewa et al., 2018). The lack of access to advanced RM tools and expertise makes SMEs more vulnerable to project disruptions and financial instability compared to larger organisations (Ranadewa et al., 2018).

2.4 ENABLERS FOR RISK MANAGEMENT ADOPTION IN SMES

Adopting RM practices is vital for SME contractors, aiding in loss reduction, employee safety, and risk mitigation (Kishan et al., 2014). Key enablers include leadership commitment, employee involvement, training, and access to resources (Carr & Tah, 2001). Leadership must emphasize RM's importance, and employees should be engaged and educated about risk mitigation (Bahamid et al., 2019). Comprehensive training in hazard recognition and risk analysis is essential (Makwana & Pitroda, 2017), along with providing necessary tools like risk assessment software and safety manuals (Philemon et al., 2018).

Technology, such as advanced risk analysis tools, enhances SMEs' RM capabilities. Policy support from governments and industry bodies, including guidelines and incentives, further encourages RM adoption (Philemon et al., 2018). Globally, collaborations with stakeholders like suppliers and industry associations provide SMEs with additional resources and knowledge (Makwana & Pitroda, 2017). Examples from the UK and Australia highlight how government initiatives and industry partnerships have improved RM practices and safety standards among SMEs (Philemon et al., 2018).

2.5 BARRIERS TO IMPLEMENTING RISK MANAGEMENT IN SMES

Adopting RM practices in SMEs is often inconsistent due to various barriers that hinder their competitiveness and ability to mitigate risks (de Araújo Lima et al., 2020). One primary barrier is the lack of expertise, resources, and reliable tools for RM, which are often financially out of reach for SMEs (Bajo et al., 2012). The principles used for larger companies are often impractical for SMEs due to their unique characteristics, such as limited management capacity and less formalized RM approaches (Marcelino-Sádaba et al., 2014).

There are no standardised RM frameworks tailored to SMEs, which leads to inconsistencies in implementation (de Araújo Lima et al., 2020). Additionally, SMEs often lack the necessary knowledge to make informed decisions about risk hedging and the managerial skills to effectively utilise RM tools (Olson & Wu, 2010). This knowledge gap can expose SMEs to significant business risks (Leopoulos et al., 2007).

Key barriers identified by El-Sayegh (2014) include a lack of understanding of RM techniques, difficulty in selecting appropriate RM methods, and challenges in estimating probabilities. Human and organisational resistance, coupled with insufficient top management support and the perceived high cost and effort of RM processes, further complicate RM adoption. Specific to small projects, barriers such as competition, complex analytical tools, limited budgets, and lack of government support are prevalent (Hwang et al., 2014).

2.6 IMPORTANCE OF CONDUCTING THE STUDY

The primary goal of construction project planning and management is to determine project objectives considering time, cost, and quality (Brown & Adams, 2000). Key challenges impacting construction performance include lack of finance, payment interruptions, design changes, low confidence, and poor planning (Asiedu & Adaku, 2019). These issues are particularly acute for SME contractors in Sri Lanka, who face unique risks and resource constraints compared to larger firms (Perera et al., 2014). Despite the high-risk nature of the construction industry globally, effective RM practices are often lacking, especially in developing countries (Serpell et al., 2015). SMEs face challenges in implementing RM due to high costs and complexity (Virglerova et al., 2016; Ferreira de Araújo Lima et al., 2021). The literature has largely focused on large organizations, leaving a gap in understanding RM in SMEs (Ferreira de Araújo Lima et al., 2021). This study aims to fill this gap by identifying issues specific to SME contractors in Sri Lanka, factors enabling RM adoption, and barriers to implementation, aiding in developing strategies for their sustainability and resilience.

3. RESEARCH METHODOLOGY

This research adopts a mixed-method approach to analyse the feasibility of implementing RM practices for SME contractors in Sri Lanka. The study combines qualitative and quantitative methods, as this approach is effective in exploring complex issues (Bazeley, 2002). A questionnaire survey was conducted to gather quantitative data from SME contractors, using Likert scale questions to assess RM awareness and application. The data were statistically analysed to determine the prevalence of RM practices. Additionally, semi-structured interviews with industry experts were conducted to validate and expand on the findings. Purposive sampling ensured the selection of knowledgeable experts, and interviews were recorded with consent. Content analysis, including manual coding, was used to evaluate both interview data, following Burla et al. (2008) and Basit (2010). This mixed-method approach provides a comprehensive understanding of RM challenges and opportunities for SME contractors in Sri Lanka, addressing a significant gap in the literature.

The interviews were conducted with six (6) experts selected according to the following criteria, and Table 1 elaborates on the interviewee's profile.

Table 1: Interviewees profile

Code	The profession of the interviewee	Additional criteria				
		CQ1	AQ1	AQ2	AQ3	AQ4
IV1	Quantity Surveying (Managing Director)	✓	✓	✓	✓	✓
IV2	Engineer (Project Manager)	✓	✓	✓		✓
IV3	Engineer (MEP Engineer)	✓		✓	✓	✓
IV4	Quantity Surveying (Managing Director)	✓	✓	✓	✓	✓
IV5	Quantity Surveying (Project Manager)	✓	✓	✓	✓	✓
IV6	Engineer (Director)	✓	✓	✓		✓

Compulsory qualification:

- **CQ1** - At least 10 years of experience in construction.

Additional qualification:

- **AQ1** - Knowledge in risk management practices
- **AQ2** - Knowledge and experience in working with SME contractors in Sri Lanka.
- **AQ3** - Knowledge in project management and planning concepts.
- **AQ4** - Current engagement with SME sector projects.

Purposive sampling was employed for a questionnaire survey, distributing it among 52 professionals, including Quantity Surveyors, Engineers, Project Managers, and researchers in academia related to the construction industry. Thirty-five responses were collected, resulting in a 67% response rate. Respondents had experience ranging from one to twenty years in the construction industry and small to medium-scale projects. Summary of the respondents are presented in Table 2.

Table 2: Summary of questionnaire respondents

Profession	Experience in construction						Experience in SME					
	0 - 5	5 - 10	10 - 15	15 - 20	Over 20	Total	0 - 5	5 - 10	10 - 15	15 - 20	Over 20	Total
Quantity Surveyor	5	7	3	3	0	18	8	6	4	0	0	18
Engineer	3	2	2	0	0	7	4	3	0	0	0	7
Project Manager	0	1	2	2	0	5	4	1	0	0	0	5
Academic Researcher	3	2	0	0	0	5	5	0	0	0	0	5
Total						35						35

4. DATA ANALYSIS AND FINDINGS

4.1 CONSTRUCTION RISKS IN SME SECTOR

The interviews with industry experts revealed several common risks for SME construction projects. These included challenges in winning new projects, receiving timely payments, maintaining continuous labour and material supply, handling price uncertainties, and managing documentation delays. Specific risks highlighted by experts also encompassed potential changes in government regulations, design errors, maintaining cash flow, clients abandoning projects due to bankruptcy, equipment theft, neighbour disturbances, and unpredictable weather conditions. Notably, experts emphasized that the financial instability of clients significantly disrupts cash flow, leading to project delays or termination.

The questionnaire survey sought to categorise the impact of these common uncertainties using a Likert scale from 1 to 5. The findings are illustrated in Table 3.

Table 3: Impact of common uncertainties faced by SME contractors

Code	Description	Negligible	Minor	Moderate	Significant	Severe	Weighted Total	WA	Rank
Weighted marks		**0.1**	**0.2**	**0.3**	**0.4**	**0.5**			
ECU1	Receiving money on time for the work done	0	0	0	4	31	17.1	11.40	**1**
ECU2	Maintaining the cash flow of the project.	0	0	0	5	30	17	11.33	**2**
ECU3	Continuously providing labour, material, and other required resources.	0	0	2	16	17	15.5	10.33	**4**
ECU4	Winning new projects to continue company workflow.	0	2	9	11	13	14	9.33	**5**
ECU5	Providing uninterrupted facilities for the labour requirement.	0	0	18	17	0	12.2	8.13	**13**
ECU6	Possibility of new taxes and changes in legislation.	0	0	11	18	6	13.5	9.00	**7**
ECU7	Changing and unpredictable weather conditions.	0	0	15	13	7	13.2	8.80	**10**
ECU8	Pricing for fixed-price projects with price fluctuations.	0	0	12	17	6	13.4	8.93	**9**
ECU9	Delays in documentation.	0	0	15	19	1	12.6	8.40	**12**
ECU10	Clients abandoning projects due to bankruptcy.	0	0	2	8	25	16.3	10.87	**3**
ECU11	Design Errors	0	0	13	18	4	13.1	8.73	**11**
ECU12	Theft issues	0	0	10	18	7	13.7	9.13	**6**
ECU13	Disturbance by neighbours and other parties due to sound, pollution, and other similar events.	0	0	6	29	0	13.4	8.93	**8**

The weighted analysis revealed that "receiving money on time for the work done" was the most critical risk, with a Weighted Average (WA) of 11.40, indicating its severe impact as noted by 88.5% of respondents. Closely following was "maintaining cash flow," with a WA of 11.33 and 85.71% of respondents rating it as severe. Other significant risks included "clients abandoning projects due to bankruptcy," "continuously providing labour, material, and other resources," and "winning new projects to continue company workflow."

Several unique risks to the Sri Lankan context emerged from the expert interviews. Experts indicated that sudden changes in government regulations and the introduction of new taxes significantly impact material and labour prices, which is particularly disruptive for SME contractors. The financial instability of clients, often resulting in delayed or halted payments, was highlighted as a critical risk, leading to substantial cash flow issues and project delays. Additionally, the high incidence of equipment theft on construction sites was identified as a unique challenge, exacerbated by insufficient security measures.

These unique findings are particularly significant when compared to existing literature. While studies by Eyiah and Cook (2010), Virglerova et al. (2016), and Siraj and Fayek (2019) emphasize financial management, particularly cash flow, as a critical challenge for SMEs globally, the issues of sudden regulatory changes and high equipment theft rates are more specific to the Sri Lankan context. This highlights the need for localised RM practices that address these specific challenges, emphasising the importance of adaptability and security measures in improving project outcomes for SME contractors in Sri Lanka.

4.2 FACTORS INFLUENCING RISK MANAGEMENT IN SME SECTOR

The interviews revealed several key factors influencing risk management in SME construction projects in Sri Lanka. Economic stability and government policies, including taxes and regulatory changes, were highlighted as significant risk influencers. Additionally, factors such as changing weather conditions, unexpected local or global catastrophes, management style, and lack of formal education among management were noted. Issues related to the lack of permanent staff and inadequate allocation for preliminary items in bills of quantities were also identified.

A total of nine factors were summarized from the above interviews and ranked using the weighted average based on a Likert scale. The survey results with analysed findings are demonstrated below in table 4.

Table 4: Impact of factors influencing risk in SME contractors in Sri Lanka.

No	Item Code	Description	Negligible	Minor	Moderate	Significant	Severe	Weighted Average (WA)	Rank
	Weighted marks		0.1	0.2	0.3	0.4	0.5		
01	EFI1	Economic instability of the country.	0	0	2	11	22	10.67	**3**
02	EFI2	Government policies on taxes	0	0	4	12	19	10.33	**5**

No	Item Code	Description	Negligible	Minor	Moderate	Significant	Severe	Weighted Average (WA)	Rank
	Weighted marks		0.1	0.2	0.3	0.4	0.5		
		and other changes in legislation.							
03	EFI3	Changing weather conditions.	0	0	15	18	2	8.47	**9**
04	EFI4	Unexpected local and global catastrophes.	0	0	15	8	12	9.13	**7**
05	EFI5	Management style and policy decision taken by organisation.	0	0	15	15	5	8.67	**8**
06	EFI6	Lack of education in organisation management.	0	0	0	10	25	11	**2**
07	EFI7	Most of the contractors are only experienced based.	0	0	0	6	29	11.27	**1**
08	EFI8	Not having permanent staff to carry out work of the organisation.	0	0	0	19	16	10.40	**4**
09	EFI9	Not allocating sufficient preliminary items to maintain head offices.	0	0	3	20	12	9.93	**6**

The subsequent questionnaire survey supported interview findings. The survey revealed that "integration of experience with formal risk management training" emerged as the most influential factor, with a weighted average (WA) of 11.27. This was followed by "lack of education in organisational management" (WA 11.00) and "economic instability" (WA 10.67). Factors such as "changing weather conditions" and "unexpected catastrophes" were less impactful, reflected in their lower WA scores.

Unique to the Sri Lankan context, the prominence of experience over formal education in managing construction risks stands out, contrasting with global literature. While Virglerova et al. (2016) highlighted financial issues as a primary risk factor for SMEs, the survey results indicate that experience and gaps in education were more critical in Sri Lanka. This underscores the need for targeted risk management practices that address local educational deficiencies and emphasise the integration of practical experience with formal risk management training in SME construction projects.

4.3 BARRIERS TO IMPLEMENT RISK MANAGEMENT AMONG SME CONTRACTORS

The data analysis of barriers to implementing RM practices among SME contractors in Sri Lanka reveals several critical insights. From the expert interviews, key barriers identified include a strong resistance to change due to outdated procedures, a lack of awareness regarding RM practices, and insufficient budget allocations for RM.

Interviewees noted that limited time and financial constraints significantly hinder RM implementation, with one expert emphasising that many SMEs lack the resources to maintain permanent staff or invest in effective RM practices.

When it comes to barrier of implementing RM practices among SME contractors in Sri Lanka, fifteen different factors were identified throughout the expert interview findings and literature review findings. All the respondents were asked to rate their opinion on these identified barriers considering the impact of these barriers to implement RM practices considering the Sri Lanka context. The findings with regard to barriers are presented in table 5 below.

Table 5: Barriers to implementing risk management among SME contractors.

Code	Description	Negligible	Minor	Moderate	Significant	Severe	Weighted Average (WA)	Rank
	Weighted marks	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**		
EBI1	Competition among SMEs	0	0	8	19	8	9.33	**10**
EBI2	Complexity of analytical tools	0	5	12	18	0	7.87	**14**
EBI3	Lack of potential benefits	0	3	22	8	2	7.60	**15**
EBI4	Lack of budget	0	0	2	13	20	10.53	**6**
EBI5	Lack of government legislation	0	0	9	18	8	9.27	**12**
EBI6	Lack of manpower	0	0	2	9	24	10.80	**5**
EBI7	Lack of time	0	0	0	10	25	11.00	**4**
EBI8	Low profit margin	0	0	6	11	18	10.13	**9**
EBI9	Not economical to implement	0	0	22	11	2	8.00	**13**
EBI10	Unawareness of available practices	0	0	0	0	35	11.67	**1**
EBI11	Not adding cost requirement needed for implement RM	0	0	0	8	27	11.13	**3**
EBI12	Not maintaining permanent staff	0	0	3	16	16	10.20	**7**
EBI13	Not keeping records on past projects	0	0	4	27	4	9.33	**10**
EBI14	Keeping the same outdated procedures	0	0	0	3	32	11.47	**2**
EBI15	Resistance for change to new systems	0	0	8	6	21	10.20	**7**

The questionnaire survey reinforced these findings, highlighting that "unawareness of available practices" emerged as the most severe barrier, with a weighted average (WA) of 11.67. This was followed by "keeping same outdated procedures" (WA 11.47) and "not adding cost requirements needed to implement RM" (WA 11.13). Notably, the survey revealed that "unawareness of available practices" was more critical in the Sri Lankan context than in existing literature, which often emphasizes financial constraints and time limitations. For instance, while El-Sayegh (2014) and Hwang et al. (2014) identify low managerial understanding and lack of time as significant barriers, the Sri Lankan data suggests that the lack of awareness and resistance to updating outdated practices are more pressing issues.

These findings indicate that RM implementation challenges in Sri Lanka are uniquely influenced by a lack of awareness and outdated procedures, suggesting the need for targeted educational initiatives and cultural shifts within SMEs to overcome these barriers.

5. CONCLUSIONS

This research investigates RM practices in Sri Lanka's SME construction sector, focusing on key issues, enablers, and barriers. The study's objectives were to identify challenges facing SME contractors, factors facilitating RM adoption, and obstacles to implementing these practices. Using a mixed-method approach, including expert interviews and a questionnaire survey, the study found that economic instability, lack of management education, and reliance on experience-based practices significantly impact RM.

The survey identified "unawareness of available practices" and "adherence to outdated procedures" as critical barriers, with weighted averages of 11.67 and 11.47, respectively. Unique to the Sri Lankan context, the study found that sudden regulatory changes and high rates of equipment theft pose significant risks, contrasting with global studies that often emphasise financial constraints and time limitations as primary challenges. This research underscores the importance of awareness and procedural updates, particularly in a sector where experience often outweighs formal education in managing construction risks.

The study's implications are broad: for practitioners, it underscores the necessity of targeted RM training and awareness initiatives to bridge knowledge gaps; for academics, it offers a foundation for further exploration of the unique challenges faced by SMEs in developing countries; and for policymakers, it highlights the need for stable regulations and incentives to encourage RM adoption. The study's limitations include a relatively small sample size and a focus on Sri Lankan SMEs, limiting broader applicability. Future research should consider RM practices in diverse contexts, including larger firms and other developing nations, to provide a more comprehensive understanding of global RM challenges and solutions. Overall, this research offers critical insights into the RM practices of Sri Lanka's SME construction sector, emphasising the need for tailored strategies to enhance RM adoption and resilience.

6. REFERENCES

Abourizk, S., & Mohamed, Y. (2002). Optimal construction project planning. *Proceedings of the winter simulation conference, San Diego, USA* (pp. 1704-1708). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/WSC.2002.1166454

Asiedu, R. O., & Adaku, E. (2019). Cost overruns of public sector construction projects: A developing country perspective. *International Journal of Managing Projects in Business, 13*(1), 66–84. https://doi.org/10.1108/IJMPB-09-2018-0177

Bahamid, R. A., Doh, S. I., & Al-Sharaf, M. A. (2019). Risk factors affecting the construction projects in the developing countries. *IOP conference series: Earth and environmental science*, *Kuantan, Malaysia*, 17–18 August 2018. IOP Publishing Ltd. https://doi.org/10.1088/1755-1315/244/1/012040

Bajo, J., Borrajo, M. L., De Paz, J. F., Corchado, J. M., & Pellicer, M. A. (2012). A multi-agent system for web-based risk management in small and medium business. *Expert Systems with Applications*, *39*(8), 6921–6931. https://doi.org/10.1016/J.ESWA.2012.01.001

Basit, T. N. (2010). Manual or electronic? The role of coding in qualitative data analysis. *Educational Research*, *45*(2), 143–154. https://doi.org/10.1080/0013188032000133548

Bazeley, P. (2002). The evolution of a project involving an integrated analysis of structured qualitative and quantitative data: From N3 to NVivo. *International Journal of Social Research Methodology*, *5*(3), 229–243. https://doi.org/10.1080/13645570210146285

Brown, A., & Adams, J. (2000). Measuring the effect of project management on construction outputs: A new approach. *International Journal of Project Management*, *18*(5), 327–335. https://doi.org/10.1016/S0263-7863(99)00026-5

Burla, L., Knierim, B., Barth, J., Liewald, K., Duetz, M., & Abel, T. (2008). From text to codings: Intercoder reliability assessment in qualitative content analysis. *Nursing Research*, *57*(2), 113–117. https://doi.org/10.1097/01.NNR.0000313482.33917.7D

Carr, V., & Tah, J. H. M. (2001). A fuzzy approach to construction project risk assessment and analysis: Construction project risk management system. *Advances in Engineering Software*, *32*(10–11), 847–857. https://doi.org/10.1016/S0965-9978(01)00036-9

de Araújo Lima, P. F., Crema, M., & Verbano, C. (2020). Risk management in SMEs: A systematic literature review and future directions. *European Management Journal*, *38*(1), 78–94. https://doi.org/10.1016/J.EMJ.2019.06.005

Egbu, C. O. (2000). Knowledge management in construction SMEs: Coping with the issues of structure, culture, commitment and motivation. In A. Akintoye (Ed.), *ARCOM Sixteenth Annual Conference, Glasgow, UK*, 6-8 September 2000. (pp. 83–92) Association of Researchers in Construction Management

El-Sayegh, S. M. (2014). Project risk management practices in the UAE construction industry. *International Journal of Project Organisation and Management (IJPOM)*, *6*(1–2), 121–137. https://doi.org/10.1504/IJPOM.2014.059748

Eyiah, A. K., & Cook, P. (2010). Financing small and medium-scale contractors in developing countries: A Ghana case study. *Construction Management and Economics*, *21*(4), 357–367. https://doi.org/10.1080/0144619032000111241

Falkner, E. M., & Hiebl, M. R. W. (2015). Risk management in SMEs: A systematic review of available evidence. *Journal of Risk Finance*, *16*(2), 122–144. https://doi.org/10.1108/JRF-06-2014-0079/FULL/PDF

Ferreira de Araújo Lima, P., Marcelino-Sadaba, S., & Verbano, C. (2021). Successful implementation of project risk management in small and medium enterprises: A cross-case analysis. *International Journal of Managing Projects in Business*, 14(4), 1023–1045. https://doi.org/10.1108/IJMPB-06-2020-0203

Hwang, B. G., Zhao, X., & Toh, L. P. (2014). Risk management in small construction projects in Singapore: Status, barriers and impact. *International Journal of Project Management*, *32*(1), 116–124. https://doi.org/10.1016/J.IJPROMAN.2013.01.007

Kamau, C. G., & Mohamed, H. B. (2015). Efficacy of Monitoring and Evaluation Function in Achieving Project Success in Kenya: A Conceptual Framework. *Science Journal of Business and Management*, *3*(3), 82-94. https://doi.org/10.11648/j.sjbm.20150303.14

Kishan, P., Bhatt, R., & Bhavsar, J. J. (2014). A study of risk factors affecting building construction projects. *International Journal of Engineering Research & Technology*, *3*(12), 831–835. https://www.ijert.org/research/a-study-of-risk-factors-affecting-building-construction-projects-IJERTV3IS120480.pdf

Leopoulos, V. N., Kirytopoulos, K. A., & Malandrakis, C. (2007). Risk management for SMEs: Tools to use and how. *Production Planning & Control*, *17*(3), 322–332. https://doi.org/10.1080/09537280500285136

Lyons, T., & Skitmore, M. (2004). Project risk management in the Queensland engineering construction industry: A survey. *International Journal of Project Management*, *22*(1), 51–61. https://doi.org/10.1016/S0263-7863(03)00005-X

Makwana, A. H., & Pitroda, J. (2017). Factors affecting risk management for construction by analytic hierarchy process (Ahp). *Journal of Structural Technology*, *2*(1), 1-7. https://www.academia.edu/download/63295463/23 _20200513-38288-9sox04.pdf

Marcelino-Sádaba, S., Pérez-Ezcurdia, A., Lazcano, A. M. E,, & Villanueva, P. (2014). Project risk management methodology for small firms. *International Journal of Project Management*, *32*(2), 327–340. https://doi.org/10.1016/J.IJPROMAN.2013.05.009

Mok, K. Y., Shen, G. Q., & Yang, J. (2015). Stakeholder management studies in mega construction projects: A review and future directions. *International Journal of Project Management*, *33*(2), 446–457. https://doi.org/10.1016/J.IJPROMAN.2014.08.007

Nieto-Morote, A., & Ruz-Vila, F. (2011). A fuzzy approach to construction project risk assessment. *International Journal of Project Management*, *29*(2), 220–231. https://doi.org/10.1016/j.ijproman.2010.02.002

Olson, D. L., & Wu, D. D. (2010). A review of enterprise risk management in supply chain. *Kybernetes*, *39*(5), 694–706. https://doi.org/10.1108/03684921011043198

Perera, B. A. K. S., Rameezdeen, R., Chileshe, N., & Hosseini, M. R. (2014). Enhancing the effectiveness of risk management practices in Sri Lankan road construction projects: A Delphi approach. *International Journal of Construction Management*, *14*(1), 1–14. https://doi.org/10.1080/15623599.2013.875271

Philemon, E., Msomba, Z., Matiko, S., & Ramadhan, S. M. (2018). Identification of enabling factors for collaboration in management of risk in construction projects: A literature review. *International Journal of Engineering Research & Technology (IJERT)*, *7*(2), 152-159. https://doi.org/10.17577/IJERTV7IS020083

Rahman, A. B. A., & Omar, W. (2006). Issues and challenges in the implementation of industrialised building systems in Malaysia. *Proceedings of the 6th Asia-Pacific structural engineering and construction conference (APSEC 2006), Kuala Lumpur, Malaysia*, 5–6 September 2006. Universiti Teknologi Malaysia Institutional Repository. https://core.ac.uk/reader/11777300

Ranadewa, K. A. T. O., Sandanayake, Y. G., & Siriwardena, M. (2018). Enabling lean among small and medium enterprise (SME) contractors in Sri Lanka. *26th Annual conference of the international group for lean construction, Chennai, India* (pp. 392–401). International Group for Lean Construction. https://doi.org/10.24928/2018/0428

Raz, T., & Michael, E. (2001). Use and benefits of tools for project risk management. *International Journal of Project Management*, *19*(1), 9–17. https://doi.org/10.1016/S0263-7863(99)00036-8

Senevirathna, T. C., Peries, C. M., & Cooray, J. T. (2015). Factors affecting to neglect formal financing sources by the SMEs; With special reference to Badulla district. *Proceedings of the research symposium of Uva Wellassa University*, 29–30 January 2015. (pp. 44–46). Uva Wellassa University.

Serpell, A., Ferrada, X., Rubio, L., & Arauzo, S. (2015). Evaluating risk management practices in construction organizations. *Procedia - Social and Behavioral Sciences*, *194*, 201–210. https://doi.org/10.1016/J.SBSPRO.2015.06.135

Siraj, N. B., & Fayek, A. R. (2019). Risk identification and common risks in construction: Literature review and content analysis. *Journal of Construction Engineering and Management*, *145*(9), 03119004. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001685

Szymański, P. (2017). Risk management in construction projects. *Procedia Engineering*, *208*, 174–182. https://doi.org/10.1016/j.proeng.2017.11.036

Virglerova, Z., Kozubíkova, L., & Vojtovic, S. (2016). Influence of selected factors on financial risk management in SMEs in the Czech Republic. *Montenegrin Journal of Economics*, *12*(1), 21–36. https://doi.org/10.14254/1800-5845/2016.12-1.1

Wang, J., & Yuan, H. (2011). Factors affecting contractors' risk attitudes in construction projects: Case study from China. *International Journal of Project Management*, *29*(2), 209–219. https://doi.org/10.1016/J.IJPROMAN.2010.02.006

Xia, N., Zou, P. X. W., Griffin, M. A., Wang, X., & Zhong, R. (2018). Towards integrating construction risk management and stakeholder management: A systematic literature review and future research agendas. *International Journal of Project Management*, *36*(5), 701–715. https://doi.org/10.1016/j.ijproman.2018.03.006

Zou, P. X. W., Zhang, G., & Wang, J. (2007). Understanding the key risks in construction projects in China. *International Journal of Project Management*, *25*(6), 601–614. https://doi.org/10.1016/J.IJPROMAN.2007.03.001

Mannapperuma, M.M.N., Disaratna, P.A.P.V.D.S. and Illeperuma, I.E., 2024. Role of micro-housing in fulfilling middle-income housing demand in urban areas: Sri Lankan perspective. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 904-916. DOI: https://doi.org/10.31705/WCS.2024.72. Available from: https://ciobwcs.com/papers/

ROLE OF MICRO-HOUSING IN FULFILLING MIDDLE-INCOME HOUSING DEMAND IN URBAN AREAS: SRI LANKAN PERSPECTIVE

M.M.N. Mannapperuma[1], P.A.P.V.D.S. Disaratna[2], and I.E. Illeperuma[3]

ABSTRACT

Urbanisation and population growth challenge the housing market in urban areas globally. The unavailability of sufficient lands, limited housing spaces, high demand and high housing prices caused housing unaffordability. Consequently, micro-living has been successfully implemented in high-density urban areas worldwide to address housing unaffordability. In Sri Lanka, middle-income households in Colombo are the most vulnerable to housing unaffordability. Accordingly, this research aimed to investigate the suitability of micro-housing to address the issues in middle-income households in Colombo, Sri Lanka. The aim was accomplished through a qualitative approach by collecting data through expert interviews and analysing through content analysis with manual coding. Findings revealed the unavailability of land and high land prices as the major challenges faced by the middle-income housing market in Colombo. Importantly, the findings acknowledged Micro Houses (MHs) and Micro Apartments (MAs) as affordable housing options that effectively address the issues. The demand and the social acceptance of MHs and MAs in Colombo are led by two middle-income groups i.e. (i) youngsters, and (ii) elderly retirees. Herein, ease of maintenance and willingness to modernise were the main positive perceptions. In contrast, limited space and usage of foldable furniture cause negative perceptions. Construction and operation costs of MHs and MAs can be lowered by maximising natural lighting and ventilation and minimising material wastage. However, operational costs will not be changed considerably. Nonetheless, prevailing building codes and regulations barrier the implementation of micro-living in Colombo.

Keywords: *Micro Apartment; Micro House; Middle-Income Housing; Unaffordability; Urbanisation.*

1. INTRODUCTION

Housing fulfils the fundamental human need for shelter (Karunasena & Ranatunga, 2009; Niriella, 2017). Ruonavaara (2018) described housing as a tangible good which can be produced or purchased, consumed, and sold or demolished. Recently, it has become more than a place of living, yet a sense of dignity and community engagement. Purchasing a

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, nwjmnp@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, vijithad@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurii@uom.lk

house is not as simple as purchasing other consumable goods. Some are willing to have one house for their entire lifetime, whereas others tend to purchase several houses during different phases of life. The decision to purchase or build a house is affected by diverse factors which are often connected with economic concerns and personal preferences (Ariyawansa, 2010). Economic concerns are formed by purchasing power (cost or price compared to income or other expenses), spending patterns (lease, rent, loan facilities, etc.), the lifespan of the product, and other factors that affect the price such as discount, allowances, payment period, etc. On the other hand, personal preferences are moulded by age, gender, educational background, occupation, social life, and other behavioural factors (Ariyawansa, 2010). During the past decades, a wide variety of housing options from tents to luxury villas, slums to luxury condominium properties and immovable to movable houses have emerged to satisfy varying customer requirements.

The population in urban areas exceeded 3.6 billion which is more than 54% of the global population in 2011 (Boeckermann et al., 2019). It is estimated to be 6.3 billion by 2050 (United Nations, 2011). Urbanisation and population growth challenge the housing market. Consequently, unavailability of sufficient land, limited housing spaces, high demand and high housing prices emerged in urban cities around the world. Consequently, housing unaffordability emerged as a critical issue especially among the middle-income class in Colombo, Sri Lanka (Kariyawasam et al. 2022). Economists define the middle-income class using the parameters of income or consumption (Shanthaarchch, 2022). On one hand, Bhalla (2021) as cited in Shanthaarchch, (2022, p.4) defined the middle-income class *"to be those earning more than US$ 3,658 (in 2020 prices) a year or US$ 10 a day in purchasing power parity terms".* Conversely, Kharas and Gertz (2020, p.3) defined middle-income class *"as those households with daily expenditure between US$ 10 and US$ 100 per person per day in purchasing parity terms*". Being specific to the Sri Lankan context, Shanthaarchch, (2022, p.4) defined the middle-income class as *"individuals living in households, spending $2 to $10 (not including $10)"*. Further to the authors, in 2010, 75.2% of Sri Lankans belonged to the middle-income class. However, it decreased significantly due to the economic crisis and was reported as 48% in 2021 (*World Bank Group*, 2021). The Sri Lankan middle-income class suffers from the aforementioned housing issues frequently due to their modest income.

Micro Houses (MHs) which are designed to provide the necessities of living while minimising space usage can address a wide range of housing requirements across various demographics. Researchers have categorised MHs into two main categories i.e. (i) MHs on Wheels (MHOW), and (ii) MHs on Foundations (MHOF) whereas MHOF can be further categorised as semi-permanent or permanent (Shearer, 2018). However, micro-living is not limited to detached houses (Renn & Armlovich, 2016). MHs are detached establishments that usually range between 100–400 ft^2 (6–37 m^2) (Brokenshire, 2019; Brown, 2016; Kilman, 2016; Mutter, 2013; Shearer, 2019; Zhang et al., 2022). Additionally, literature identified Micro Apartments (MAs) which are conjoined establishments usually less than 215 ft^2 (20 m^2) in floor area (Mutter, 2013). However, this study focused on permanent MHOF. Even though the origin of the micro-housing movement was in the late 1990s in the United States of America (USA) (Shearer, 2015, 2019), it has been in demand recently due to affordability, simplicity, and sustainability (Brokenshire, 2019). Indeed, MHs and MAs offer limited living space prompting occupants to possess fewer material belongings and reduce consumerism. Consequently, they reported a rising popularity among people with middle to lower income (Brown, 2016; Mutter, 2013; Shearer, 2015). Particularly, it has become popular among young individuals, couples, and retirees with middle income (Zhang et al., 2022).

Colombo is the commercial capital of Sri Lanka and the most densely populated area (Ariyawansa, 2009). By the year 2018, the total population of Sri Lanka was 21.80 million whereas in Colombo it was 6.15 million which accounted for nearly 30% of the total population (Economics and Social Statistics of Sri Lanka, 2020). Importantly, Colombo is the most active and significant region in Sri Lanka in socioeconomic, political, and administrative aspects. Consequently, Colombo is facing a continuous escalation of housing demand especially in the Middle-Income Housing Market (MIHM) whose contribution is significant to the economic development (Rathnayaka et al., 2020). However, the housing market faces severe challenges in providing quality and affordable housing to meet the growing demand (Munmulla et al., 2023). Researchers highlighted the burning issues such as poor maintenance, illegal modifications, compacted spaces, inefficient arrangements, and neighbourhood disturbances (Ariyawansa & Perera, 2018). Further, Kariyawasam et al. (2022) emphasised that higher market prices restrict the affordability of quality housing in the middle-income society in Colombo. The aforementioned facts make consumer satisfaction with middle-income housing in Colombo questionable (Rathnayaka et al., 2020). Researchers have taken several noteworthy steps to investigate the use of MHs in addressing housing-related issues in Sri Lanka. Herein, Natasha (2023) explored the tendency of lower income society in Sri Lanka towards MHs. Munmulla et al. (2023) highlighted the economic viability of MHs via a comparative study between a modular construction MH and a conventional house. However, less research has been conducted in investigating the use of MHs in the middle-income society of Sri Lanka. Accordingly, this research aimed to investigate the suitability of permanent detached MHOF and MAs to address the issues in MIHM in Colombo, Sri Lanka. Hereafter, to avoid the convoluted language the term MHs referred to the permanent detached MHOF. The research has two objectives, i.e. (i) study the status of the MIHM in Colombo, Sri Lanka, and (ii) investigate the ability of MHs and MAs to address the issues in the MIHM in Colombo, Sri Lanka.

2. LITERATURE REVIEW

2.1 MIDDLE-INCOME HOUSING MARKET IN URBAN AREAS

The ancient practice of housing with mud, charcoal and leaves gradually changed with the evolution of the social economy (Jayasooriya, 2003). According to the author, the evolution resulted in rapid changes in the needs and behavioural patterns of the people. Subsequently, diverse architectural features were incorporated into Sri Lankan houses during the colonisation period (Edirisinghe, 2014).

The rapid population growth and urbanisation constantly escalate the demand for the MIHM in urban areas. More than half of the global population is now residents in cities, which occupy only 2% to 3% of Earth's land area (Hemakumara & Rainis, 2018). According to the United Nations (2022), urban areas will hold 68% of the world's population by 2050. Similarly, Colombo, Sri Lanka has attracted a large population who are seeking better standards of living, employment, and education (Ariyawansa & Perera, 2018; Rathnayaka et al., 2020). In 2018, the population of Sri Lanka was 21.80 million, and in Colombo, it was 6.15 million which was 28.21% (Economics and Social Statistics of Sri Lanka, 2020). According to the United Nations (2022) projections, the Sri Lankan population will exceed 22 million by 2030 while the Colombo region will hold 7 million.

Government policies play an important role in the MIHM. However, in the Sri Lankan context, the MIHM in urban areas is ill-treated by government policies (Niriella, 2017; Wickramaarachchi et al., 2021). According to Samaratunga and O' Hare (2013), the focus of government policies is mainly on the high-rise high-density low-income public housing in Colombo. Moreover, developers are struggling to put sustainable housing options into practice due to constantly changing government regulations including building codes, zoning regulations, national rules, ordinances, and council rules (Kariyawasam et al., 2022). For instance, Urban Development Authority (UDA) Law, No. 41 of 1978 had been amended by parliament acts in 1979, 1982, 1984, 1987, and 1988 further, gazettes have been issued from 1978 and the latest gazette on UDA Law, No. 41 of 1978 was issued on 17th November in 2022 (Urban Development Authority [UDA], 2024). In addition, housing affordability is highly affected by purchasing power (Adabre & Chan, 2019; Hemakumara & Rainis, 2018; Jackson et al., 2020; Jayalath & Gunawardhana, 2017; Stone, 2006). Accordingly, rising housing prices, high construction costs, high interest rates, and limited supply are the key influencing factors of housing unaffordability (Leindecker & Kugfarth, 2019).

Figure 1 was developed based on the findings of several previous studies to provide an overview of the factors that influence housing unaffordability in the MIHM and the related implications.

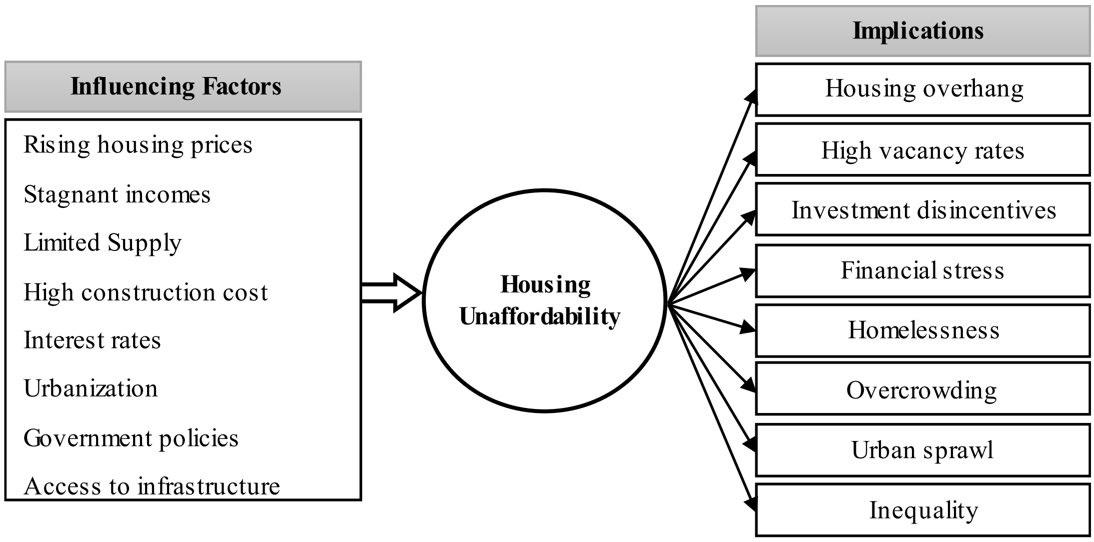


Figure 1: Factors that influence housing unaffordability and their implications

Sources: (Adabre & Chan, 2019; Hemakumara & Rainis, 2018; Jackson et al., 2020; Jayalath & Gunawardhana, 2017; Kariyawasam et al., 2022; Samaratunga & O' Hare, 2013)

Housing unaffordability causes housing overhang, a situation where there is an oversupply of housing, leading to high vacancy rates due to the inability to afford it (Adabre & Chan, 2019). It negatively affects housing investments, and causes homelessness and overcrowding (Hemakumara & Rainis, 2018). Consequently, people are forced to move to cheap places or suburban areas, leading to urban sprawl (Hemakumara & Rainis, 2018). Ultimately, housing prices increase while the supply of affordable housing options is limited for the middle-income class in urban areas.

Due to the aforementioned factors most of the detached houses in Colombo have been currently shifted into in-built amenities in apartment buildings (Dunuwila & Devapriya, 2022; Jayalath & Gunawardhana, 2017). However, most of the apartments in Colombo fall into the luxury or semi-luxury category challenging the affordability of the middle-income population (Jayalath & Gunawardhana, 2017). Besides, researchers revealed that, in Sri Lanka, 10% of the residents spend not less than 50% of their monthly income on housing (Weeraratne, 2020). Importantly, Musa et al. (2015) contended that developers are less enthusiastic about low to medium-cost housing projects. Nonetheless, Jayalath and Gunawardhana (2017) explored an increasing demand for apartments among middle incomers due to the escalated land price. However, most of the middle-income population living in urban areas of developing countries reside in temporary accommodations with low security, inadequate infrastructure, and serious health issues (Ariyawansa & Perera, 2018; Musa et al., 2015).

Thus, MIHM in urban areas faces significant challenges due to the aforementioned demographic and economic factors (Dash & Das, 2020). Consequently, providing affordable housing for middle incomers who meet the required standards of living is a crucial problem in Colombo (Kariyawasam et al., 2022; Rathnayaka et al., 2020).

2.2 MICRO HOUSES AND MICRO APARTMENTS

MHs and MAs consist of a spacious room integrating the kitchen, dining area, and living room, a small bathroom near the kitchen with all the facilities, and sleeping lofts with ladders for the maximum utilisation of vertical spaces (Kilman, 2016). Initially, MHs and MAs became popular due to their simplicity and later catalysed as an effective solution for housing unaffordability (Shearer et al., 2019). Consequently, it is a growing concept particularly in the USA, Canada, New Zealand, and Australia who experience severe housing unaffordability (Shearer et al., 2019). Particularly, MHs become famous among retirees, youngsters, couples, and small families who identified the effectiveness and efficiency of micro-living (Dash & Das, 2020; Mutter, 2013; Renn & Armlovich, 2016; Shearer, 2018). In highly-demand real estate markets such as Tokyo, San Francisco, New York, Singapore, and Hong Kong MAs have increasing demand, particularly among young professionals (Dash & Das, 2020; Gazdag & Torlegård, 2018). For instance, a rental apartment named ‘My Micro NY’ by nARCHITECTS in New York and a rental apartment series named ‘Kyosho Jutaku’ by Yasuhiro Yamashita in Japan incorporated MAs in highly populated areas thereby redefined living in small. ‘My Micro NY’ comprises 55 apartment units of 260 ft^2 in nine stories (Arcilla, 2015). Figure 2 shows the arrangement of an apartment of ‘My Micro NY’ and Figure 3 illustrates how it is arranged for day use and night use by folding the convertible sofa to a bed. A ‘Kyosho Jutaku’ complex comprises more than 300 apartment units starting from 182 ft^2.

Accordingly, MHs and MAs provide affordable low-rise and medium-rise housing options by regulating per-capita housing costs in expensive urban areas (Renn & Armlovich, 2016; Shearer, 2018). Further, Rack (2016) introduced the concept of “small space, big city” describing the opportunity offered by MAs to reside in urban areas with all the facilities for a lower monthly rent compared to other housing options. Moreover, MAs are acknowledged as the most appropriate housing option for densely populated urban areas with a high demand for housing (Gazdag & Torlegård, 2018).

Figure 2: View of an apartment in 'My Micro NY'

Source: (Arcilla, 2015)

Figure 3: Day use of the apartment (above) and night use of the apartment (below)

Source: (Arcilla, 2015)

Even though, MHs and MAs have been widely acknowledged globally as an unconventional approach to broadening the boundaries of middle-income housing affordability in urban areas (Dash & Das, 2020; Keable, 2017), their applications are limited in Sri Lanka.

3. RESEARCH METHODOLOGY

Qualitative research focuses on phenomena related to kind and quality which explore the reasons for human behaviours and discover motives and desires through in-depth interviews (Kothari, 2004). Accordingly, a qualitative approach was adopted to accomplish the research aim. Initially, a comprehensive literature review was conducted to understand the MIHM in urban areas and the primary reasons behind the housing unaffordability. Additionally, it perceives the potential of MHs and MAs to address housing unaffordability in urban areas.

Subsequently, expert interviews were selected as the research strategy to explore the MIHM in Colombo and the use of MHs and MAs to overcome the challenges. Using the purposive sampling method, twelve experts were selected based on their experience, knowledge and expertise in the Sri Lankan housing market, MHs and MAs. Accordingly, the sample consisted of five quantity surveyors, five architects, and two marketing directors. Table 1 presents the profiles of the interviewees.

Table 1: Details of the expert interviewees

Respondent	Current Designation	Current working sector	Experience in housing construction	Qualifications			
				BSc.	MSc.	PhD	Ch.
E1	QS	Consultant	10 years	√	√		√
E2	Director (QS)	Consultant	31 years	√	√		
E3	Chief QS	Client	10 years	√	√		
E4	QS	Client	9 years	√	√		
E5	General Manager (QS)	Contractor	18 years	√	√		√
E6	Chief Architect	Consultant	27 years	√	√		√
E7	Professor/ Architect	Consultant	29 years	√	√	√	√
E8	Professor/ Architect	Consultant	49 years	√	√	√	√
E9	Assistant Director (Architect)	Client	20 years	√	√		√
E10	Architect	Consultant	25 years	√	√	√	√
E11	Executive Director (Marketing)	Client	25 years	√	√		
E12	Marketing Director	Contractor	28 years	√	√	√	

Paradis et. al. (2016) asserts that interviewing is a two-way method that examines the known data and shares knowledge. Accordingly, semi-structured interviews were conducted with the selected experts to collect the data. A document on micro living was prepared to brief the concept and to explain the aim, objectives and scope of the study to the interviewees. Interviewees were questioned under four major sections. In the first section, the interviewee's background details were inquired. The second section focused on the current status of the Sri Lankan housing market to explore the current trends and challenges whereas the third section focused on assessing the viability of MHs and MAs as a solution for identified issues in the MIHM. In the last section, the perception of the middle-income class in Colombo towards micro-living was focused on discerning the acceptance of micro-living by MIHM. Additionally, situational questions were raised to clarify and explore the details further. Finally, collected data were analysed by data reducing and displaying through content analysis with manual coding.

4. RESEARCH FINDINGS AND DISCUSSION

4.1 CURRENT STATUS OF THE COLOMBO MIDDLE-INCOME HOUSING MARKET

The second section of the interview guideline focused on the current status of the MIHM in Colombo. The Sri Lankan MIHM experienced several trends concerning demand, supply, social conditions, and economic conditions over the last decades. Conforming the findings of Dunuwila and Devapriya (2022) and Jayalath and Gunawardhana (2017) regarding the increasing demand for apartments, all the interviewees highlighted the trend towards apartments in Colombo in the last decade. Moreover, E5 specified that "*there are two trends in apartments i.e. (i) as a second home, and (ii) as an elderly home*". As per E1, E2, E3, E4, E5, E7, E9 and E10, the main reason for the higher demand is the higher land prices and scarcity of lands. Further, E3 indicated that "*the trend towards apartment is driven by the easy maintenance, convenient life with facilities, flexibility, safety and security, modern amenities and services, simple living and the sense of community*". However, the contribution of the middle-income class for the increased demand is less compared to that of the higher income class. In fact, E5 said that "*approximately 90% of* *the luxury and semi-luxury apartments are already occupied and new projects of similar kind are being initiated even with the prevailing economic crisis*". E3 recognised unaffordability as the underlying cause of the lower demand of the middle-income class. Additionally, E9 emphasised reasons behind the decreased demand of middle-income society as external migration and the change of the priority of needs with the stagnant income. In brief, there is an upward trend in the demand for apartments in Colombo, however, high price/rent restricts the demand of the middle-income society.

All the interviewees identified the unavailability of land and high land prices as the major challenges faced by the MIHM in Colombo. Additionally, E1 mentioned that "*construction cost gets doubled with the inflation, tax provisions and other government policies such as import restrictions*". According to E9, the exaggerated prices cause owning a house to be no longer considered a necessity by the middle-income society.

4.2 MICRO HOUSES AND MICRO APARTMENTS AS OPTIONS IN THE MIDDLE-INCOME HOUSING MARKET IN COLOMBO

The third section of the interview focused on the MHs and MAs as solutions for the identified challenges in the MIHM in Colombo. As the initiation, the interviewees' experience in the MHs and MAs construction projects was examined. According to the responses all the interviewees were involved in MHs and MAs construction projects. However, some of those projects were not termed as MHs or MAs even though they align with the definition. Most of the interviewees acknowledged MHs and MAs as affordable housing options for the MIHM in Colombo whereas E10 believed that MHs are not suitable and stated that "*even low incomers will not be satisfied with these sizes*".

Construction cost is a primary factor that determines the cost/price of a house. E1, E2, E3, E4, and E5 stated that the total construction cost of an MH or MA is lower compared to a conventional house or apartment. However, Shearer (2015, 2018, 2019) repeatedly highlighted the higher cost per m^2 of an MH compared to a conventional house. Confirming that E3, E4, and E5 noted higher cost per unit floor area of MH or MA and explained the reason as the cost significant items such as sanitary fittings and finishes are divided among a small floor area. However, E3 and E5 focused on smaller-scale MA projects highlighting the shorter construction period and use of less advanced technologies. By implementing it on a smaller scale, the construction cost of MAs can be lowered compared to conventional apartments. Furthermore, the construction cost of an MA is lower compared to a luxury or semi-luxury apartment due to the reduced size. Similarly, interviewees suggested using natural light and natural ventilation and minimising material wastage to promote sustainability and reduce construction and operation costs. E3 and E4 stated that minimising wastage from the design is the most optimal way to achieve resource efficiency. Herein, E6 suggested designing the floor and ceiling areas based on the size of the tiles. However, operational costs will not be changed considerably in MHs or MAs as the capacity of the services is determined based on the number of occupants but not on the size of the house. Nonetheless, there may be a slight reduction in electricity costs due to the low number of lighting points in smaller areas.

Buildings play a vital role in urban aesthetics. Confirming, E9 noted that high-rise buildings and apartment complexes become an icon of Colombo without damaging the value of the city. *Thus, MAs will be fit* while enhancing urban aesthetics. Herein, E9 identified the significance of prioritising the changing needs of the country by stating that "*if we go with old patterns to protect the ancient look, we will remain as a developing* *country without any improvement*". Dunuwila and Devapriya (2022) discussed how Colombo's urban aesthetic has shifted to accommodate the growing need for urban living.

As identified in the literature, traditions and religions affect the housing designs in Sri Lanka. However, people who are keen on traditions have innovatively modified the activities to be suited to modern housing. Furthermore, interviewees noted that integrating culture into the MHs and MAs is not an issue. On the other hand, E5 mentioned that *"most of the middle-income society living in Colombo have been there for work or education and thus not highly focusing on cultural and social icons"*.

However, all the interviewees assuredly pointed out that prevailing building codes and regulations barrier the implementation of micro-living in Colombo. In Sri Lanka, residential construction should be in accordance with UDA Law, No. 41 of 1978. Accordingly, the minimum floor area of an apartment should be 400 ft^2. Further, apartments should follow the Apartment Ownership Law, No. 11 of 1973 and its amendments and should be approved by the Condominium Management Authority (CMA). However, MHs or MAs are not aligned with these regulations. Thus, E6 and E9 highlighted the requirement to change the regulations indicating the necessities.

4.3 ACCEPTANCE OF MICRO HOUSES AND MICRO APARTMENTS BY THE MIDDLE-INCOME SOCIETY IN COLOMBO

The fourth section of the interviews focused on the perception of the middle-income society in Colombo towards micro-living. All the interviewees mentioned that initial perception is primarily based on attitudes and personalities which change with time. Confirming the findings of Brown (2016), Kilman (2016) and Mutter (2013) regarding the acceptance of micro-living interviewees indicated that both MHs and MAs will be accepted by young individuals and couples with a middle-income while retirees are more likely to choose MAs. Herein, **E6** highlighted the willingness of the youngsters living in Colombo to have an easy and simple life. Additionally, **E6** emphasised the rising willingness of elders such as retirees having a middle income, to live in MAs as maintaining large houses alone is difficult for them. Most elders choose MAs over MHs as they want to be in a community. Nevertheless, **E2**, **E4**, **E7**, and **E11** stated that the acceptance of MAs as an affordable option by the Sri Lankans with the current inflation and economic crisis is questionable. In summary, the acceptance of MHs or MAs as an affordable housing option by the middle-income society in Colombo will depend on the perception towards simplicity, quality, ease of maintenance, and willingness to change.

Table 2 shows the perceptions of middle-income households in Colombo towards MHs and MAs in the view of experts. All the experts mentioned that initial perception towards anything is primarily based on the attitudes and personalities of people. However, it can be changed with time once they are experiencing it in real life. Eleven experts (91.6%) perceived the identification of MHs and MAs by MIHM for easy maintenance. In contrast, three experts (25%) identified 'reduced living cost' as a positive perception. Further, the positive perception towards MAs and MHs will be driven by affordability, simpler life, quality of living and interest in modernising. However, most experts identified the possibility of negative perception towards the limited space and usage of foldable furniture. Surprisingly, only one expert identified 'isolation' as a cause of negative perception towards MHs and MAs in the MIHM.

Table 2: Experts opinion on public perception towards adapting MHs and MAs to Colombo, Sri Lanka

No.	Idea on Public Perception	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
	Positive Perceptions												
a.	Affordability	√	-	√	-	√	√	-	-	√	√	-	√
b.	Simpler life	-	√	√	√	-	√	-	√	√	-	√	-
c.	Reduced living cost	-	-	√	√	-	-	-	√	-	-	-	-
d.	Quality of living	√	-	√	√	-	√	-	√	√	√	√	√
e.	Ease of maintenance	√	√	√	√	√	√	-	√	√	√	√	√
f.	Positive attitudes towards changing, adapting, modernizing, etc.	-	√	√	√	-	√	-	√	√	√	√	√
	Negative Perceptions												
a.	Isolation	-	-	√	-	-	-	-	-	-	-	-	-
b.	Lack of privacy	-	√	-	-	-	√	√	-	-	-	-	-
c.	Limited space	√	-	√	√	√	-	√	-	-	√	-	√
d.	Unfriendly furniture	√	√	-	√	-	-	√	-	√	√	√	√
e.	Reliance on social norms	√	-	-	-	-	-	√	-	-	√	√	√

5. CONCLUSIONS

Colombo MIHM is experiencing a continuous escalation of demand and facing severe challenges in providing quality and affordable housing. Poor maintenance, illegal modifications, compacted spaces, inefficient arrangements, and neighbourhood disturbances are the burning issues. Literature acknowledged micro-living as a viable solution for the said issues. MHs and MAs have been successfully implemented to overcome the housing issues in Canada, New Zealand, the USA, and Australia. However, it has not been sufficiently investigated in Sri Lanka. Thus, this research aimed to investigate the suitability of micro-housing in addressing the issues in the MIHM in Colombo, Sri Lanka. The aim was accomplished through a qualitative approach by collecting data through expert interviews and analysing through content analysis.

Findings revealed the unavailability of land and high land prices as the major challenges faced by the MIHM in Colombo. Additionally, inflation, tax provisions and import restrictions negatively impacted the MIHM. The exaggerated prices caused owning a house to be no longer considered a necessity by the middle-income society. Importantly, the findings acknowledged MHs and MAs as affordable housing options that effectively address the above issues. The construction cost of MAs can be lowered compared to conventional apartments by implementing them on a smaller scale. Construction and operation costs can be further lowered by maximising natural lighting and ventilation and minimising material wastage. However, operational costs will not be changed considerably in MHs or MAs as the capacity of the services is determined based on the number of occupants but not on the size of the house. Furthermore, integrating culture into the MHs and MAs is not a challenge. The demand and the social acceptance of MHs and MAs in Colombo are led by two major factors i.e., (i). the willingness of the middle-income younger generation living in Colombo to have an easy and simple life, and (ii). the willingness of middle-income elders living in Colombo such as retirees to be in a community while getting rid of maintaining large houses. Herein, ease of maintenance and willingness to modernise were identified as the main positive perceptions. In contrast, limited space and usage of foldable furniture cause negative perceptions. However, prevailing building codes and regulations barrier the implementation of micro-living in Colombo. In Sri Lanka, residential construction should be in accordance with UDA Law, No. 41 of 1978. Furthermore, apartments should follow the Apartment Ownership Law, No. 11 of 1973 and its amendments and should be approved by the CMA. However, MHs or MAs are not aligned with these regulations. Thus, it is crucial to amend the regulations to ensure the effective implementation of micro-living in Colombo.

This research is significant as it addresses a crucial issue of the country by shedding light on an emerging concept as a solution. However, this research was limited to the context of Colombo Sri Lanka and examined only the experts' opinions. Thus, future researchers are encouraged to expand the realm by studying the occupants' perspectives. Similarly, expanding the study beyond Colombo will be noteworthy. Furthermore, studying the legal infrastructure associated with MHs and MAs is essential.

6. REFERENCES

Arcilla, P. (2015, February 24). *New York to complete first prefabricated "micro-apartments" this yea*r. Arch Daily. https://www.archdaily.com/602157/new-york-to-complete-first-prefabricated-micro-apartments-this-summer?ad_campaign=normal-tag

Adabre, M. A., & Chan, A. P. C. (2019). The ends required to justify the means for sustainable affordable housing: A review on critical success criteria. *Sustainable Development 27*(4), 781-794. John Wiley and Sons Ltd. https://doi.org/10.1002/sd.1919

Ariyawansa, R. G. (2009). Demographic characteristics and planning challenges: The case of Colombo city. *Sri Lanka Journal of Population Studies*, *11*, 93–106. www.statistics.gov.lk

Ariyawansa, R. G. (2010). An empirical study of consumer behavior in the housing market in Colombo. *Built-Environment Sri Lanka*, *8*(1), 11–19. https://doi.org/10.4038/besl.v8i1.1906

Ariyawansa, R. G., & Perera, M. A. N. R. M. (2018). Socio-economic insight of the secondary housing market in Colombo suburbs: Seller's point of view. *World Academy of Science, Engineering and Technology International Journal of Architectural and Environmental Engineering*, *12*(10), 982–986. http://dr.lib.sjp.ac.lk/handle/123456789/7031

Boeckermann, L. M., Kaczynski, A. T., & King, S. B. (2019). Dreaming big and living small: Examining motivations and satisfaction in tiny house living. *Journal of Housing and the Built Environment*, *34*(1), 61–71. https://doi.org/10.1007/s10901-018-9616-3

Brokenshire, S. (2019). Tiny houses desirable or disruptive? *Australian Planner*, *55*(3), 226–231. https://doi.org/10.1080/07293682.2019.1634114

Brown, E. (2016). *Overcoming the barriers to micro-housing: Tiny houses, big potential*. University of Oregon. http://hdl.handle.net/1794/19948

Central Bank of Sri Lanka. (2020). *Economics and social statistics of Sri Lanka*. Central Bank of Sri Lanka, Statistics Department. https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/statistics/otherpub/ess_2020_e1.pdf

Dash, S. P., & Das, I. (2020). Feasibility of incorporating open spaces in the design of micro-apartments in residential environments. *PalArch's Journal of Archaeology of Egypt/ Egyptology*, *17*(9), 6915–6939. https://www.researchgate.net/publication/354674821

Dunuwila, S. R., & Devapriya, K. A. K. (2022). Analysis of the current housing market in Colombo metro region to enhance prospective consumer satisfaction. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (Eds.), *Proceedings of the 10th world construction symposium* (pp. 102-112). DOI: https://doi.org/10.31705/WCS.2022.9.Central Bank of Sri Lanka. (2020). *Economics and social statistics of Sri Lanka*. Central Bank of Sri Lanka, Statistics Department. https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/statistics/otherpub/ess_2020_e1.pdf

Edirisinghe, J. (2014). Revitalizing the built heritage for urban development: A case study on city of Colombo, Sri Lanka. *European Academic Research*, *2*(5), 6365–6397. https://www.researchgate.net/publication/283571520

Gazdag, N., & Torlegård, A. (2018). *Micro-apartments: A potential solution for the severe shortage of small affordable apartments in Stockholm* [Unpublished master's theses]. University of Stockholm.

Hemakumara, G., & Rainis, R. (2018). Spatial behaviour modelling of unauthorised housing in Colombo, Sri Lanka. *Kemanusiaan*, *25*(2), 91–107. https://doi.org/10.21315/kajh2018.25.2.5

Jackson, A., Callea, B., Stampar, N., Sanders, A., Rios, A. D. L., & Pierce, J. (2020). Exploring tiny homes as an affordable housing strategy to ameliorate homelessness: A case study of the dwellings in Tallahassee, FL. *International Journal of Environmental Research and Public Health*, *17*(2), 661. https://doi.org/10.3390/ijerph17020661

Jayalath, A., & Gunawardhana, T. (2017). Towards sustainable constructions: Trends in Sri Lankan construction industry-A review. *International Conference on Real Estate Management and Valuation*, Sri Lanka. 137–143. https://www.researchgate.net/publication/320907730

Jayasooriya J.A.D.C.K. (2003). *A study of the relationship between house form and behaviour pattern of people within their socio-economic background in Sri Lanka* [Unpublished master's theses]. University of Moratuwa.

Kariyawasam, T. D., Wickramaarachchi, N. C., Udawatthe, C., & Weerakoon, K. G. P. K. (2022). *Sustainable housing for middle-income society in Sri Lanka*. International Conference on Real Estate Management and Valuation, Sri Lanka. https://doi.org/10.31357/icremv.v6.6236

Karunasena, G., & Ranatunga, D. S. (2009). *Customer satisfaction of residential condominiums in the Colombo city: Developers' perspective*. Proceedings of international conference on business management, *6*, 202–209. https://www.researchgate.net/publication/324497003

Keable, E. (2017). Building on the tiny house movement: A viable solution to meet affordable housing needs. *University of St. Thomas Journal of Law and Public Policy*, *11*(2), 111. http://www.jchs.harvard.edu/sites/jchs.harvard.edu/files/jchs_2016_state_of_the_n

Kharas, H., & Gertz, G. (2020). The New Global Middle Class: A Cross-Over from West to East. In H. Kharas, & G. Gertz, *China's Emerging Middle Class: Beyond Economic Transformation*. Washington: Brookings Institution Press.

Kilman, C. (2016). Small house, big impact: The effect of tiny houses on community and environment. *Undergraduate Journal of Humanistic Studies*, *2*. http://tinyhousecommunity.com/faq.htm.

Kothari, C. R. (2004). *Research methodology: Methods and techniques* (2nd ed.). New Age International (Pvt) Ltd, Publishers.

Leindecker, H. C., & Kugfarth, D. R. (2019). Mobile tiny houses - sustainable and affordable? *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012010. https://doi.org/10.1088/1755-1315/323/1/012010

Munmulla, T., Hidallana-Gamage, H. D., Navaratnam, S., Ponnampalam, T., Zhang, G., & Jayasinghe, T. (2023). Suitability of modular technology for house construction in Sri Lanka: A survey and a case study. *Buildings*, *13*(10). 2592. https://doi.org/10.3390/buildings13102592

Musa, A. R., Tawil, N. M., Ani, A. I. C., & Basri, H. (2015). An analysis of the selection criteria in purchasing a house in Klang Valley towards the quality affordable housing. *Life Science Journal*, *12*(3), 51–57. http://www.lifesciencesite.comhttp://www.lifesciencesite.com.8

Mutter, A. (2013). *Growing tiny houses: Motivations and opportunities for expansion through niche markets* [Unpublished master's theses]. Lund University.

Natasha, K. A. D. M. (2023). *Tiny housing as a sustainable and affordable housing alternative for low-income earners of Sri Lanka*. [Unpublished student thesis]. University of Moratuwa.

Niriella, C. (2017). Emerging social-spatial polarisation within the housing market in Colombo, Sri Lanka. *Journal of Urban Regeneration and Renewal*, *11*(2), 43–52. Emerging social-spatial polarisation within the housing market in...: Ingenta Connect

Paradis, E., O'Brien, B., Nimmon, L., Bandiera, G., & Martimianakis, M. A. T. (2016). Design: Selection of data collection methods. *Journal of Graduate Medical Education*, *8*(2), 263–264. https://doi.org/10.4300/JGME-D-16-00098.1

Rack, F. (2016). *Micro-apartments as an emerging real estate market*: *Does the "small space, big city trade off work in Europe?* [Master's Thesis]. EBS Business School – Real Estate Management Institute. GRIN Verlag. https://www.grin.com/document/351831

Rathnayaka, R. M. K. B., Ariyawansa, R. G., & Endagamage, D. (2020). Factors affecting to buying decision of middle-income house buyers: Study on selected middle-income house projects in Colombo. *International Conference on Real Estate Management and Valuation*, Sri Lanka. journals.sjp.ac.lk/index.php/icremv/article/view/4950

Renn, A., & Armlovich, A. (2016). Microunits: A tool to promote affordable housing. In *Retooling metropolis: How social media, markets, and regulatory innovation can make America's cities more livable*. Manhattan Institute.

Ruonavaara, H. (2018). Theory of housing, from housing, about housing. *Housing, Theory and Society*, *35*(2), 178–192. https://doi.org/10.1080/14036096.2017.1347103

Samaratunga, T. C., & O'Hare, D. (2014). Sahaspura: The first high-rise housing project for low-income people in Colombo, Sri Lanka. *Australian Planner*, *51*(3), 223–231. https://doi.org/10.1080/07293682.2013.820204

Shanthaarchch, A. (2022). Middle class Sri Lankans forced to migrate due to proposed new income tax policy? *The Island* p. 4. http://epaper.island.lk/paper/2022/11/15

Shearer, H. (2015). *Tiny houses: A radical new solution for addressing urban housing affordability, or just another niche market?* 7th State of Australian Cities Conference, 9-11 December 2015, Gold Coast, Australia. https://apo.org.au/node/63199.

Shearer, H. (2018). *Tiny houses: Planning for affordability and inclusion*. 2018 Joint Asia-Pacific Network for Housing Research and Australasian Housing Researchers Conference, Gold Coast, Queensland, Australia.Tiny houses: Planning for affordability and inclusion.... - Google Scholar

Shearer, H. (2019). *Tiny houses: Love, live or leave? what factors influence the decision*? 9th State of Australian Cities Conference, 30 November-5 December 2019, Perth, Australia. https://apo.org.au/node/306846

Shearer, H., Bares, V., Pieters, R., Winkle, B., & Meathrel, K. (2019). Planning for tiny houses. *Australian Planner*, *55*(3–4), 147–156. https://doi.org/10.1080/07293682.2019.1632358

Stone, M. E. (2006). What is housing affordability? The case for the residual income approach. *Housing Policy Debate, 17(*1), 151–184. https://doi.org/10.1080/10511482.2006.9521564

United Nations. (2022). *World population prospects*. Department of Economic and Social Affairs Population Division https://population.un.org/wpp/

United Nations. (2011). *World Urbanization Prospects*. https://www.un.org/en/development/desa/population/publications/pdf/urbanization/WUP2011_Report.pdf

Urban Development Authority (2024, June 25). *UDA act and amendments*. Urban Development Authority. https://www.uda.gov.lk/uda-acts-and-amendments_2021.html

Weeraratne, B. (2020). Urban housing in Sri Lanka. In S. Bandyopadhyay, C. R. Pathak, & T. P. Dentinho (Eds.), *Urbanization and regional sustainability in South Asia: Socio-economic drivers, environmental pressures and policy responses*, 109–134. Springer Nature Switzerland.

Wickramaarachchi, N. C., Chandani, S. K., & Thilini, M. (2021). Key determinants of time on the market: an analysis of residential housing market in Sri Lanka. *International Journal of Housing Markets and Analysis*, *14*(5), 913–935. https://doi.org/10.1108/IJHMA-06-2020-0071

World Bank Group. (2021). *Annual Report 2021*. Washinton. World Bank Group. https://thedocs.worldbank.org/en/doc/cd05d27f0203b90751fcfe7145cd5a3d-0330122021/original/EDS05-Annual-Report-2021-English-Summary.pdf

Zhang, D., Gong, M., Zhang, S., & Zhu, X. (2022). A review of tiny houses in North America: Market demand. *Sustainable Structures*, *2*(1), 2789-3111. https://doi.org/10.54113/j.sust.2022.000012

Madushan, F., Abeynayake, M.D.T.E. and Illeperuma, I.E., 2024. Role of prefabricated prefinished volumetric construction in enhancing construction productivity: Sri Lankan perspective. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 917-932. DOI: https://doi.org/10.31705/WCS.2024.73. Available from: https://ciobwcs.com/papers/

ROLE OF PREFABRICATED PREFINISHED VOLUMETRIC CONSTRUCTION IN ENHANCING CONSTRUCTION PRODUCTIVITY: SRI LANKAN PERSPECTIVE

F. Madushan[1], M.D.T.E. Abeynayake[2] and I.E. Illeperuma[3]

ABSTRACT

Low productivity is an inherent characteristic of the construction industry. Prefabricated Prefinished Volumetric Construction (PPVC) is widely acknowledged for its high level of productivity. Thus, this study focuses on increasing the Construction Productivity (CP) in Sri Lanka through the implementation of PPVC. Herein, the research objectives are to explore the role of PPVC in increasing the CP and investigate the barriers to implementing PPVC in Sri Lanka. The research aim was accomplished by collecting data through expert interviews and analysing it through manual content analysis. Findings revealed that in Sri Lanka, the average CP rate can be doubled by implementing PPVC. Overall, PPVC increases the CP by reducing labour, accelerating project duration, making project management much more effective and minimising wastage. Nonetheless, the use of PPVC is relatively limited in Sri Lanka. The high initial cost is the main barrier to the adoption. Findings identified the necessity of specialised machinery, production plants, and skilled labour as the main cost drivers. Complications and high costs in transporting PPVC modules are critical barriers to the implementation of PPVC in Sri Lanka. Additionally, less demand, lack of technical expertise and less enthusiasm for research and development act as barriers. Most of the contractors do not have the technical capability needed for PPVC. Moreover, less governmental support and material shortages hinder the adoption of PPVC. Having an in-depth understanding of the barriers forms the foundation to tailor strategies and overcome the challenges. Accordingly, this research sheds light on the realm of concurring PPVC in Sri Lanka.

Keywords: *Barriers; PPVC; Prefabrication; Productivity; Sri Lanka.*

1. INTRODUCTION

The Construction Industry (CI) plays a predominant role in a country's economic development (Adebowale & Agumba, 2023; Manoharan et al., 2023). 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).

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, madushan9874@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mabeynayake@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurii@uom.lk

In Sri Lanka, the CI contributed 6.1 % of the GDP (Central Bank of Sri Lanka [CBSL], 2021). Moreover, the sector inherits unique characteristics including lengthy timelines, complex procedures, high resource consumption, low productivity, high risks, and extensive stakeholder involvement (Dixit, 2018; Ma et al., 2016; Vogl, 2015; Zou et al., 2007).

Productivity dictates how efficiently the resources are utilised to deliver the outcomes. Literature acknowledged it as a major parameter of assessing the economic performance and competitive advantages of an industry (Adebowale & Agumba, 2023; Manoharan et al., 2023). Productivity could be measured in different aspects including labour productivity, capital productivity, energy productivity etc (Navaratna & Jayawardane, 2007). However, measuring productivity only through a single aspect will misinterpret the efficiency of utilising other resources (Zhan & Pan, 2020). Consequently, the phenomenon of 'total factor productivity' which considers all inputs concerning the production process was introduced (Navaratna & Jayawardane, 2007). The construction total factor productivity is defined as "a measure of the efficiency of the industry in exerting resources (i.e., labour, capital, and materials) to produce output, as measured by the value-added of physical construction quantities produced" (Zhan & Pan, 2020). To avoid the use of convoluted language, hereafter 'construction total factor productivity' will be referred to as 'Construction Productivity' (CP). Further to the authors, fluctuating economic environment, low technological innovation in construction, labour issues, and complex management systems cause the low CP. Additionally, due to the prevailing economic crisis in the country, Sri Lankan CI has been experiencing stringent challenges such as cost overruns, material shortages, difficulties in obtaining funds and less governmental support thus resulting in low CP (Soyza, 2022).

Notwithstanding the efforts to enhance the CP, it remains low compared to other industries (Borg & Song, 2015; Jarkas & Radosavljevic, 2013). However, enhancing the CP is crucial for a country's sustainable economic development (Abdel-Wahab & Vogl, 2011). The CP enhancement framework introduced by Zhan and Pan (2020) identified encouraging technological innovation in construction as a key productivity enhancement strategy. Further to the authors, the prime objective of encouraging technological innovation is to promote advanced construction management and labour-saving technologies which ultimately enhance the CP.

Literature acknowledged prefabrication as an innovative technological approach which greatly enhances the CP (Jayawardana et al., 2023; Li et al., 2016; Mao et al., 2016). It is a good solution for limited land availability and site access as it provides a unique opportunity to commence construction even before the site is available (Gunawardena et al., 2016). In the 2nd Construction Productivity Roadmap, the Building and Construction Authority of Singapore contended the widespread adoption of prefabrication to achieve a quantum leap in productivity improvement (Shang et al., 2021). Importantly, Prefabricated Prefinished Volumetric Construction (PPVC) is a technically advanced branch of prefabrication which recorded a high level of productivity compared to other prefabrication methods (Shang et al., 2021; Xu et al., 2020). It involves manufacturing completed modules with finishes for walls, floors, and ceilings in off-site factories, transporting them to the construction sites and installing them (Arif & Egbu, 2010; Kamali & Hewage, 2017; Mao et al., 2016). The execution of PPVC is significantly higher in developed countries compared to developing economies such as Sri Lanka (Jayawardana et al., 2023; Kamali & Hewage, 2016). For example, by 2019, about 35%

of the newly constructed public housing projects in Singapore were PPVC (Hwang et al., 2018b). When considering the Asian region, developing economies such as China and Malaysia have demonstrated greater progress over the last two decades in promoting, adopting, and supporting PPVC compared to Sri Lanka (Balasbaneh & Ramli, 2020; Chang et al., 2018). Herein, Hwang et al. (2018b) developed a computerised knowledge-based decision support system for PPVC to facilitate construction professionals in the implementation. In the Sri Lankan Context, Gunawardena et al. (2016) studied the feasibility of adopting prefabricated technologies as a whole. Further, Jayawardana et al. (2023) proposed an adoption strategy to overcome the barriers to implementing prefabrication as a whole in the Sri Lankan context. Even though there are studies conducted about the performance evaluation, technology system, identifying barriers, and developing strategies of PPVC globally (Xu et al., 2020), seldom literature focuses on the productivity aspect of PPVC in the Sri Lankan context. Importantly, PPVC has not reached the limelight in Sri Lanka yet and thus it is necessary to overcome the inherent barriers to take PPVC into the mainstream and stabilise its applications (Jayawardana et al., 2023). As the initial step of achieving that goal, this study aims to enhance the CP in Sri Lanka through the implementation of PPVC. Accordingly, the study has two objectives i.e., (i) Explore the role of PPVC in increasing the CP, and (ii) Investigate the barriers to implementing PPVC in SL.

2. LITERATURE REVIEW

2.1 PREFABRICATED CONSTRUCTION

Prefabrication replaces most of the on-site construction with off-site manufacturing and has played a significant role in the CI for a long time. Consequently, it is rapidly evolving into an essential component in the CI (Gunawardena et al., 2016). Sri Lanka has used prefabrication from time to time, especially in bridges and road works (Gunawardena et al., 2016). There are various categories of prefabricated construction. However, most of the classifications are based on industry practices and theoretical assumptions rather than a rigorous systematic evaluation (Ginigaddara et al., 2022). The numerous taxonomies and terminologies cause blurred boundaries between different systems (Gosling et al., 2016). For instance, the difference between volumetric pods, modules, and complete buildings is not defined in most of the classifications (Ginigaddara et al., 2022). Consequently, the researchers deployed a systematic scientific process and developed an off-site construction typology (refer to Figure 1) that depicts the holistic nature of different types.

However, partially agreeing with the findings of Ginigaddara et al. (2022), focusing on the Sri Lankan CI, Uthpala and Ramachandra (2015) identified two volumetric construction types i.e., (i) modular constructions, and (ii) pod constructions. Herein, referring to Wu and An (2014), Uthpala and Ramachandra (2015) defined modular constructions as prefabricated room-sized volumetric units that are normally fully fit out while manufacturing and are installed on-site as load-bearing building blocks. Further analysis of the two classifications revealed that upon a critical review of different terms Ginigaddara et al. (2022) selected the term ‘module’ to refer to what was referred to as ‘modular construction’ in various studies. Outstanding the other forms of prefabrication, prefabricated modules are acknowledged as the future of the CI (Liew, 2018; Xu et al., 2020).

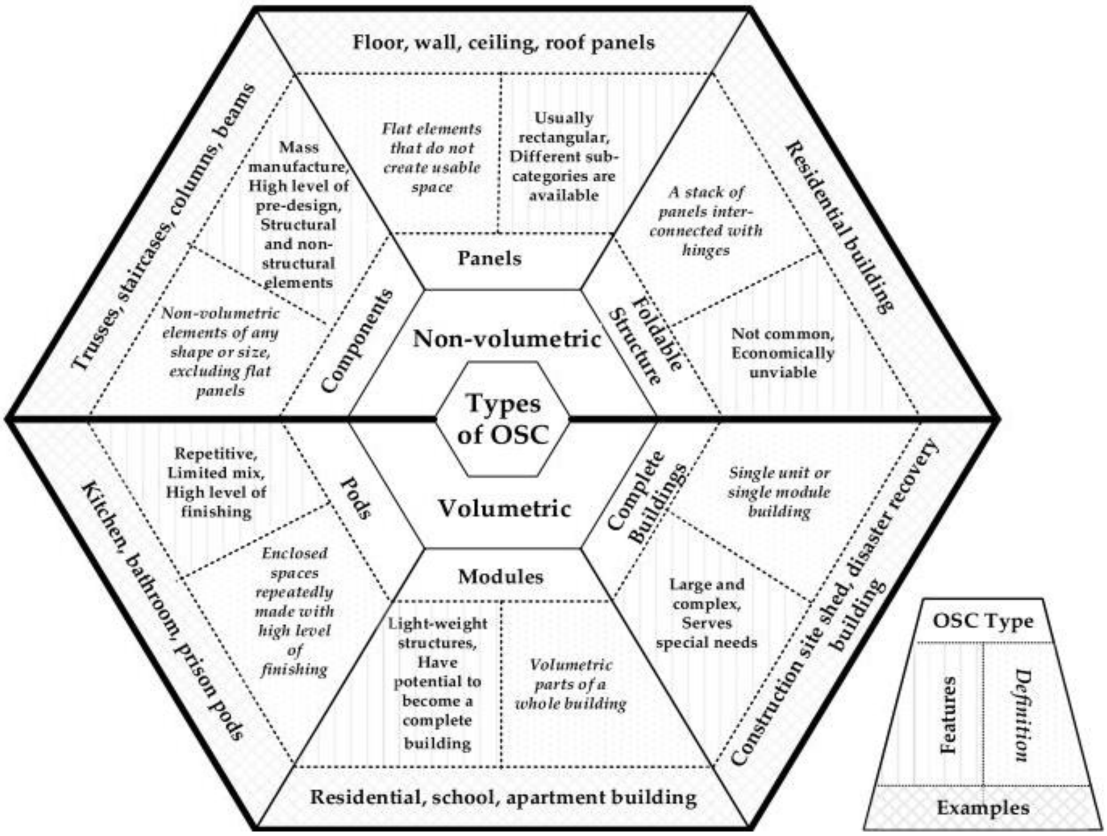


Figure 1: Definitions, examples, and features of the validated OSC typology

Source : (Ginigaddara et al., 2022)

PPVC is the synonym terminology of prefabricated modules (Xu et al., 2020). Based on the load path PPVC modules can be categorised into two types i.e., (i) load-bearing wall modules, and (ii) corner-supported modules as shown in Figures 2 and 3, respectively (Liew, 2018).

In China, PPVC has been actively practising since 2017 (Xu et al., 2020). Further to the authors, North Hill Residence Hall of Nanyang Technological University (NTU) is the first PPVC project in Singapore (Xu et al., 2020). Importantly, PPVC plays a vital role in post-disaster reconstruction (Gunawardena et al., 2016). Herein, the authors highlighted key examples such as Post Katrina Housing in Mississippi, USA and reconstruction after Haiti Earthquake in 2010, Haiti. Compared to other prefabrication methods PPVC has several advantages such as reduced labour and time consumption (Gunawardena et al., 2016), minimum disruption to the adjacent services, improved quality, increased productivity, and sustainability (Xu et al., 2020). Despite the advantages and the fact that Sri Lankan CI is suffering from limited availability of domestic labour (Nawarathna et al., 2023), prefabrication does not own a satisfying share in the Sri Lankan construction market yet (Uthpala & Ramachandra, 2015). Thus, there is a critical need to investigate the potential of PPVC in addressing the issues in the CI and the reasons behind the limited implementation in the Sri Lankan context.

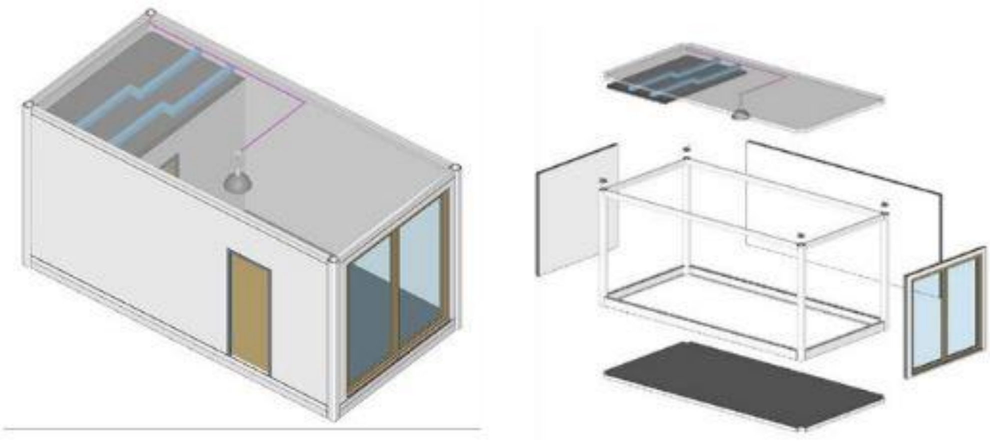


Figure 2: Load bearing wall modules

Source: Liew (2018)

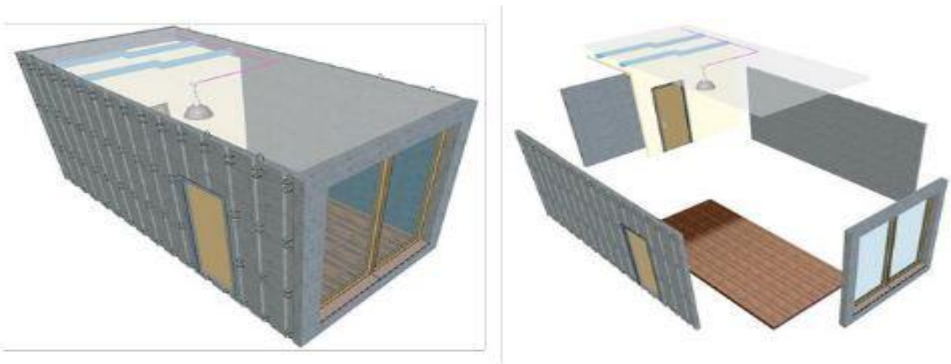


Figure 3: Corner supported modules

Source: Liew (2018)

2.2 ROLE OF PREFABRICATED PREFINISHED VOLUMETRIC CONSTRUCTION IN INCREASING CONSTRUCTION PRODUCTIVITY

Literature encapsulates four salient factors that negatively affect CP i.e., (i) inefficient project management, (ii) unfavourable economic conditions, (iii) low technological innovations, and (iv) less governmental support (Soyza, 2022; Zhan & Pan, 2020). Construction project management involves four crucial steps of planning, executing, coordinating, and controlling the key resources: material, labour, and capital (i.e. funds and machinery) (Zhan & Pan, 2020; Zwikael, 2009). Managing construction projects is challenging due to the complexity of the CI, high stakeholder involvement, labour intensiveness, and dynamic organisational structures (Adebowale & Agumba, 2023; Dixit, 2018; Ma et al., 2016; Vogl, 2015; Zou et al., 2007). Inefficient project management causes cost enhancement, material wastage, subpar work, rework, and project delays and thus results in low CP (Albert et al., 2022; Khaled et al., 2017). On the other hand, unfavourable economic conditions and less governmental support are closely linked. Sri Lanka has experienced the significant impacts of this duo over the past few years. Consequently, the country has suffered from high inflation, high interest rates, high taxes and frequent changes in laws and regulations (Penttilä, 2006). The said conditions cause cost overruns, material shortages, difficulties in obtaining funds, and project delays and thus result in low CP (Soyza, 2022). The most notable repercussion of low technological innovations is the wastage of resources which paves the way for low CP. However, PPVC effectively addressed the above-discussed causes of lesser CP and thereby enhanced the CP.

PPVC is a lean production approach which consumes less labour compared to conventional construction (Hwang et al., 2018a; Jayawardana et al., 2023). Hence, PPVC has been highly acknowledged in Singapore as a sustainable mechanism to deal with the limited working-age population (Adebowale & Agumba, 2023). Furthermore, PPVC accelerates the construction process significantly and thus enhances CP (Jayawardana et al., 2023; Murali & Sambath, 2020). This was evidenced by the Crowne Plaza Changi Airport extension project which reported a 50% reduction in the construction programme as a result of adopting PPVC (Building Construction Authority [BCA], 2016). North Hill Residence Hall Project of NTU reported a six-month time saving as a result of adopting PPVC (Liew, 2018). Similarly, Chen et al. (2010); Jaillon and Poon (2008) and Wong et al. (2003) ascertained a nearly 50% time reduction in various projects compared to on-site construction. Because PPVC carries out the majority of the work in a controlled factory environment, it is less impacted by adverse environmental conditions (Murali & Sambath, 2020) and makes project management convenient (Shang et al., 2021). Further, the on-site installation is cleaner and safer compared to traditional on-site construction and thereby enhances the CP (BCA, 2017). Furthermore, Murali and Sambath (2020) contented reduced wastage as a widespread characteristic of prefabrication. Thus, PPVC greatly enhances the CP compared to traditional on-site construction.

2.3 BARRIERS TO IMPLEMENTING PREFABRICATED PREFINISHED VOLUMETRIC CONSTRUCTION

Notwithstanding the benefits, prefabrication is associated with inherent challenges (Murali & Sambath, 2020). By extensively investigating the adoption of PPVC in Singapore Shang et al. (2021) highlighted three critical barriers i.e., (i) ineffective on-site storage, (ii) high up-front payment, and (iii) transportation issues. Similarly, Murali and Sambath (2020) analysed the challenges in the Indian context and emphasised inadequate suppliers of prefabrication, lack of technical training, lack of adequate transport and logistics, and clients' less willingness as significant barriers. Cost intensity was discovered as the main cause of the slow application of prefabrication in the United Kingdom and China (Shang et al., 2021). Further, Hong et al. (2018) explored its significant impacts in developing countries. Correspondingly, Sri Lanka is facing several significant challenges as a developing economy with less industrialised construction and manufacturing sectors (Jayawardana et al., 2023). The authors identified six barriers i.e., (i) cost-related complications, (ii) unfavourable government policies and less support, (iii) low societal acceptance, (iv) shortage of experienced and skilled labour, (v) technical incapacity, and (vi) lack of country-specific life cycle databases.

Studies discovered the main cost drivers of PPVC as setting up manufacturing and holding yards, high-capacity tower cranes, staff training, storing and transporting. Moreover, researchers emphasised the complications and high costs associated with transportation in developing countries (Chiang et al., 2006; Murali & Sambath, 2020; Salama et al., 2017). Additionally, Sri Lanka is suffering from a lack of supportive policies, regulations, and incentives to encourage the implementation of PPVC (Jayawardana et al., 2023). Further, Uthpala and Ramachandra (2015) highlighted the resistance among construction companies and the public in adopting these technologies. The resistance is driven by beliefs such as low quality, loss of aesthetic appearance, inflexibility for design changes, high stress, and less long-term durability of prefabricated components (Jayawardana et al., 2023; Murali & Sambath, 2020). Further, contractors are reluctant to initiate the adoption of PPVC due to the risks associated with being the forerunner (Lee, 2017). Moreover, there is a concern that PPVC buildings are less stable against lateral loads, especially in circumstances such as earthquakes. However, the less vulnerable geographical position of the country favours the applicability of PPVC in Sri Lanka (Jayawardana et al., 2023). Accordingly, it is essential to make the community aware and thereby popularise PPVC (Murali & Sambath, 2020).

Effective implementation of PPVC requires expertise and knowledge of workers and management. However, Sri Lanka is lacking in originating and transferring knowledge and specialisation (Jayawardana et al., 2023). Notably, Sri Lanka is indolent in embracing innovative construction technologies and less enthusiastic in research and development initiatives (Jayawardana et al., 2023). Similarly, lack of technical training is a pressing issue in the adoption of PPVC in India (Murali & Sambath, 2020). The researchers discovered that though most of the construction stakeholders are rich in theoretical knowledge they are lacking in practical applications. Jayawardana et al. (2023) identified the absence of country-specific construction databases, essential for benchmarking PPVC against conventional construction, as a barrier to the widespread adoption of PPVC in Sri Lanka.

3. METHODOLOGY

The less application of PPVC in Sri Lanka constrained drawing a large sample of respondents for data collection. However, the qualitative approach collects data from comparatively a lesser number of participants and analyses in-depth (Creswell, 2012). Thus, this study used a qualitative approach to accomplish the research aim. Further, exploring the role of PPVC in increasing the CP and investigating the barriers to implementing PPVC in Sri Lanka require experts' inputs with in-depth knowledge of the context. Importantly, the accuracy of the data significantly influences in reaching of the aim. Thus, this study conducted expert interviews to collect data. In-depth interviews reflect interviewees' perspectives based on their experiences and understanding. Semi-structured interviews, while being guided by a defined framework allow the researcher for situational questioning based on the responses. Hence, semi-structured interviews were chosen for this research. Interviewees were selected through purposive sampling considering knowledge and experience in PPVC. Accordingly, twelve construction professionals were interviewed. Table 1 presents the profiles of the interviewees.

Table 1: Interviewee profile

Interviewee Code	Designation	Years of Experience
E1	General Manager	16+
E2	Project Manager	8+
E3	Quantity Surveyor	5+
E4	Project Manager	12+

Interviewee Code	Designation	Years of Experience
E5	Quantity Surveyor	4+
E6	Engineer - Modular building solutions	4+
E7	Planning & QA/QC Engineer	4+
E8	Quantity Surveyor	14+
E9	Site Manager	15+
E10	Site Engineer	18+
E11	Quantity Surveyor	4+
E12	Site Engineer	10+

Interviewees were questioned under three major sections. In the first section, the interviewee's background details were questioned. The second section focused on the role of PPVC in increasing CP whereas the third section focused on the implementation of PPVC in Sri Lanka. Accordingly, the current level of implementation and associated barriers to the implementation were discussed. Situational questions were raised to clarify and explore the details further. Collected data was analysed through manual content analysis and conclusions were drawn.

4. RESEARCH FINDINGS AND DISCUSSION

4.1 ROLE OF PREFABRICATED PREFINISHED VOLUMETRIC CONSTRUCTION IN INCREASING CONSTRUCTION PRODUCTIVITY IN SRI LANKA

All the experts acknowledged the ability of PPVC to enhance the CP. Especially, E4 strongly insisted that "PPVC is the most productive and efficient volumetric construction technology". Moreover, E1 stated that "*implementation of PPVC can double the CP compared to the conventional methods used in Sri Lanka.* According to the interviewee, the average CP rate is 40% whereas the achievable CP rate by implementing PPVC is 80%. Strengthening the argument further, E5, E6, E11, and E12 highlighted the requirement of taking necessary steps to enhance the implementation of PPVC in Sri Lanka and thereby mitigate the productivity loss. Importantly, E8 contented that PPVC can carry out the Sri Lankan construction industry to the next stage.

Empirical findings regarding the less human resource consumption of PPVC resonate with those of the literature findings. In line with the findings of Adebowale and Agumba (2023), E5 emphasised that PPVC is mostly used in developed countries such as Singapore and Australia and developing countries such as Malaysia due to the reduced human resources involvement. E3, E5, and E9 pinpointed that in PPVC each labour is specialised in a certain task to ensure that each activity is finished promptly and effectively. This ultimately lowers the overall labour requirement. Further, as emphasised by E1 the use of advanced machinery and equipment reduces the need for manual labour resulting in a more productive and streamlined manufacturing process. On the other hand, lack of on-site labour has been identified as a cause of enhanced costs and project delays. However, PPVC will mitigate the issue greatly due to the lower labour requirement. Similarly, E2 identified PPVC as an effective solution for the severe skill labour shortage in Sri Lanka. Accordingly, PPVC enhances the CP by reducing the labour input.

All the experts agreed that PPVC greatly accelerates the project duration compared to traditional on-site construction. While BCA (2016); Chen et al. (2010); Jaillon and Poon

(2008) and Wong et al. (2003) reported about 50% time reductions in PPVC projects, E1 pointed out that PPVC can achieve about 40% time-saving. Findings revealed several reasons for the reduced project duration. For example, E2, E7, E9, E10, and E11 commented that this is because the majority of the construction processes take place in controlled factory environments which are free from the disturbances by extreme weather conditions. Additionally, E2 identified simultaneous work both on and off-site as the primary reason for achieving reduced project duration in PPVC. Further, E3, E4 and E6 pinpointed that the repetitive nature of the units and completion of all elements including services insulation in one single plant provides fast-track construction. E9 added that "*early involvement of contractor shortens the construction period*". Thus, the findings of the expert interviews confirm the findings of the previous researchers regarding the significantly accelerated construction processes of PPVC. Importantly, E8 contended that "*the reductions in project durations followed by reduced preliminaries and opportunity costs and thereby enhance the CP*".

Being a less labour-intensive factory-oriented manufacturing process, PPVC allows more efficient project management compared to traditional construction. Accordingly, E3 and E9 mentioned that PPVC allows for better quality control, reduces rework, and improves the quality as the modules are manufactured in a factory. Additionally, as highlighted by E9, "*improved quality of the units reduces the onsite inspection*". Further, the application of finishes such as flooring, paint, and tiles in a factory under controlled circumstances lowers the possibility of mistakes. Moreover, E8 stated that "*innovative construction techniques used in PPVC guarantee that all parts are precisely measured and assembled and thus reduces the structural failures*". Adding to that, E1 pinpointed the use of steel formwork which achieves more accurate unit dimensions compared to the conventional formwork methods. Thus, the findings confirm that of Murali and Sambath (2020) and Shang et al. (2021) regarding the ability of PPVC to plan, execute, coordinate, and control the key resources efficiently thereby increasing the CP. Further to that, as highlighted by E3 and E5 PPVC enables cleaner and safer working conditions and reduces the risk of accidents as a result of carefully monitored production setting with strict adherence to safety protocols. In addition, E9 contented that "*early involvement of the contractor facilitates efficient project planning*". Further E1 claimed that the contractor's early involvement improves the buildability of PPVC and allows the project to be finished with fewer disputes.

According to E2 "*PPVC uses resources more productively and significantly minimizes the wastage compared to traditional construction*". E1, E3 and E11 explained the reason as PPVC modules are produced to precise specifications and thus result in little material waste.

4.2 BARRIERS TO IMPLEMENTING PREFABRICATED PREFINISHED VOLUMETRIC CONSTRUCTION IN SRI LANKA

Findings revealed that the use of PPVC is relatively limited in the Sri Lankan CI. According to E1 and E3 certain construction companies in Sri Lanka have started to explore the use of PPVC, but not widely practicing. It is remaining as a relatively new and relatively less-used method of construction with inherent barriers to be overcome. The experts highlighted various reasons for the less acceptance of PPVC in Sri Lanka.

In line with the findings based on Singapore, the United Kingdom, and China, E1 discovered high initial costs as the main barrier to the adoption of PPVC in Sri Lanka.

Accordingly, experts identified the necessity of specialised machinery, production plants, and specialised labour as the main cost drivers. E9, E10, and E12 contented that the cost of the yard erection is significantly high to the extent that resists the contractors from adopting PPVC in Sri Lanka. Confirming the findings of Chiang et al. (2006); Murali and Sambath (2020); Salama et al. (2017) regarding the complications and high costs associated with transportation in developing countries. E10 claimed that "*requirements associated with module handling and transportation such as heavy vehicles and heavy capacity cranes make PPVC costly*". Additionally, E9 insisted that the project scope, complexity of the design, and the degree of customisation affect the initial cost of PPVC. Acknowledging the findings of Hong et al., (2018), regarding the significance of the higher upfront cost of PPVC in developing countries E11 and E12 stated that "*PPVC is cost-effective for larger projects rather than small-scale projects and thus it is challenging to justify the adoption of PPVC particularly for small-scale or low-budget projects*". However, E2 believed that PPVC is cost-effective for both small and large-scale projects.

Resonating with the literature findings regarding complications associated with module transportation, most of the expert's highlighted transportation as a critical barrier to the implementation of PPVC in Sri Lanka. Experts further mentioned that the "weight of the unit with the vehicle's weight will be considerably huge, where most of the bridges and culverts in Sri Lanka will not able to bear the weight". Additionally, tunnel clearance as well as abstractions by lower-level electrical and telecommunication cabling systems were identified as the challenges during the mobilisation of PPVC units. E1 and E9 pointed out that the long transportation routes and high traffic will increase the overall cost and cause delays which ultimately reduces the CP. Transporting the PPVC units on unsuitable or damaged roads could damage the modules causing additional rectification costs and reducing the quality. On the other hand, E6 pointed out the risks in handling and loading as another barrier to the implementation of PPVC in Sri Lanka. Since most of the accidents and damages happen during the lifting processes, additional precautions need to be taken. Additionally, E1 and E4 insisted on the storage problem as another barrier. Since the PPVC modules are huge and are being produced simultaneously in manufacturing yards, a large space is required for storage. Especially, E3 emphasised that "*preservation and curing of the modules also need large space*".

On the other hand, E7, E8, and E11 emphasized the lack of demand for PPVC as a barrier to the implementation in the Sri Lankan CI. Confirming the literature findings of Jayawardana et al. (2023) and Uthpala and Ramachandra (2015) regarding the low public acceptance, empirical findings revealed that reliance on conventional on-site construction methods and resilience to adopt innovative technologies lower the demand for PPVC. Herein, E3 stated that "*ordinary traditional citizens oppose residing in prefabricated buildings*". Further, E1, E4, and E5 highlighted that the low public acceptance resulted in a low demand for PPVC which is a significant barrier in the Indian context as well. Similarly, E6 contended that even though there is a good demand for prefabricated elements such as beams, wall panels, columns, and slabs the demand for PPVC is not at a satisfactory level. However, E2 believed that there is a rising demand for PPVC in Sri Lanka. In-depth analysis revealed that lack of knowledge and understanding is a critical barrier that prevents people from adopting PPVC. According to E1 "*most of the people have a myth about the durability of PPVC buildings and have an overconfidence on traditional construction*". Similarly, E1 and E9 mentioned that "the *general public as* *well as most of the construction stakeholders in Sri Lanka not aware of the long-term benefits of PPVC such as the high potential to enhance the CP*". Additionally, E1 stated that investors are reluctant to invest in PPVC due to the unawareness of its benefits. Accordingly, E12 stated that the lack of awareness leads to a lack of demand. However, E6 and E11 noticed an increasing trend in the level of acknowledgement of PPVC in the Sri Lankan CI.

The findings of the expert interviews strongly confirm the literature findings regarding the lack of technical expertise and specialisation which act as barriers to the implementation of PPVC. E5 stated that most of the construction professionals practising in Sri Lanka hesitate to implement PPVC due to the lack of necessary experience and expertise in PPVC. Thus, as pointed out by E2 "they only focus on the high initial cost of PPVC, instead of focusing on innovative approaches to reduce the cost". Similarly, E8 insisted that most of the construction companies do not have the technical capability needed for PPVC. For instance, precision engineering and logistical knowledge are needed for the assembly of building modules, which may not be a skill set possessed by conventional contractors. Further to the expert, the absence of experienced contractors may result in delays, higher costs, and poor quality of work, which discourage stakeholders from implementing PPVC. Similarly, E9 mentioned that implementing PPVC required considering several technological aspects such as design-related standards, load calculations, and wind patterns assessments which the construction professionals are not very familiar with. According to E5 "*service integration is more complex in PPVC compared to conventional construction*". Conversely, E1 and E2 mentioned that the repetitive design nature of the PPVC technology will make future project execution easier.

Findings revealed another significant barrier to the adoption of PPVC in Sri Lanka: less focus on research and development. E3, E6, and E7 emphasised that without adequate research it is challenging to drive the industry in the long term and to attract investors. Especially E6 mentioned that universities should play leading roles in disseminating knowledge regarding the globally trending innovative construction techniques such as PPVC. However, E2 noticed several noteworthy efforts taken by educational institutes, professional bodies, and the cooperate sector to overcome these barriers. According to E8, "*the level of awareness and expertise of PPVC in the Sri Lankan CI is slowly increasing, but there are still pressing requirements to fully realize its potential in the country*".

In addition to the literature findings, empirical findings identified a material shortage as a significant barrier to implementing PPVC in Sri Lanka. Further to experts, "*concrete, steel, and insulation are just a few key materials of PPVC which short supply may cause significant production delays and increased costs*". Especially E1 and E2 identified the impact of the COVID-19 pandemic, the economic crisis of the country, high inflation, and import restrictions as the root causes of the possible material shortages. On the other hand, most of the interviewees highlighted poor procurement methods as a major barrier to the implementation of PPVC in Sri Lanka. E1 stated that "*it can be challenging to ensure that these modules fulfil the quality and legal requirements without proper procurement procedures in place*".

Confirming the findings of Jayawardana et al. (2023) regarding the less governmental support, E1 claimed that "*PPVC is not sufficiently promoted by the Sri Lankan government*". However, Singapore experienced the complete opposite of this when implementing PPVC. Moreover, E2 mentioned that "*the government should promote the adoption through favourable policies, tax reductions, releasing import restrictions, and facilitating research and development*". Adding further to this argument E6 and E11 mentioned that experienced manufacturers and contractors should be the forerunners and thereby promote PPVC through knowledge and experience sharing. Figure 4 summarises the findings through a cause-and-effect diagram.

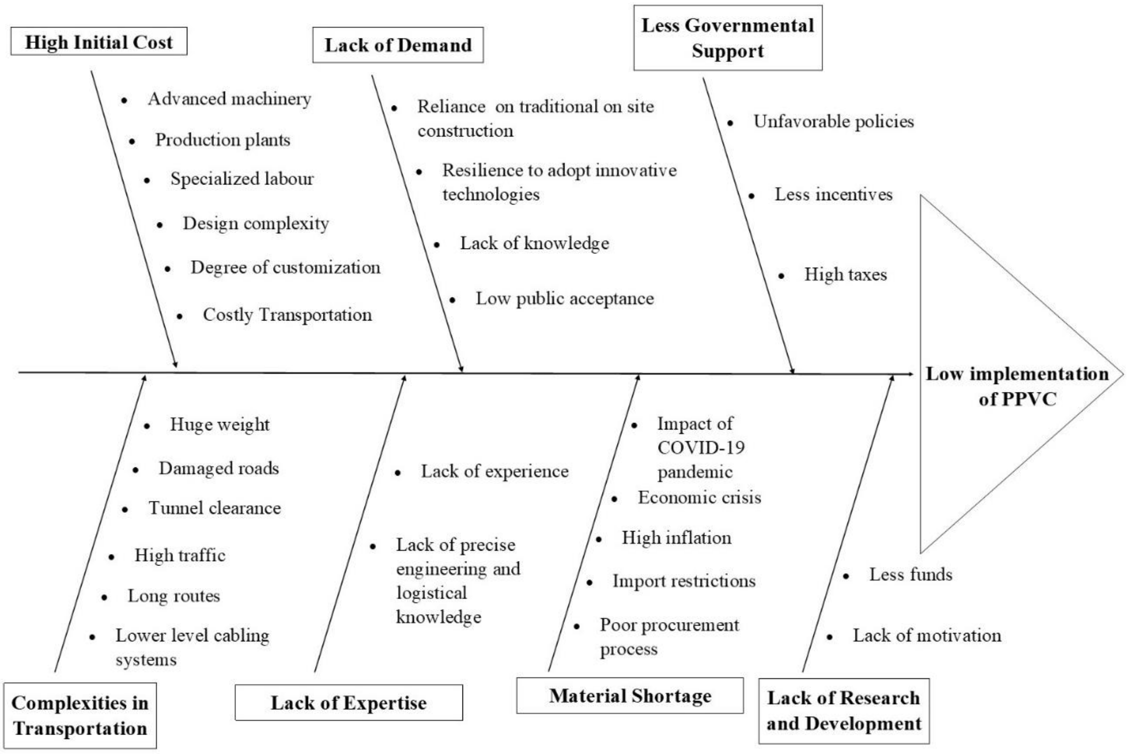


Figure 4: Cause and effect diagram of barriers to the implementation of PPVC in Sri Lanka

5. CONCLUSIONS

Low productivity is an inherent characteristic of the CI. Productivity could be measured in different aspects but measuring productivity only through a single aspect will misinterpret the efficiency of utilising other resources. Literature encapsulates four salient factors that negatively affect CP namely inefficient project management, unfavourable economic conditions, low technological innovations, and less governmental support. PPVC is an advanced branch of prefabrication which recorded a high level of productivity. The execution of PPVC is significantly higher in developed countries compared to developing economies. However, it has not reached the limelight in Sri Lanka. Even though studies have been conducted focusing on prefabrication or volumetric construction, seldom literature has specifically focused on PPVC. Addressing the niche, this study focuses on increasing the CP in Sri Lanka through the implementation of PPVC. The research aim was accomplished through a qualitative approach by collecting data through expert interviews and analysing it through manual content analysis.

Findings highly acknowledged the ability of PPVC to enhance the CP. In Sri Lanka, the average CP rate can be doubled by implementing PPVC. It lowers the overall labour requirement as a result of specialised labour, advanced machinery, and streamlined manufacturing processes. Similarly, PPVC greatly accelerates the project duration as a result of simultaneous work, controlled factory environments, the repetitive nature of the units and the early involvement of contractors. The reductions in project durations are followed by reduced preliminaries and opportunity costs. Additionally, PPVC can plan, execute, coordinate, and control the key resources efficiently thereby increasing the CP. Further, PPVC significantly minimises the wastage because of the production according to the precise specifications. Overall, PPVC enhances the CP by reducing labour, accelerating project duration, effective project management and minimising wastage.

Nonetheless, the use of PPVC is relatively limited in Sri Lanka. The high initial cost is the main barrier to the adoption of PPVC in Sri Lanka. Findings revealed the necessity of specialised machinery, production plants, and skilled labour as the main cost drivers. Moreover, the cost of the yard erection is significantly high to the extent that resists the contractors from adopting PPVC in Sri Lanka. The higher upfront costs make PPVC cost-effective only for mega-scale projects. Similar to the other developing countries Sri Lanka experiences complications and high costs in transporting PPVC modules which are critical barriers to the implementation of PPVC. Challenges during the mobilisation of PPVC units are identified as the inability of the bridges and culverts to bear the weight, tunnel clearance, abstractions by lower-level electrical and telecommunication cabling systems and accidents and damages during handling. Additionally, a lack of demand hinders the implementation of PPVC in Sri Lanka. Lack of knowledge is identified as the underlying reason for low public acceptance and low demand. Resilience to adopt innovative technologies also impacts the lower demand. However, certain experts noticed a rising demand for PPVC in Sri Lanka. Moreover, a lack of technical expertise and enthusiasm for research and development initiatives act as barriers to the implementation of PPVC. Most of the construction professionals practising in Sri Lanka hesitate to implement PPVC due to the lack of necessary experience and expertise. Similarly, most of the construction companies do not have the technical capability needed for PPVC. Additionally, the material shortage was identified as a barrier to implementing PPVC in Sri Lanka.

Implications of this research shed light on the realm of concurring PPVC in the Sri Lankan CI. An in-depth understanding of the barriers forms the foundation for tailoring strategies to overcome the challenges. Importantly, the government has a leading role to play in overcoming the barriers. Thus, it is recommended to pay attention to the findings when tailoring the government policies. Similarly, practitioners and researchers are encouraged to be inspired by the findings and work collaboratively to overcome the barriers. Despite the fulfilment of the objectives, this study has certain limitations. Herein, all the interviewees represented the contractor’s perspective and no statistical data was collected. Future researchers are encouraged to broaden the study while overcoming the limitations. Herein, investigating the pathways to overcome the identified barriers and comparatively quantifying the CP of PPVC are recommended.

6. REFERENCES

Abdel-Wahab, M., & Vogl, B. (2011). Trends of productivity growth in the construction industry across Europe, US and Japan. *Construction Management and Economics*, *29*(6), 635–644. https://doi.org/10.1080/01446193.2011.573568

Adebowale, O. J., & Agumba, J. N. (2023). A meta-analysis of factors affecting labour productivity of construction SMEs in developing countries. *Journal of Engineering, Design and Technology*, *21*(5), 1441–1460. https://doi.org/10.1108/JEDT-05-2021-0277

Albert, I., Shakantu, W., & Ibrahim, S. (2022). The effect of poor materials management in the construction industry: A case study of Abuja, Nigeria. *Acta Structilia*, *28*(1), 142–167. https://www.ajol.info/index.php/actas/article/view/223096

Arif, M., & Egbu, C. (2010). Making a case for offsite construction in China. *Engineering, Construction and Architectural Management*, *17*(6), 536–548. https://doi.org/10.1108/09699981011090170

Balasbaneh, A. T., & Ramli, M. Z. (2020). A comparative life cycle assessment (LCA) of concrete and steel-prefabricated prefinished volumetric construction structures in Malaysia. *Environmental Science and Pollution Research*, *27*(34), 43186–43201. https://doi.org/10.1007/s11356-020-10141-3

Borg, L., & Song, H. S. (2015). Quality change and implications for productivity development: Housing construction in Sweden 1990–2010. *Journal of Construction Engineering and Management*, *141*(1), 5014014. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000928

Building Construction Authority. (2016). *BIM for DFMA (Design for Manufacturing and Assembly) essential guide*. *Singapore Building and Construction Authority and Bryden Wood*. https://www.corenet.gov.sg/media/2032999/bim_essential_guide_dfma.pdf

Building Construction Authority. (2017). *2nd construction productivity roadmap [media factsheet]*. https://www.nas.gov.sg/archivesonline/data/pdfdoc/20170307002/Annex A - 2nd Construction Productivity Roadmap.pdf

Central Bank of Sri Lanka [CBSL]. (2021). *Annual report: Volume I*. https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annualreports

Chang, Y., Li, X., Masanet, E., Zhang, L., Huang, Z., & Ries, R. (2018). Unlocking the green opportunity for prefabricated buildings and construction in China. *Resources, Conservation and Recycling*, *139*, 259–261. https://doi.org/https://doi.org/10.1016/j.resconrec.2018.08.025

Chen, Y., Okudan, G. E., & Riley, D. R. (2010). Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction*, *19*(2), 235–244. https://doi.org/https://doi.org/10.1016/j.autcon.2009.10.004

Chiang, Y. H., Chan, E. H. W., & Lok, L. K. L. (2006). Prefabrication and barriers to entry—a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, *30*(3), 482–499. https://doi.org/https://doi.org/10.1016/j.habitatint.2004.12.004

Creswell, J. W. (2012). *Educational research: planning, conducting, and evaluating quantitative and qualitative research*. Boston, MA: Pearson Education.

Dixit, S. (2018). Analysing enabling factors affecting the on-site productivity in Indian construction industry. *Periodica Polytechnica Architecture*, *49*(2), 185–193. https://doi.org/10.3311/PPar.12710

Ginigaddara, B., Perera, S., Feng, Y., & Rahnamayiezekavat, P. (2022). Development of an offsite construction typology : A delphi study. *Buildings*, *12*(1), 20. https://doi.org/https://doi.org/10.3390/buildings12010020

Gosling, J., Pero, M., Schoenwitz, M., Towill, D., & Cigolini, R. (2016). Defining and categorizing modules in building projects: An international perspective. *Journal of Construction Engineering and Management*, *142*(11), 4016062. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001181

Gunawardena, T., Karunaratne, R., Ngo, T. D., Mendis, P., & Ngo, T. (2016). Prefabricated construction technologies for the future of Sri Lanka's construction industry. *Proceedings of the 7th International Conference on Sustainable Built Environment*, *December*, 16–18. https://www.researchgate.net/profile/Tharaka-Gunawardena/publication/312032697_Prefabricated_Construction_Technologies_for_the_Futur e_of_Sri_Lanka's_Construction_Industry/links/586b6ef108ae329d6211efc8/Prefabricated-Construction-Technologies-for-the-Futur

Hong, J., Shen, G. Q., Li, Z., Zhang, B., & Zhang, W. (2018). Barriers to promoting prefabricated construction in China: A cost–benefit analysis. *Journal of Cleaner Production*, *172*, 649–660. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.10.171

Hwang, B. G., Shan, M., & Looi, K.-Y. (2018a). Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. *Journal of Cleaner Production*, *183*, 183–193. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.02.136

Hwang, B. G., Shan, M., & Looi, K. Y. (2018b). Knowledge-based decision support system for prefabricated prefinished volumetric construction. *Automation in Construction*, *94*(June), 168–178. https://doi.org/10.1016/j.autcon.2018.06.016

Jaillon, L., & Poon, C. S. (2008). Sustainable construction aspects of using prefabrication in dense urban environment: A Hong Kong case study. *Construction Management and Economics*, *26*(9), 953–966. https://doi.org/10.1080/01446190802259043

Jarkas, A. M., & Radosavljevic, M. (2013). Motivational factors impacting the productivity of construction master craftsmen in Kuwait. *Journal of Management in Engineering*, *29*(4), 446–454. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000160

Jayawardana, J., Jayasinghe, J. A. S. C., Kulatunga, A. K., Sandanayake, M., & Zhang, G. (2023). Prefabricated construction in Sri Lanka: A proposed adoption strategy and a pilot case study from sustainability perspective. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *56*(1), 71–80. https://doi.org/10.1007/978-981-99-3471-3_32

Kamali, M., & Hewage, K. (2016). Life cycle performance of modular buildings: A critical review. *Renewable and Sustainable Energy Reviews*, *62*, 1171–1183. https://doi.org/https://doi.org/10.1016/j.rser.2016.05.031

Kamali, M., & Hewage, K. (2017). Development of performance criteria for sustainability evaluation of modular versus conventional construction methods. *Journal of Cleaner Production*, *142*, 3592–3606. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.10.108

Khaled, F. J., Jawdat, F., & Khalid, I. (2017). The impact of poor planning and management on the Duration of construction projects: A review. *Multi-Knowledge Electronic Comprehensive Journal for Education and Science Publications*, *1*(2), 161–182. https://www.mecsj.com/ar/uplode/images/photo/The_Impact_of_Poor_Planning_and_Management_on_the_Duration_of_Construction_Projects__A_Review_2.pdf

Lee, M. (2017, September 06). HDB widens use of prefab to hit building productivity targets. The Business Times. https://www.businesstimes.com.sg/international/hdb-widens-use-prefab-hit-building-productivity-targets

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X., & Luo, L. (2016). SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. *Habitat International*, *57*, 74–87. https://doi.org/https://doi.org/10.1016/j.habitatint.2016.07.002

Liew, J. Y. R. (2018). *Innovation in modular building construction.* 9th International Conference on Advances in Steel Structures. https://doi.org/10.18057/ICASS2018.K.05

Ma, L., Liu, C., & Mills, A. (2016). Construction labor productivity convergence: a conditional frontier approach. *Engineering, Construction and Architectural Management*, *23*(3), 283–301. https://doi.org/10.1108/ECAM-03-2015-0040

Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2023). Assessment of critical factors influencing the performance of labour in Sri Lankan construction industry. *International Journal of Construction Management*, *23*(1), 144–155. https://doi.org/10.1080/15623599.2020.1854042

Mao, C., Xie, F., Hou, L., Wu, P., Wang, J., & Wang, X. (2016). Cost analysis for sustainable off-site construction based on a multiple-case study in China. *Habitat International*, *57*, 215–222. https://doi.org/https://doi.org/10.1016/j.habitatint.2016.08.002

Murali, K., & Sambath, K. (2020). Prefabrication as a solution to improve productivity of construction industry, Tamilnadu, India. *International Journal of Scientific and Research Publications*, *10*(4), 10068. https://doi.org/10.29322/ijsrp.10.04.2020.p10068

Navaratna, D., & Jayawardane, A. K. W. (2007). Total factor productivity in the building construction industry in Sri Lanka. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *40*(1), 63-70. https://doi.org/10.4038/engineer.v40i1.7129

Nawarathna, W. G. H. K., Abeynayake, M. D. T. E., & Illeperuma, I. E. (2023). Issues caused by employment of migrant workers in the Sri Lankan construction industry. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, T. Ramachandra & Ranadewa K. A. T. O. (Eds.), *11th world construction symposium* (1, pp. 645–657). https://doi.org/10.31705/WCS.2023.53

Nawaz, A., Chen, J., & Su, X. (2023). Exploring the trends in construction and demolition waste (C&DW) research: A scientometric analysis approach. *Sustainable Energy Technologies and Assessments*, *55*, 102953. https://doi.org/10.1016/j.seta.2022.102953

Penttilä, H. (2006). Describing the changes in architectural information technology to understand design complexity and free-form architectural expression. *Electronic Journal of Information Technology in Construction*, *11*, 395–408. https://www.itcon.org/2006/29

Salama, T., Salah, A., & Moselhi, O. (2017). Configuration of hybrid modular construction for residential buildings. *International Journal of Innovation, Management and Technology*, *8*(2), 106–112. https://doi.org/10.18178/ijimt.2017.8.2.712

Shang, G., Pheng, L. S., & Gina, O. L. T. (2021). Understanding the low adoption of prefabrication prefinished volumetric construction (PPVC) among SMEs in Singapore: from a change management perspective. *International Journal of Building Pathology and Adaptation*, *39*(5), 685–701. https://doi.org/10.1108/IJBPA-08-2020-0070

Soyza, S. (2022, May 5). The Sri Lankan construction industry: past, present and future. PIM Aloka Buisness Blog. https://blog.pim.sjp.ac.lk/2022/05/05/the-sri-lankan-construction-industry-past-present-and-future/

Uthpala, H. M. M., & Ramachandra, T. (2015, December). *Study on modern methods of constructions used in Sri Lanka*. 6th International Conference on Structural Engineering and Construction Management, Kandy. 155–162.

Vogl, B. (2015). Measuring construction: prices, output and productivity [Review of the book *Measuring construction: prices, output and productivity*, by R. Best & J. Meikle (Eds.)]. *Construction Management and Economics*, *33*(9), 775–777. https://doi.org/10.1080/01446193.2015.1090616

Wong, R., Hao, J., & Ho, C. M. (2003, June). *Prefabricated building construction systems adopted in Hong Kong*. International Association for Housing Science on Word Congress of Housing: Process and Product, Montreal, Canada.

Wu, Q., & An, X. (2014). Development of a mix design method for SCC based on the rheological characteristics of paste. *Construction and Building Materials*, *53*, 642–651. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.12.008

Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *Journal of Cleaner Production*, *245*, 118861. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.118861

Zhan, W., & Pan, W. (2020). Formulating systemic construction productivity enhancement strategies. *Journal of Construction Engineering and Management*, *146*(8). 05020008 https://doi.org/10.1061/(asce)co.1943-7862.0001886

Zou, P. X. W., Zhang, G., & Wang, J. (2007). Understanding the key risks in construction projects in China. *International Journal of Project Management*, *25*(6), 601–614. https://doi.org/https://doi.org/10.1016/j.ijproman.2007.03.001

Zwikael, O. (2009). Critical planning processes in construction projects. *Construction Innovation*, *9*(4), 372–387. https://doi.org/10.1108/14714170910995921

Bandara, R.M.O.H., Abeynayake, M.D.T.E., Illeperuma, I.E. and Eranga, B.A.I., 2024. Smart contract applications for mitigating disputes in the construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 933-946. DOI: https://doi.org/10.31705/WCS.2024.74. Available from: https://ciobwcs.com/papers/

SMART CONTRACT APPLICATIONS FOR MITIGATING DISPUTES IN THE CONSTRUCTION INDUSTRY

R.M.O.H. Bandara[1], M.D.T.E. Abeynayake[2], I.E. Illeperuma[3], and B.A.I. Eranga[4]

ABSTRACT

Disputes frequently arise in construction projects due to the complexity of the processes and challenging environment, resulting in cost overruns, delays, wastage, and low productivity. Thus, the Construction Industry (CI) is enthusiastic about innovative dispute mitigation measures by incorporating digital technologies. Consequently, Smart Contracts (SCs) have emerged as a pioneering approach to digitise construction contracts and thereby mitigate construction disputes. Accordingly, this research aims to investigate the applications of SCs to mitigate disputes in the Sri Lankan CI. The research aim was approached through an explanatory mixed method. Initially, a questionnaire survey was carried out to collect quantitative data which was followed by qualitative expert interviews. Quantitative data were statistically analysed through Mean Weighted Average (MWA) and Relative Importance Index (RII) whereas qualitative data were analysed through content analysis. The study identified the root causes of construction disputes in the Sri Lankan context as poorly written contracts, poor preparation and approval of drawings, lack of communication and coordination, poor supervision and site management, and contain of contradictory and inaccurate information in the contract documents. The findings highlighted that SCs can significantly reduce construction disputes by replacing ambiguous processes with clear, automated processes. By linking payments to milestones, storing project data transparently, and potentially triggering actions based on safety or quality data, SCs streamline communication, ensure everyone plays by the agreed-upon rules, and thereby minimise disputes. Future researchers are suggested to explore the practical challenges and strategies for implementing SCs in the Sri Lankan CI.

Keywords: *Disputes; Mitigation; Smart Contracts; Sri Lanka.*

1. INTRODUCTION

The inherent complexity and the challenging operational environment of the CI lead to disputes that have detrimental effects on projects such as cost overruns, project delays, high wastage, and low productivity (Kisi et al., 2020; EI-Sayegh et al., 2020). Cheung and Yiu (2007) describe a dispute as a disagreement over an issue related to project

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, oshadha1998hirushan@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mabeynayake@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurii@uom.lk
[4] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurue@uom.lk

operations, typically stemming from differences in the understanding of the situation between two or more parties. A substantial portion of construction projects, ranging from 10% to 30%, encounter significant disputes (Alaloul et al., 2017). Escalating construction disputes are associated with negative social consequences as well. Moreover, infrastructure development projects and government projects face disputes more frequently due to the high complexity (Min et al., 2018).

Understanding the root causes of disputes is crucial for completing construction projects on time and within budget while minimising conflicts (De Alwis et al., 2016; Viswanathan et al., 2020). Researchers discovered factors such as erroneous designs, harsh weather conditions, change orders, and additional work as frequent causes of construction disputes (Kisi et al., 2020). Arcadis reports (2014, 2015, 2016, 2017, 2018, 2019, 2020) further identified failures in managing and administrating contracts, poorly drafted claims, errors in contract documents, inadequate design information, lack of understanding or non-compliance of contractual obligations, negligence in issuing interim decisions on time extensions and compensations as causes of construction disputes.

The literature identified two broad dispute resolution approaches i.e., (i) early resolution methods, and (ii) late resolution methods. However, construction disputes are unavoidable due to differing perceptions among project participants. Consequently, experts focus more on mitigating and resolving disputes (Cheung & Pang, 2014). Dispute Mitigation refers to the strategies and processes used to prevent, manage, and resolve disagreements or conflicts that arise in the CI (El-Adaway, 2008). The goal is to resolve conflicts efficiently, maintain professional relationships, and keep the project on track (Abotaleb, 2018). Importantly, the incorporation of digital technologies is acknowledged as an effective pathway to address the root causes and thereby mitigate construction disputes (Rugină, 2021).

Smart Contracts (SCs) are prime examples of digital technologies that offer a pioneering approach to digitise construction contracts. SCs are self-executing contracts with terms directly written into lines of code and stored using blockchain technology, providing transparency, security, and immutability (Allen et al., 2019). Thus, SCs closely align with conventional construction contracts yet enhance efficiency and effectiveness through automation and thereby mitigate disputes (Li & Kassem, 2021). Additionally, they provide transparent, traceable, and real-time updated construction contracts which improve project management and stakeholder collaboration (Rugină, 2021). Thus, incorporating SCs presents a proactive approach to mitigate disputes in construction contracts by ensuring faithful adherence to the parties' original contractual intentions.

However, the Sri Lankan CI is less immune to the disputes that arise during the project lifecycle (Selvarajha, 2019). Existing studies have explored the applicability, advantages, challenges, and implementation strategies of SCs in the Sri Lankan CI (Anuradha et al., 2023; Weerakoon & Chandanie, 2021). Despite the commendable research efforts that describe the problems and solutions to the application of new technologies in the Sri Lankan CI and the impact of these technologies still, there is a critical gap in using SCs to mitigate construction disputes. However, the potential of SCs in mitigating construction disputes is a crucial aspect to be widely investigated. Thus, this research aims to investigate the applications of SCs to mitigate disputes in the Sri Lankan CI.

2. LITERATURE REVIEW

2.1 CAUSES OF CONSTRUCTION DISPUTES

Causes of construction disputes have been identified by various researchers 1990s. Accordingly, Jahren and Dammeier (1990) categorised the causes as changes in project conditions, payment-related matters, time-related delays, bidding errors, and communication deficiencies. Focusing on the Middle Eastern region, Awwad et al. (2016) categorised causes of disputes into twelve sets, including administrative, contractual, and cultural. Similarly, Cheung and Pang (2014) identified five primary causes of disputes and numerous underlying causes, whereas Marzouk et al. (2011) identified 44 causes. Upon consolidating the various causes of disputes, this study refined a total of 27 causes of disputes and categorised them into five groups, including design-related, employer-related, contractor-related, contractual, and other factors as shown in Table 1.

Table 1: Causes of construction disputes

	Causes of disputes	Reference
Design-related	Time limitations in the design phase	[1], [3], [4], [5], [6], [7],[8]
	Poor design	[2], [9], [17]
	Inadequate or incomplete technical plans/specifications	[1], [18]
	Poor preparation and approval of drawings	[2], [10], [11], [12], [13], [14]
	Material changes and approval during the construction phase	[2], [8], [10], [15], [16]
Employer-related	The slowness of the Employer's decision-making process	[3], [10], [23]
	Inadequate early planning of the project	[3], [10], [22], [23]
	Failure to make interim awards on extensions of time and compensation by the Employer	[1], [20], [21], [22], [23]
	Variations initiated by the Employer (additive/deductive)	[1], [24], [25], [26]
	Poor Financing by the Employer	[2], [10], [12], [19], [26]
Contractor-related	Low financing by the contractor during construction	[2], [10], [12], [14]
	Shortage and unproductive workers	[10], [19], [24], [28]
	Inadequate site investigation	[2], [11], [14]
	Poorly defined scope of work	[3], [7], [8], [10], [16], [19]
	Poor supervision and site management	[3], [10], [30],
	Unsuitable leadership style of construction/project manager	[3], [4], [5], [10], [27], [28]
	Underestimation and incompetence of contractors	[1], [10], [23],
Contract - related	Poorly written contracts	[5], [10], [12], [27], [30]
	Differing Site Conditions	[9], [18], [29]
	Contract Amendments	[1], [20], [21]
	Contradictory and inaccurate information in the contract documents	[1], [5], [16]
Other	Lack of communication and coordination between parties during construction	[1], [5], [9]
	Modifying legislation and regulations	[3], [5], [7] , [15] , [16]

Reference :- [1] - (Awwad et al., 2016) , [2] - (Zaneldin, 2006) , [3] - (AL Mousli & El-Sayegh, 2016) , [4] - (Arain et al., 2006) , [5] - (Arain & Assaf, 2007) , [6] - (Lopez & Love, 2012), [7] - (Love et al., 2011), [8] - (Love et al., 2014), [9] - (Gad et al., 2011), [10] - (Faridi & El-Sayegh, 2006), [11] -

Causes of disputes	Reference
(Mehany & Grigg, 2015) , [12] - (Farooqui et al., 2014), [13] – (Jergeas, 2001), [14] - (Mishmish & El-Sayegh, 2018), [15] - (Al-Dubaisi, 2000), [16] - (Weshah et al., 2013), [17] - (Ng et al., 2007), [18] - (Pineda Jr et al., 2023), [19] - (Ling & Poh, 2008), [20] - (Braimah, 2013), [21] - (Iyer et al., 2008), [22] - (Bramble & Callahan, 2010), [23] - (Shabbab, 2016), [24] - (Keane et al., 2010), [25] - (Enshassi et al., 2010), [26] - (Al-Nuaimi et al., 2010), [27] - (El-Sayegh, 2008), [28] - (Elmualim & Gilder, 2014), [29] - (Hickson & Ellis, 2014), [30] - (Charehzehi et al., 2017)	

Design-related disputes arise due to short deadlines for design submission, insufficient technical plans, material specifications changes, and disputes between designers and employers (Mohd et al., 2014). Employer-related disputes result from prolonged decision-making, insufficient early planning, and seeking project variations (Mishmish & El-Sayegh, 2018). Contractor-related disputes arise from insufficient funding, subpar productivity, inadequate site investigations, and inadequate supervision (Trangkanont et al., 2018). Contract-related disputes can arise from poorly drafted contracts, particularly when differing site conditions occur (Eastman, 2011; Mitropoulos & Howell, 2001).

Other disputes can arise from nation-specific laws and regulations, unsuitable weather, lack of coordination, and projects requiring permissions or approvals from municipalities or government bodies. According to De Alwis et al (2016) and Illankoon et al (2022) poorly written contracts, poorly defined scope of work and poor design were the most significant causes of disputes in Sri Lankan CI.

2.2 ROLE OF SMART CONTRACTS IN MITIGATING DISPUTES IN THE CONSTRUCTION INDUSTRY

SCs powered by blockchain technology are revolutionising the CI by reducing uncertainty and ensuring clear terms (Samarasinghe & Wood, 2021). These self-executing contracts with immutable records significantly reduce disputes by improving transparency, efficiency, and automation. Further, SCs provide a record of all agreements and transactions on the blockchain, eliminating misunderstandings or disagreements over contract terms (Ye et al., 2022). According to Li and Kassem (2021), SC used an automated payment process, transparency, supply chain management, streamlined claim management process and dispute management process and enhanced safety compliance as a dispute mitigation application. Automated payments are tied to specific milestones, removing subjectivity and disputes over delayed or withheld payments (Sigalov et al., 2021). This improves transparency by providing an immutable record of all transactions and project data. Dubai's One Museum Project is a great example of a consortium piloting SCs for automated payments and streamlined approvals (Al Barghuthi et al, 2019). Additionally, SCs eliminate intermediaries such as lawyers or brokers, reducing the likelihood of disputes caused by miscommunication or conflicting interpretations of contract terms (Ahmadisheykhsarmast & Sonmez, 2018). SCs act as automated referees, enforcing clear terms and linking payments to achieved milestones. This transparency combined with the ability to tie actions to real-time data on safety or quality can streamline communication, ensure everyone follows the agreed-upon rules, and minimise disagreements. Integration with IoT devices facilitates real-time updates and monitoring, which helps in immediate reporting and issue resolution (Borgia, 2014). Accordingly, SCs can be effectively used to mitigate disputes in the CI. However, SCs have not yet been extensively studied resulting in a research niche to be fulfilled.

3. METHODOLOGY

Identifying the causes of disputes and their relative importance requires quantitative data whereas investigating the applicability of SCs in the Sri Lankan context needs qualitative data. Accordingly, this research employed a mixed-method approach to accomplish the research aim. An explanatory design was followed as it was necessary to assess quantitative before qualitative data to comprehensively investigate the applications of SC technology to mitigate disputes in the Sri Lankan CI.

As the first step of the data collection, a questionnaire survey was conducted to collect the quantitative data. The questionnaire consisted of two sections where section A focused on the background information of respondents and section B focused on the causes of disputes in the CI. The questionnaire was disseminated among a group of 50 CI professionals who were selected through convenience sampling based on their experience in handling construction disputes. Accordingly, 34 completed responses were received, reporting a response rate of 68%. Collected data were statistically analysed through Mean Weighted Average (MWA) and Relative Importance Index (RII) (Equation 01). A 5-point Likert scale analysis was used to rank the responses of experts where; 1-Not impacted; 2-Less impacted; 3-Average; 4-impacted; 5-Strongly impacted. By considering both significance and severity, the RII scores greater than 0.750 were identified as having the most significant impact on disputes in the CI.

$$RII = \frac{5n5+4n4+3n3+2n2+1n1}{A*N} \qquad \textit{(Eq. 01)}$$

Where, n5=Number of respondents for strongly substantial; n4=Number of respondents for substantial; n3=Number of respondents for average; n2=Number of respondents for less substantial; nl=Number of respondents for not substantial; A=Highest average and N=Total number of respondents (n1+n2+n3+n4+n5)

The qualitative approach allows the collection of data from comparatively a lesser number of participants and analyses in-depth (Creswell, 2012). Thus, the survey was followed by expert interviews to collect qualitative data. In-depth interviews reflect interviewees' perspectives based on their experiences and understanding. Semi-structured interviews, while being guided by a defined framework allow the researcher for situational questioning based on the responses. Thus, semi-structured interviews were conducted with six interviewees who were selected through purposive sampling, considering knowledge and experience in working with SCs. Table 2 presents the profiles of the interviewees together with the selection criteria.

Table 2: Interviewee profiles and selection criteria

Interviewee	Criteria: Compulsory Qualifications: At least 10 years of working experience in the CI	Criteria: Compulsory Qualifications: Knowledge and interest in SCs	Criteria: Additional Qualifications (at least two criteria must be satisfied): Completed a post-graduate qualification related to claims management	Knowledge and interest in BIM	Knowledge and interest in Blockchain	Knowledge and interest in IoT	Knowledge in construction dispute mitigation	Accessibility
E1	√	√	√	√	√		√	√

Interviewee	Criteria							Accessibility
	Compulsory Qualifications		Additional Qualifications (at least two criteria must be satisfied)					
	At least 10 years of working experience in the CI	Knowledge and interest in SCs	Completed a post-graduate qualification related to claims management	Knowledge and interest in BIM	Knowledge and interest in Blockchain	Knowledge and interest in IoT	Knowledge in construction dispute mitigation	
E2	√	√		√	√		√	√
E3	√	√		√	√		√	√
E4	√	√		√	√	√	√	√
E5	√	√		√	√	√	√	√
E5	√	√		√	√	√	√	√
E6	√	√		√	√	√	√	√

Interviews were conducted through online platforms, i.e., Zoom and Microsoft Teams, and each spanned between 45 and 60 minutes. Interviewees were questioned under three major sections based on the prepared interview guidelines. In the first section, the interviewee's background details were questioned. The second section focused on the applications of SC in the CI, whereas the third section focused on SC in mitigating construction disputes. Situational questions were raised to clarify and explore the details further. Collected data was analysed through manual content analysis, and conclusions were drawn.

4. RESEARCH FINDINGS AND DISCUSSION

4.1 ANALYSIS OF THE QUESTIONNAIRE SURVEY

The questionnaire survey was conducted to identify the causes of disputes in the Sri Lankan CI. Table 3 provides the characteristics of the respondents based on their employment.

Table 3: Respondents' profiles based on employment.

Employment	No. of Responses	Percentage
Consultant party	16	47%
Contractor party	15	44%
Employer party	3	9%

Accordingly, consultants comprised 47% of the respondents, followed by contractors at 44% and employers at 9%. This diverse representation of different perspectives provides a comprehensive understanding of dispute dynamics. Additionally, Figure 1 represents the respondents' level of experience.

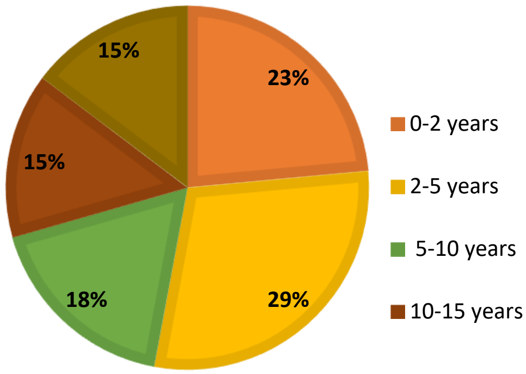


Figure 1: Respondents' level of experience

Results reflected that the survey employed respondents with varying levels of experience, with 66% falling within the two to ten years bracket and 15% having over 15 years of experience.

Upon collecting the background data, respondents were given a list of causes of construction disputes identified through the literature review and asked to measure the significance of each cause in the Sri Lankan context. As per the results of the questionnaire survey, the causes were ranked under the RII score. Table 4 presents the overall ranking of the causes of disputes along with the RII score.

Table 4: Ranking of the causes of disputes

Causes	RII	MWA	Rank
Poorly written contracts	0.827	4.198	1
Poor preparation and approval of drawings	0.809	3.923	2
Lack of communication and coordination between parties during construction	0.809	4.066	2
Poor supervision and site management	0.797	4.000	4
Contradictory and inaccurate information in the contract documents	0.786	3.923	5
Poorly defined scope of work	0.768	3.802	6
Poor design -Conflicts in construction drawings	0.762	3.758	7
Underestimation and incompetence of contractors	0.762	3.945	7
The slowness of the Employer's decision-making process	0.751	3.846	9
Unsuitable leadership style of construction/project manager	0.735	3.780	10
Inadequate or incomplete technical plans/specification	0.729	3.615	11
Variations initiated by the Employer (additive/deductive)	0.729	3.582	11
Poor Financing by the Employer	0.729	3.626	11
Inadequate site investigation	0.729	3.703	14
Inadequate early planning of the project	0.724	3.648	15

Causes	RII	MWA	Rank
Failure to make interim awards on extensions of time and compensation by the Employer	0.724	3.538	15
Material changes and approval during the construction phase	0.712	3.538	17
Differing site conditions	0.694	3.418	18
Modifying legislation and regulations	0.676	3.330	19
Shortage and unproductive workers	0.671	3.385	20
Low financing by the contractor during construction	0.647	3.176	21
Contract Amendments	0.647	3.121	21
Time limitations in the design phase	0.641	3.385	23

In a similar study, Abotaleb (2018) considered the causes with more than 0.750 RII scores as highly impacted causes of disputes. Accordingly, out of the 23 analysed causes, nine were in highly impacted category. Moreover, poorly written contracts were the most significant cause of dispute in the Sri Lankan CI. Further, the results highlighted the importance of unambiguous contractual agreements in preventing and resolving conflicts. The lack of effective communication and coordination between parties during construction is another impactful cause of disputes. Confirming the findings of Awwad et al. (2016), results revealed that design, planning, and decision-making challenges contribute to disputes, creating issues in the preparation and approval of drawings and technical plans and delays in decision-making. In support of Abrey and Smallwood (2014), contractual ambiguities and inconsistencies exacerbate disputes, emphasising the need for precise contractual frameworks. In favour of Mehany and Grigg (2015) operational and managerial challenges such as poor financing practices, inadequate site investigation, and poor workforce productivity fuel disputes. Thus, the findings underscore the need for robust financial planning, thorough site assessments, and diligent project oversight to address potential triggers of disputes before they escalate.

4.2 Analysis of the Expert Interviews

Since the literature review primarily explored the causes of disputes in the CI and using SCs in dispute mitigation, the expert interviews aimed to study the application of SCs in the Sri Lankan context and its potential benefits in mitigating construction disputes.

4.2.1 Potential Applications of Smart Contracts in the Sri Lankan Construction Industry

Initially, the interviewees were questioned about the potential applications of SCs in the Sri Lankan CI. The literature revealed five potential SC applications in dispute mitigation. Thus, the interviewees were asked to comment on their suitability in the Sri Lankan context and to suggest any possible applications. Table 5 presents the findings.

Table 5: Application of SCs in the Sri Lankan CI

Applications of SCs in the Sri Lankan CI	E1	E2	E3	E4	E5	E6
Automated payment process	√	√	√	√	√	√
Enhanced transparency	√	√	√	√	√	√
Improved supply chain management	√	√	√	√	√	√

Applications of SCs in the Sri Lankan CI	E1	E2	E3	E4	E5	E6
Streamlined claim management process & dispute management process	√	√	√	√	√	√
Enhanced safety compliance	√	√	√	√	√	√
Quality Assurance (QA) & Quality Control (QC) procedure	√	√	√			√

Accordingly, all the experts confirmed the findings of the literature regarding the applications of SC to mitigate construction disputes. E1 additionally suggested the use of SCs in QA and QC procedures which was confirmed by E2, E3, and E6. Agreeing with Ahmadisheykhsarmast and Sonmez, (2020), all the interviewees discussed the benefits of SCs in the automated payment process highlighting the importance of accurate billing and informing contractors about completed tasks. Furthermore, E5 mentioned that "*after all updates happen the SC takes a look at the quantities of work that have been completed automatically calculated from the updated module. Then, based on those quantities, it processes the payment*". Clarifying Sigalov et al. (2021), E1 and E3 highlighted the roles of blockchain and BIM integration in providing complete records of project progress and transactions, increasing accountability and trust among stakeholders. E4, E5, and E6 emphasised the immutability of SC data, enhancing transparency and minimising errors. Confirming the idea of Li and Kassem (2021) E5 claimed that "*transparency is very high in SCs as once something is stored or stated in the system, it cannot be changed"*.

Agreeing with Lu et al. (2021) E1, E2, E3, and E6 emphasised the importance of integrating construction programs with supply chain management systems to monitor activities effectively. SCs facilitate keeping projects on schedule and within budget by reducing costs and minimising delays. Moreover, E1 stated, "*SCs are used in QA and QC procedures by gathering real-time data on construction progress and quality and analysing it against predefined quality criteria*." Accordingly, it refines the quality standards and processes for future projects, leading to continuous improvements in project quality and efficiency.

The application of SC can be used to mitigate construction disputes. SC are self-written programs based on clear terms. This removes ambiguity and ensures everyone involved is on the same page. Additionally, Smart Contracts (SCs) can link approved drawings to material orders and payments. If there is a discrepancy, the automated process can be halted, preventing issues and potential disputes. Apart from that all information about the project, including approvals, changes, and communication, is stored on a secure, shared ledger. This fosters better communication and reduces misunderstandings. Moreover, SC can be linked to sensors or monitoring systems that track safety protocols and quality control measures. If a breach occurs, the contract can automatically trigger corrective actions or halt work, preventing accidents and rework disputes

4.2.2 Benefits of using Smart Contracts in Mitigating Construction Disputes

According to E1, E4, E5 and E6, SCs automate several manual tasks in claim management, such as data collection, verification, and payment processing. This significantly reduces the administrative burden on contracting parties. E1 stated that "*traditional claim management involves a lot of paperwork, back-and-forth communication, and manual data processing. However, SCs automate many of these tasks"*. For instance, SCs trigger payments upon completion of specific milestones as defined in the contract. Moreover, E1, E2 and E3 highlighted the SC's capability in document storing, document managing and communicating electronically, which allows automatic claim calculations and verification based on pre-defined criteria. SCs provide a transparent record of transactions and interactions between parties, fostering trust and reducing disputes by ensuring everyone clearly understands the contractual terms and obligations.

E1, E2, E4, and E6 highlighted the benefits of SCs in dispute resolution. SCs automate contract terms, release withheld funds, and trigger arbitration mechanisms, saving time and money compared to traditional litigation methods. E2, E3, and E5 highlighted the importance of a complete record of contract activity for accurate decision-making. SCs facilitate better communication and collaboration between parties by providing a shared platform for storing and accessing contract information. E4 highlighted the reduction in administrative costs associated with claim management and faster dispute resolution with minimal legal fees.

According to SC E1, E2, E4 and E6 based strategies offer innovative solutions to design-related disputes, such as using messaging or flagging systems within contracts to address ambiguities or discrepancies in drawings and integrating smart validation tools within BIM systems to automate checks for compliance and accuracy. This streamlines the drawing review and approval process, ensuring efficiency and consistency while minimising disputes. Additionally, SC-based strategies can assist engineers in making informed decisions more efficiently, leveraging advanced technologies and automation. These strategies aim to minimise delays and ensure smoother project execution in the construction industry.

5. CONCLUSIONS

This research provides valuable insights into the causes of construction disputes and the potential use of SCs to mitigate the disputes. Importantly, it contributes to filling a research gap in the technology-based dispute mitigation measures in the Sri Lankan context. The findings reveal that poorly written contracts, poor preparation and approval of drawings, and lack of communication and coordination between parties during construction are the most significant contributors to disputes in the Sri Lankan CI. Subsequently, the application of SCs presents a proactive approach to mitigate these disputes by ensuring faithful adherence to the parties' original contractual intentions. SCs enhance transparency, improve supply chain management, streamline claim and dispute management processes, and enhance safety compliance and QA QC procedures.

Furthermore, the research underscores the transformative potential of SCs in revolutionising the CI. By automating payment processes, enhancing transparency and traceability, facilitating efficient dispute resolution, improving communication and collaboration, enabling accurate decision-making, and enhancing value for money, SCs offer a promising solution to the perennial problem of construction disputes. However, the successful implementation of SCs requires a comprehensive understanding of their potential benefits and challenges, as well as a conducive regulatory and technological environment. Thus, future research could further explore the practical challenges and strategies for implementing SCs in the Sri Lankan CI.

6. REFERENCES

Alaloul, W. S., Liew, M. S., & Zawawi, N. A. W. (2017). Communication, coordination and cooperation in construction projects: Business environment and human behaviours. *IOP Conference Series: Materials Science and Engineering*, *291*(1), 012003. https://doi.org/10.1088/1757-899X/291/1/012003

Al-Dubaisi, A. H. (2000). *Change orders in construction projects in Saudi Arabia*. [Masters thesis, King Fahd University of Petroleum and Minerals]. https://faculty.kfupm.edu.sa/CEM/assaf/Students_Reports/Change-Orders-in-Construction.pdf

Allen, D. W. E., Lane, A. M., & Poblet, M. (2019). The governance of blockchain dispute resolution. *Harvard Negotiation Law Review*, *25*, 75-101. https://dx.doi.org/10.2139/ssrn.3334674

Al-Nuaimi, A. S., Taha, R. A., Al Mohsin, M., & Al-Harthi, A. S. (2010). Causes, effects, benefits, and remedies of change orders on public construction projects in Oman. *Journal of Construction Engineering and Management*, *136*(5), 615–622. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000154

Anuradha, I. G. N., Ambagala, K. K., Nanayakkara, S., & Perera, S. (2023, July 22*). Adaptation of blockchain and smart contracts to the construction industry of developing countries*. 11th World Construction Symposium 2023, Sri Lanka [Online]. https://doi.org/10.31705/WCS.2023.7

Arain, F., & Assaf, S. (2007). Consultant's prospects of the sources of design and construction interface problems in large building projects in Saudi Arabia. *Journal of King Abdulaziz University-Environmental Design Sciences*, *5*(1), 15–37. https://doi.org/10.4197/env.5-1.2

Arain, F. M., Pheng, L. S., & Assaf, S. A. (2006). Contractors' views of the potential causes of inconsistencies between design and construction in Saudi Arabia. *Journal of Performance of Constructed Facilities*, *20*(1), 74–83. https://doi.org/10.1061/(ASCE)0887-3828(2006)20:1(74)

Arcadis. (2014). *Global construction disputes report: Getting the basics right*. https://www.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/2020/global-construction-disputes-2020/global-construction-disputes-report-2014.pdf

Arcadis. (2015). *Global construction disputes report: The higher the stakes, the bigger the risk*. https://www.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/2020/global-construction-disputes-2020/global-construction-disputes-report-2015.pdf

Arcadis. (2016). *Global construction disputes report 2016*. https://media.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/2020/global-construction-disputes-2020/global-construction-disputes-report-2016.pdf?rev=-1

Arcadis. (2017). *Global construction disputes report: Avoiding the same pitfalls. https://www.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/2020/global-construction-disputes-2020/global-construction-disputes-report-2017.pdf*

Arcadis. (2018). Global construction disputes report 2018 does the construction industry learn from its mistakes?. https://www.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/2020/global-construction-disputes-2020/global-construction-disputes-report-2018.pdf

Arcadis. (2019). *Global construction disputes report: Laying the foundation for success*. https://www.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/2020/global-construction-disputes-2020/global-construction-disputes-report-2019.pdf

Arcadis. (2020). *Global construction disputes report: Collaborating to achieve project excellence.* https://www.arcadis.com/-/media/project/arcadiscom/com/perspectives/middle-east/2020/global-construction-disputes-report-2020/me-global-construction-disputes-report-2020.pdf

Awwad, R., Barakat, B., & Menassa, C. (2016). Understanding dispute resolution in the Middle East region from perspectives of different stakeholders. *Journal of Management in Engineering*, *32*(6), 05016019. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000465

Braimah, N. (2013). Construction delay analysis techniques—A review of application issues and improvement needs. *Buildings*, *3*(3), 506–531. https://doi.org/10.3390/buildings3030506

Bramble, B. B., & Callahan, M. T. (2010). *Construction delay claims*. Aspen publishers. https://www.semanticscholar.org/paper/Construction-Delay-Claims-Bramble-Callahan/077d7e8a9f317d84bd12930e57f341e659d55aee

Borgia, E. (2014). The internet of things vision: Key features, applications and open issues. *Computer Communications*, *54*, 1-31. https://doi.org/10.1016/j.comcom.2014.09.008

Charehzehi, A., Chai, C., Yusof, M. D., Chong, H-Y., & Loo, S. C. (2017). Building information modeling in construction conflict management. *International Journal of Engineering Business Management*, *9*. https://doi.org/10.1177/1847979017746257

Cheung, S. O., & Pang, H. Y. (2014). Conceptualising construction disputes. In *Construction Dispute Research* (pp. 19–37). Springer International Publishing. https://doi.org/10.1007/978-3-319-04429-3_2

Cheung, S. O., & Yiu, K. T. W. (2007). A study of construction mediator tactics—part I: Taxonomies of dispute sources, mediator tactics and mediation outcomes. *Building and Environment*, *42*(2), 752–761. https://doi.org/10.1016/j.buildenv.2005.09.004

Creswell, J.W. (2012). Educational research: planning, conducting, and evaluating quantitative and qualitative research (4th edition). Pearson Education.

De Alwis, I., Abeynayake, M., & Francis, M. (2016). Dispute avoidance model for Sri Lankan construction industry. In Y.G. Sandanayake, G.I. Karunasena & T. Ramachandra (Eds.), *Greening environment, eco-innovations & entrepreneurship* (pp. 162-173). Ceylon Institute of Builders. https://ciobwcs.com/downloads/WCS2016-Proceedings.pdf

Eastman, C. M. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. Wiley. https://doi.org/10.1002/9781119287568

El-adaway, I. H. (2008). *Construction dispute mitigation through multi-agent based simulation and risk management modeling*. [Doctoral dissertation, Iowa State University]. Digital Repository, Iowa State University. https://dr.lib.iastate.edu/entities/publication/bcda7356-87e7-43df-b88d-ce3ce00a6608/full

Elmualim, A., & Gilder, J. (2014). BIM: Innovation in design management, influence and challenges of implementation. *Architectural Engineering and Design Management*, *10*(3–4), 183–199. https://doi.org/10.1080/17452007.2013.821399

El-Sayegh, S., Ahmad, I., Aljanabi, M., Herzallah, R., Metry, S., & El-Ashwal, O. (2020). Construction disputes in the UAE: Causes and resolution methods. *Buildings, 10*(10). https://doi.org/10.3390/BUILDINGS10100171

El-Sayegh, S. M. (2008). Risk assessment and allocation in the UAE construction industry. *International Journal of Project Management, 26*(4), 431–438. https://doi.org/10.1016/j.ijproman.2007.07.004

Enshassi, A., Arain, F., & Al-Raee, S. (2010). Causes of variation orders in construction projects in the Gaza Strip. *Journal of Civil Engineering and Management*, *16*(4), 540–551. https://doi.org/10.3846/jcem.2010.60

Faridi, A. S., & El-Sayegh, S. M. (2006). Significant factors causing delay in the UAE construction industry. *Construction Management and Economics*, *24*(11), 1167–1176. https://doi.org/10.1080/01446190600827033

Farooqui, R. U., Azhar, S., & Umer, M. (2014, June). *Key causes of disputes in the Pakistani construction industry-assessment of trends from the viewpoint of contractors*. (pp. 26–28). 50th ASC Annual International Conference, Blacksburg, Virginia. https://www.researchgate.net/publication/354537287_Key_Causes_of_Disputes_in_the_Pakistani_Construction_Industry-Assessment_of_Trends_from_the_Viewpoint_of_Contractors

Gad, G. M., Kalidindi, S. N., Shane, J., & Strong, K. (2011). Analytical framework for the choice of dispute resolution methods in international construction projects based on risk factors. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 3*(2), 79–85. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000067

Hickson, B. G., & Ellis, L. A. (2014). Factors affecting construction labour productivity in Trinidad and Tobago. *The Journal of the Association of Professional Engineers of Trinidad and Tobago*, *42*(1), 4–11.

Illankoon, I. M. C. S., Tam, V. W. Y., Le, K. N., & Ranadewa, K. A. T. O. (2022). Causes of disputes, factors affecting dispute resolution and effective alternative dispute resolution for Sri Lankan construction industry. *International Journal of Construction Management, 22*(2), 218–228. https://doi.org/10.1080/15623599.2019.1616415

Iyer, K. C., Chaphalkar, N. B., & Joshi, G. A. (2008). Understanding time delay disputes in construction contracts. *International Journal of Project Management*, *26*(2), 174–184. https://doi.org/10.1016/j.ijproman.2007.05.002

Jahren, C. T., & Dammeier, B. F. (1990). Investigation into construction disputes. *Journal of Management in Engineering*, *6*(1), 39–46. https://doi.org/10.1061/(ASCE)9742-597X(1990)6:1(39)

Jergeas, G. F. (2001). Claims and disputes in the construction industry. AACE international transactions. *2001 AACE international transactions* CD31.

https://www.proquest.com/openview/ff19b40e8584a57f47f2472775885836/1?pq-origsite=gscholar&cbl=27161

Keane, P., Sertyesilisik, B., & Ross, A. D. (2010). Variations and change orders on construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *2*(2), 89–96. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000016

Kisi, K. P., Lee, N., Kayastha, R., & Kovel, J. (2020). Alternative dispute resolution practices in international road construction contracts. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 12*(2). https://doi.org/10.1061/(ASCE)LA.1943-4170.0000373

Viswanathan, S.K., Panwar, A., Kar, S., Lavingiya, R., & Jha, K. N. (2020). Causal modeling of disputes in construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 12*(4). https://doi.org/10.1061/(ASCE)LA.1943-4170.0000432

Li, J., & Kassem, M. (2021). Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. *Automation in Construction*, *132*, 103955. https://doi.org/10.1016/j.autcon.2021.103955

Ling, F. Y. Y., & Poh, B. H. M. (2008). Problems encountered by owners of design–build projects in Singapore. *International Journal of Project Management*, *26*(2), 164–173. https://doi.org/10.1016/j.ijproman.2007.04.001

Lopez, R., & Love, P. E. D. (2012). Design error costs in construction projects. *Journal of Construction Engineering and Management*, *138*(5), 585–593. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000454

Love, P. E. D., Davis, P. R., Cheung, S. O., & Irani, Z. (2011). Causal discovery and inference of project disputes. *IEEE Transactions on Engineering Management*, *58*(3), 400–411. https://doi.org/10.1109/TEM.2010.2048907

Love, P. E. D., Lopez, R., Kim, J. T., & Kim, M. J. (2014). Influence of organizational and project practices on design error costs. *Journal of Performance of Constructed Facilities*, *28*(2), 303–310. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000415

Lu, W., Li, X., Xue, F., Zhao, R., Wu, L., & Yeh, A. G. O. (2021). Exploring smart construction objects as blockchain oracles in construction supply chain management. *Automation in Construction*, *129*, 103816. https://doi.org/10.1016/j.autcon.2021.103816

Marzouk, M., El-Mesteckawi, L., & El-Said, M. (2011). Dispute resolution aided tool for construction projects in Egypt. *Journal of Civil Engineering and Management*, *17*(1), 63–71. https://doi.org/10.3846/13923730.2011.554165

Mehany, M., & Grigg, N. (2015). Causes of road and bridge construction claims: Analysis of Colorado department of transportation projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *7*(2), 04514006. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000162

Min, J. H., Jang, W., Han, S. H., Kim, D., & Kwak, Y. H. (2018). How conflict occurs and what causes conflict: Conflict analysis framework for public infrastructure projects. *Journal of Management in Engineering*, *34*(4), 04018019. https://doi.org/10.1061/(ASCE)ME.1943-5479.00006

Mishmish, M., & El-Sayegh, S. M. (2018). Causes of claims in road construction projects in the UAE. *International Journal of Construction Management*, *18*(1), 26–33. https://doi.org/10.1080/15623599.2016.1230959

Mitropoulos, P., & Howell, G. (2001). Model for understanding, preventing, and resolving project disputes. *Journal of Construction Engineering and Management*, *127*(3), 223–231. https://doi.org/10.1061/(ASCE)0733-9364(2001)127:3(223)

Mohd Nawi, M. N., Baluch, N., & Bahauddin, A. Y. (2014). Impact of fragmentation issue in construction industry: An overview. *MATEC Web of Conferences*, *15*, 01009. https://doi.org/10.1051/matecconf/20141501009

Ng, H. S., Peña-Mora, F., & Tamaki, T. (2007). Dynamic conflict management in large-scale design and construction projects. *Journal of Management in Engineering*, *23*(2), 52–66. https://doi.org/10.1061/(ASCE)0742-597X(2007)23:2(5

Pineda Jr, H. E., Salvacion, A. M., De Leon, P. J. A., Rafanan, J. D., Magat, A. J. A. Y. P., & Manalang, J. S. (2023). Alternative Dispute Resolution Methods: An Action Plan for Construction-Related Disputes within the City of San Fernando, Pampanga. *Iconic Research and Engineering Journals*, *6*(12), 625-645. https://www.irejournals.com/formatedpaper/17047091.pdf

Rugină, C. R. (2021). Smart contracts technology and avoidance of disputes in construction contracts. *Lex ET Scientia International Journal*, *28*(2), 30-46. https://www.ceeol.com/search/article-detail?id=1002745

Samarasinghe, D. A. S., & Wood, E. (2021). Innovative digital technologies. *Handbook of Research on Driving Transformational Change in the Digital Built Environment* (pp. 142–163). IGI Global. https://doi.org/10.4018/978-1-7998-6600-8.ch006

Selvarajha, S. (2019). *An analysis of disputes related to earth retaining structure construction projects in Sri Lanka*. [master's theses]. University of Moratuwa.

Shabbab Al Hammadi, M. (2016). Study of delay factors in construction projects. *International Advanced Research Journal in Science, Engineering and Technology*, *3*(4), 87–93. https://doi.org/10.17148/IARJSET.2016.3420

Sigalov, K., Ye, X., König, M., Hagedorn, P., Blum, F., Severin, B., Hettmer, M., Hückinghaus, P., Wölkerling, J., & Groß, D. (2021). Automated Payment and Contract Management in the Construction Industry by Integrating Building Information Modeling and Blockchain-Based Smart Contracts. *Applied Sciences*, *11*(16), 7653. https://doi.org/10.3390/app11167653

Trangkanont, S., Wichaiphruek, T., & Uttaraphon, P. (2018). Impacts of dispute on project cost: Contractors'perspective. *International Journal of GEOMATE* , *14*(45), 210–221. https://doi.org/10.21660/2018.45.cem62

Weerakoon, H. D., & Chandanie, H. (2021). Analysis of feasibility of blockchain technology for international trade related to Sri Lankan construction industry. In Y.G. Sandanayake, S. Gunatilake, and K.G.A.S. Waidyasekara, (Eds.), Proceedings of the 9th World Construction Symposium (pp. 75-85) https://doi.org/10.31705/WCS.2021.7.

Weshah, N., Ghandour, W. El, Jergeas, G., & Falls, L. C. (2013). Factor analysis of the interface management (IM) problems for construction projects in Alberta. *Canadian Journal of Civil Engineering*, *40*(9), 848–860. https://doi.org/10.1139/cjce-2012-0531

Ye, X., Zeng, N., & König, M. (2022). Systematic literature review on smart contracts in the construction industry: Potentials, benefits, and challenges. *Frontiers of Engineering Management 9*(2), 96–213). https://doi.org/10.1007/s42524-022-0188-2

Zaneldin, E. K. (2006). Construction claims in United Arab Emirates: Types, causes, and frequency. *International Journal of Project Management*, *24*(5), 453–459. https://doi.org/10.1016/j.ijproman.2006.02.006

Parameswaran, A., Ranadewa, K.A.T.O., Rajini, P.A.D. and Jayanetti, J.K.D.D.T., 2024. State-of-the-art lean learning practices in construction: A case study in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 947-960. DOI: https://doi.org/10.31705/WCS.2024.75. Available from: https://ciobwcs.com/papers/

STATE-OF-THE-ART LEAN LEARNING PRACTICES IN CONSTRUCTION: A CASE STUDY IN SRI LANKA

Agana Parameswaran[1], K.A.T.O. Ranadewa[2], P.A.D. Rajini[3] and J.K.D.D.T. Jayanetti[4]

ABSTRACT

Integrating lean learning practices in construction is paramount for elevating project quality, thus bolstering industry competitiveness and sustainability. However, there exists a notable dearth of research addressing lean learning practices specifically within the Sri Lankan construction industry. Therefore, this study aims to investigate the state-of-the-art lean learning practices in the Sri Lankan construction industry. An interpretivism stance is adopted, and a qualitative research approach is used. A case study strategy was adopted, focusing on three large Sri Lankan contracting organisations selected through purposive sampling. Data was collected through semi-structured interviews with fifteen experienced individuals, and document reviews. The collected data was then analysed using code-based content analysis using NVivo 12. Different lean tools, including Last Planner System (LPS), Value Stream Mapping (VSM), and 5S, are presently being utilised in an ad-hoc manner within contracting organisations. Comprehensive lean learning practices, including regular training sessions, workshops, and hands-on exercises, were emphasised to translate theoretical lean concepts into practical knowledge. By identifying the ad-hoc nature of their implementation, the study shed light on the importance of structured lean learning initiatives tailored to different organisational levels. It is recommended to implement clear communication channels, ongoing training, and a culture of continuous improvement for sustaining lean transformation in the Sri Lankan construction industry. By focusing on lean learning practices, the topic acknowledges the continuous improvement aspect of lean construction, emphasising the need for ongoing education and skill development within construction teams. This study has the potential to contribute valuable insights to both academia and industry practitioners seeking to enhance efficiency, quality, and sustainability in construction projects.

Keywords: *Construction Industry; Lean Construction; Lean Learning; Lean Tool; Sri Lanka.*

1. INTRODUCTION

[1] PhD Scholar, School of Engineering, Design and Built Environment, Western Sydney University, Australia, aganaparameswaran@gmail.com

[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, tharushar@uom.lk

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

[4] Lecturer, Department of Quantity Surveying, General Sir John Kotelawala Defence University, Sri Lanka, qsthamasha@gmail.com

Lean construction is the outcome of a new type of production management being applied to the construction industry. As Aziz and Hafez (2013) outlined, key elements of lean construction include establishing clear delivery process objectives to enhance client performance at the project level, implementing production control throughout the product lifecycle from design to delivery, and integrating concurrent product and process design. On the other hand, Albalkhy and Sweis (2021) defined lean construction as a philosophy that focuses on improving collaboration among all project-relevant stakeholders to increase value for the client. Accordingly, Asri and Nawi (2015) explored that through lean construction, lean thinking was also introduced into the construction industry. Further, the implementation and adaption of the fundamental principles, and concepts of the Toyota Production System (TPS), which had been already established in the 1950s to create a new approach for managing construction projects, is referred to as lean construction (Al-aomar, 2012; Albalkhy & Sweis, 2021; Sacks et al., 2010). Moreover, Oey and Lim (2021) underlined since its introduction in the early 1990s, lean construction has drawn many firms to incorporate it into their construction business processes. Koskela (1992; 2020) presents construction as a manufacturing process, describing the construction process as a flow of information and material, transformation, and value creation. Furthermore, Koskela who created the Transformation Flow View philosophy of production on the construction was a pioneer of lean construction (Ogunbiyi et al., 2014). Consequently, Mostafa et al. (2016) findings confirmed new production philosophies may be adopted and transferred to handle construction project processes. While numerous tools and principles from the TPS are applicable in construction, there are specific principles and techniques within lean construction that are underutilised (Sacks et al., 2010).

Tezel and Nielsen (2013) listed government studies, institutes, construction management researchers, certain occupational organisations, and practitioners who have all promoted and studied the lean construction idea since the beginning of the 1990s. Subsequently, the International Group for Lean Construction and the United States Lean Construction Institute are the two most significant organisations dedicated to the promotion of lean concepts in the construction sector (Salem et al., 2005; Tezel & Nielsen, 2013). Moreover, lean construction has been implemented with considerable benefits in countries construction industries all over the world including Sri Lanka (Ranadewa et al., 2021). Several researchers have highlighted that lean construction is an approach, which can be used to maximise value, minimise waste, reduce costs, balance the resources, and deliver projects on time in Sri Lanka (Uhanovita et al., 2023).

Nevertheless, to gain the advantages of lean practices in the construction sector, researchers emphasise the importance of embracing lean learning concepts for the successful implementation of construction projects (Parameswaran et al., 2024; Parameswaran & Ranadewa, 2023). Before integrating lean learning into construction organisations to effectively adopt lean principles in this sector, it is essential to address key research questions such as identifying the lean tools utilised in construction and understanding the lean learning practices specifically within the Sri Lankan construction industry. Numerous studies have explored the application of lean principles and practices, the implementation of lean tools, the benefits of lean, challenges in implementing lean, lean culture, and related topics within the construction industry in Sri Lanka (Ranadewa et al., 2021; Uhanovita et al., 2023). However, there is a lack of research on lean learning practices in Sri Lankan construction (Parameswaran et al., 2024; Parameswaran &

Ranadewa, 2023) Therefore, this study aims to investigate the state-of-the-art lean learning practices in the Sri Lankan construction industry. This paper commences with a literature review on lean learning practices in construction, followed by a discussion of the methodology employed. The research outcomes are then presented, focusing on the lean tools implemented in the construction industry and detailing the specific lean learning practices observed in Sri Lanka's construction sector.

2. LITERATURE REVIEW

2.1 LEAN LEARNING PRACTICES IN THE CONSTRUCTION INDUSTRY

The transition to lean construction also necessitates increased support and awareness of lean construction knowledge. Since lean construction is still considered a relatively new concept, it is often absent from the curricula of most educational programs. Encouraging labour participation in the adoption of lean construction entails supporting their education and training, as well as integrating them into the mindset transformation process. (Albalkhy & Sweis, 2021). Further, Pasquire and Court (2013) stresses that knowledge management is a critical component of lean construction's success. Even though understanding every element of the project is impractical, all stakeholders must have a holistic picture of the entire (Mano et al., 2021). Mano et al. (2021) recognised this is achieved mainly by communication among the different parties involved, and that necessitates extra effort on the part of everyone engaged to comprehend the changes that will influence their job as a result of the implementation of lean management. The firm used the strength of “experience-based learning” to facilitate the integration of lean practices and the related culture shift. This approach enabled site managers and workers to personally experience the benefits, utilising “learning-by-doing” to effectively implement the concept of lean construction principles (Bygballe, 2014; Ranadewa et al., 2021). Five steps of learning processes were identified in Figure .

Figure 1: Five steps of learning processes
Source: (Freitas & Heineck, 2012)

In the construction industry, the SECI (socialisation, externalisation, combination, internalisation) model provides a connection between lean construction approaches and knowledge management (Zhang & Chen, 2016). In addition, Brioso (2015) established through lectures, discussion sessions, and workshops, the training course offered knowledge of the lean construction method and principles. Further, simulation (Neeraj et al., 2016), the game with computer simulation (Biotto et al., 2021), and digital solutions (Cisterna et al., 2021) provide the learning environment as it is simpler to comprehend the operation of an actual system under real-time settings. Furthermore, before commencing the deployment, establish a robust knowledge base among company leaders since, as managers gain experience with lean construction, being aware of successful instances as well as the challenges that may occur during deployment, they will be able to commit and support the project and also well prepared to carry out the change (Mano et al., 2021). However, owing to the influence of COVID-19, traditional educational models needed to be adapted to meet societal needs through lean simulations powered by digitalisation (Cisterna et al., 2021). Even though, Deshpande and Huang (2011) revealed there are numerous reasons why games with computer simulation should not be used: a lack of understanding of simulation technologies' capabilities, acquiring the required resources is challenging, and the incapacity of the instructor to employ the latest technologies. Moreover, a lean construction coach, consultant, trainer, or teacher, the facilitator must have the following qualifications shown in Figure .

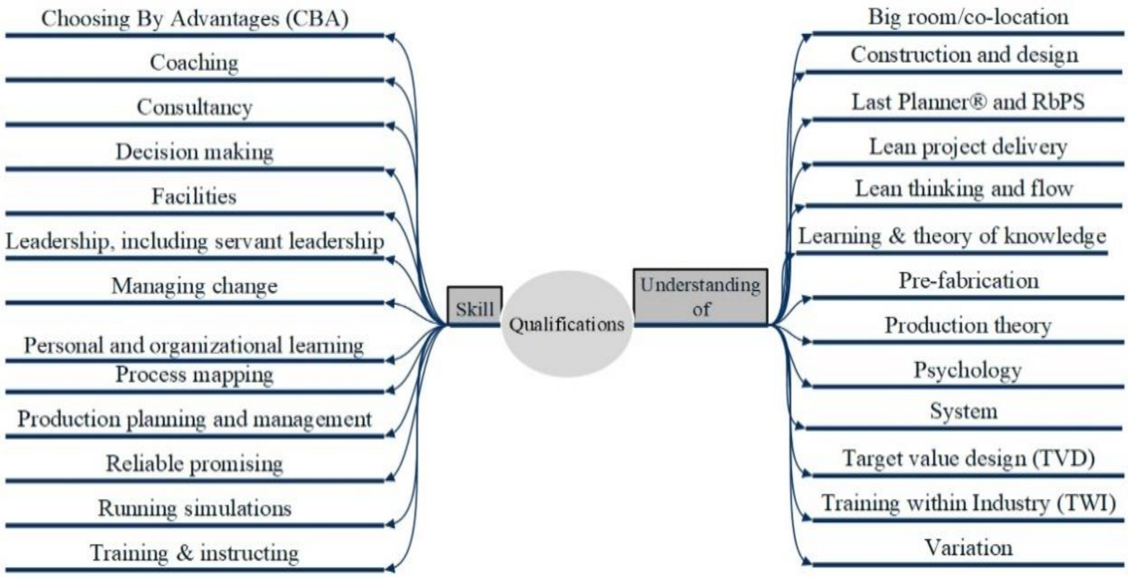


Figure 2: Qualifications of a lean construction coach
Source: Adapted from Mossman (2015)

A lean transformation for success in design, construction, or facilities management requires a coach with the appropriate skills and knowledge, as shown in Figure . Mossman (2015) highlighted those owners, clients, designers, constructors, and consultancy, along with educational institutions like universities and colleges, seeking to engage lean leaders, coaches, facilitators, instructors, trainers, or consultants are inclined to select individuals who demonstrate evidence of practical application across a diverse spectrum of skills, knowledge, and experiences. Furthermore, they value candidates who exhibit an ongoing commitment to learning and professional development.

3. RESEARCH METHODOLOGY

This research aimed to investigate and analyse the implementation of lean learning practices within the Sri Lankan construction industry. A thorough literature review was conducted to establish a theoretical background. To gain diverse perspectives from experts regarding lean learning practices in the Sri Lankan context, the study emphasised and valued the exchange of ideas, opinions, perceptions, and experiences within the research environment, recognising human interaction as pivotal to the study (Altheide & Johnson, 2011). Therefore, the research aligns with an interpretivism stance. A case study offers researchers a comprehensive understanding of a specific phenomenon or sequence of events by integrating various sources of evidence (Noor, 2008). It provides a complete picture and can effectively capture the dynamic nature of organisational life, particularly in rapidly evolving environments. Moreover, Noor (2008) stated that it enables the exploration of emergent properties and the fluctuating patterns of organisational activities. Therefore, the research strategy employed in this study was a 'case study strategy' focused on analysing lean learning practices within the Sri Lankan construction industry. Through the examination of multiple cases, generalisations can be drawn, enhancing the potential for findings to be replicated (Verschuren, 2003). Specifically, case studies were carried out in three large-scale Sri Lankan contracting organisations (CA.1, CA.2, & CA.3), each involving five interviews (R1 to R15), document reviews and observations. Consequently, each case involved conducting five interviews with various experts from different organisational levels, all experts in lean principles and lean learning methodologies within the organisation. All three cases were Sri Lanka's leading construction companies that had the highest grade according to Construction Industry Development Authority (CIDA) registration. Further, these three cases were chosen for this investigation through purposive sampling. Although these organisations are large-scale, they operate across various sectors within the construction industry. Further, semi-structured interviews were conducted with three cases, each consisting of five interviewees selected through purposive sampling. Purposive sampling is known for its effectiveness in identifying suitable respondents and selecting subject matter experts for research (Tongco, 2007). Purposive sampling is widely employed in qualitative research to select and identify information-rich cases. It allows researchers to efficiently utilise limited resources and enhance the depth of understanding within the study (Campbell et al., 2020). The selection criteria for the sample were based on years of experience and expertise in lean construction principles. The profile of the case study contracting organisations is summarised in following Table 1.

Table 1: The profile of the case study contracting organisations.

	Case one – CA.1	**Case two – CA.2**	**Case three – CA.3**
Certifications	ISO 9001:2015, ISO 14001:2015, & ISO 45001:2018.	ISO 9001, 18001, & 14001	ISO 9001:2015, ISO 14001:2015, & BS OHSAS 18001: 2007.
Respondents	R1 to R5	R6 to R10	R11 to R15
Description	There is a department called Training & Development in this organisation that is dedicated to providing chances for continual learning, career advancement, and personal improvement for all employees. Furthermore, supervisory skills development, management training programs, and continuous professional development (CPD) programs are also part of our training and development activities.	The board of directors' chairman was at the top of the organisation's hierarchy. Following that, the CEO (Chief Executive Officer) reports to the chairmen. Thereafter, six directors are in charge of several functional units such as Designs and Estimates, Roads and Bridges, Plant & Equipment or International Division, Project Division, administration division HR (Human Resources) and administration, IT (Information Technology), and compliance, and finance division.	This organisation is led by the Chairman, who is the organisation's senior management. Following that, the Managing Director. Thereafter, the Leasing, Mechanical, Quantity Surveying, Tendering division, as well Designs division and Ready-mix Batching Plant division of the organisation, have two Executive Directors in charge. Nevertheless, the organisation contained various departments led by the Deputy General Manager (DGM), including Finance, Projects, Specialised Services, Asset Management, HR and Administration, and others.

The interviews were limited to fifteen respondents due to data saturation, ensuring insights from experienced individuals with over ten years of industry experience and knowledge of lean construction. The interviews were conducted at different levels of the organisation, including project and head office levels, to understand lean learning practices comprehensively. If there was a designated individual responsible for lean learning within the organisation, they were also interviewed. The data collected from these interviews underwent code-based content analysis using NVivo 12. NVivo 12 facilitated the organisation, exploration, and acceleration of the data analysis process, particularly beneficial for handling unstructured data (Dalkin et al., 2021).

4. RESEARCH FINDINGS

4.1 LEAN TOOLS IMPLEMENTED IN THE CASE STUDY ORGANISATIONS

The first question in the interview guideline part two was regarding lean construction opinions. As a result, every respondent expressed their thoughts on lean construction in the way they understood it. The key term chosen by the respondents when defining lean construction was “decrease non-value-adding activities”. Further, the phrase “manage the project efficiently” was used by a few more respondents. According to the respondents' opinions, lean construction may be defined as “the elimination of non-value-adding activities and maximisation of value-adding activities throughout the project to accomplish the target and manage the project effectively”. Furthermore, in section two, the question was framed to discover the lean techniques used in this organisation. Figure presents all recognised existing lean tools in the organisations.

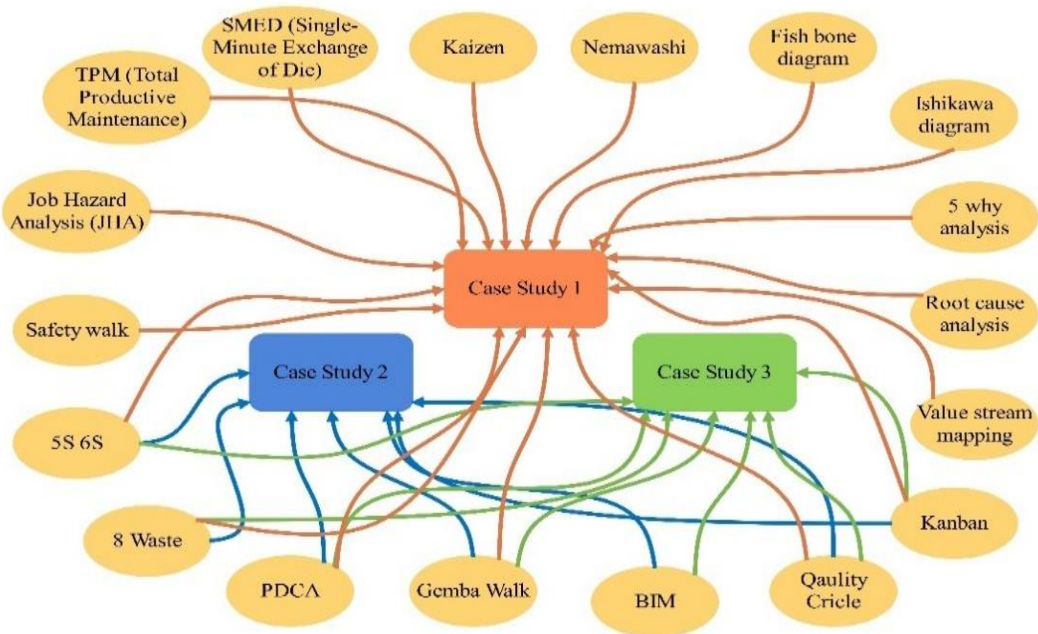


Figure 3: Lean tools implemented in the case study organisations.

All the respondents indicated that there have been many lean practices in the organisation, which are practised in an ad-hoc manner. Subsequently, R2, R9, and R15 also stated that “the quality management system contains several lean approaches such as 5S, Plan–Do–Check–Act (PDCA), and quality circle as a result of the organisation's adaptation of the

ISO standard". Since R2 has worked in the manufacturing industry, he has emphasised most of the lean tools with practical examples.

4.2 LEAN LEARNING PRACTICES IN THE SRI LANKAN CONSTRUCTION INDUSTRY

Reviewing the lean learning practices in the Sri Lankan construction industry is one of the research objectives. However, the major question in section two was to determine the organisation's lean learning procedures, since several lean learning processes have been discovered in the construction industry, according to literature findings. Therefore, lean learning practices in the Sri Lankan construction industry have been recognised, through empirical investigation.

To enhance lean implementation in the organisation, all the respondents anonymously agreed that adequate lean learning is essential. Furthermore, R4 noted, "*The Lean Learning Program is significant since individuals are not that knowledgeable in theory. However, when it comes to lean construction, everyone should be aware of it, including the labourers. For example, when it comes to not wasting cement, even labourers are aware of this. As a result, those kinds of extremely systematic theoretical jargon must be translated into practical language acceptable for construction workers. Let's assume engineers or the project management can handle half of the task, while the other half is handled by construction workers. Therefore, if they do not even know what they are attempting to achieve. Whatever effort you put forth will be worthless. That is a circumstance in which proper learning should be provided*". Furthermore, all respondents mentioned sufficient knowledge and awareness are required; otherwise, waste would grow. As a result, there should always be a proper learning procedure in place.

According to CA.1.R1, they highlighted that there have been a lot of lean practices in the organisation, however not under the label of lean. Furthermore, the Training & Development department, as the main custodian, and the Activity Centre, as the project leader, are both jointly responsible and actively work together to accomplish the lean practices throughout the organisation. Additionally, R2, R3, R4, and R5 stated that the project manager is responsible for lean learning at the project or site level.

Moreover, R4 emphasised that *"When considering lean learning procedure, generally continuing training sessions like monthly or type of regular training session, that is how inside our organisation applying that kind of theory, thus lean is there, nevertheless they are coming up and demonstrating them with the practical word".* Despite this, the training department conducts an annual training session with the consent of top management. Therefore, in December, the training department will finalise all training needs by negotiating with the site, and then they will meet with the steering committee with senior management. Thereafter, publish what type of training is needed for the coming year include lean in this as well. Following that, multiple segments exist, with project managers being the first, followed by project engineers, quantity surveyors, and finally supervisors and foremen. Furthermore, certain individuals verbally encourage workers to execute or implement procedures. This suggests that labourers' competence is accountable to the project manager and the entire team, as they are required to learn, necessitating education for the workers. Therefore, for example, shop floor workers will be trained by the Supervisor, gang leader, or technical officers who are mostly on the site mostly through verbally and occasionally prepare a small instruction manual that they may retain in their hands. Finally, while not exactly a lean tool, they were taught to use it with similar terminologies, such as minimising waste, project management, and others. Consequently, when it comes to the organisation level, training is managed in a variety of departments, as well as different sectors such as construction, road, water, and others. Accordingly, the organisation has a variety of departments, and they are always striving to get the maximum benefit from it.

Similarly, R5 remarked that this training would take place individually for different levels of individuals since their understanding level, knowledge, and expectations fluctuate depending on their level. Therefore, supervisors and top management personnel provide knowledge to labourers in regular practice. Further, the training took place alone in a training room. Thus, the practical or continuing procedure that the project manager and team will undertake. In addition to that, usually undertake in-house training through the training department. Training takes the form of a presentation, and all of these experts may be from a university or another institution. Further, they are giving their lectures by several well-known professionals.

However, R3 indicated that *"before commencing activities, they should have a specific or site meeting with a quality engineer and a technical engineer to explain to the workers what we expect as an outcome and how to achieve it using lean procedures. Likewise, within the site, come together every day and share our knowledge on any difficulty facing and how to improve the product. Workers are briefed daily in the morning meeting. Every day, after the briefing, only sending the people to work, during this time not directly advising about the lean, informing about the concept of whatever you want to do, whatever don't want to do, what is the problem facing, how to solve that one, everything to improve the process or improve the product or output".* Additionally, R2 stated that rather than training sessions, project managers at the site level and the training department at the corporate level have incorporated CPD or any other sessions linked to lean concepts, published by professional institutions. Moreover, they send their selective employees and obtain individual knowledge updates on lean and its procedures. Thereafter, they will share their expertise in meetings, discussions, spot meetings, and presentations.

CA.2.R6 emphasised that there have been a lot of lean practices in the organisation, not under the term lean. In addition, R9 identified the Divisional Head or Project Manager as the primary custodian of lean learning. Even though a lean implementation for an organisation requires training needs should be addressed at the project or division level. There are numerous tools in lean, and the designated lean training-related division will start the training program at the head office and the project level. The Compliance section will handle any recognised lean training that is connected to quality, safety, or the environment, such as 5S, PDCA, Gemba Walk, quality circle, and others. The training will be conducted by either the head Office Compliance Division, which has a different manager for each discipline, or the Project Quality Assurance Engineer, or the Project Safety Officer, depending on the severity of the training required. Further, it necessitates a high level of attention or gravity, which will be handled by the Chief of the Compliance Division, who will be engaged in this training. On the other hand, Minor site improvements, or "regular" improvements, imply that there are requirements. For example, site worker productivity and efficiency will be improved by lean training provided by project staff, such as a quality assurance engineer, a site health and safety environment officer, a site planning engineer, or a project manager. Furthermore, conducted physical training at the head office, and project-level staff were forced to come to the head office. It is not the complete team. The project management, namely the project manager, chooses who will attend this training and who will gain knowledge from it. Thereafter, returned to the project, conducting another project-wide awareness training. Moreover, depending on the scenario, they may be required to attend training for their specific project.

Further, there is a meeting room or conference room for every project. At the project site, a PowerPoint presentation or awareness or training will be given, it is situational. For example, some things cannot be done in the conference room and others cannot be done on the site. Moreover, labourers are sometimes asked to come to the conference room or project meeting room, and in certain cases, they are given physical training in the project at specific sites where they work. Subsequently, site workers receive training in groups. As an example, to deliver quality-related lean training to a block work worker, have to notify them that this is the desired quality, this is the requirement, this is how the process will be carried out, and these are the standards that we must follow. Thereafter, go to the conference room with the targeted group and have a conversation or an awareness session. Likewise, to provide a common training or awareness presentation, have a meeting every Tuesday morning or a toolbox meeting before starting work. This meeting may include training provided by the project manager, individuals from the head division, or experts from the outside, depending on the circumstances. Similarly, R7 stated, "*The project noticed that they needed to improve their BIM skills as the client requested it. They had outsourced Trained officers instructing them in handling BIM at the head office; in this example, the head office Design team conducted the training for three months. Once a week to draft persons and engineers at the site level, and to design teams at the head office level".*

Even though R10 recognised the need for training on some lean tools, and there is a well-trained officer within the division who can handle the lean tool very well, therefore the division head can arrange training for other officers with the help of that specifically trained officer, and if that person also needs to improve his knowledge, the division head can request that the training be done by an outside party. Alternatively, the Divisional Manager or Project Manager knows of a specific party, an external party, who is qualified to do this training. For that, notify HR and administration that require this training, and this external entity is capable of providing it. As well as ready to get this training from these individuals, with HR and administration making the appropriate preparations to send this training to that specific project or division. In addition to training, R8 underlined that the lean concept has been incorporated into the organisation through CPD. The sessions were organised by a project manager or divisional head as an internal committee, with participants ranging from top management to site engineers from each project. However, the number of participants is determined by the program type. After gaining knowledge, the project manager or engineer or any other staff who attended and gained knowledge should share their knowledge and information with their subordinates through small pocket meetings.

Further, R9 specified that lean training needs related to the project are recognised by the HR division, notify and request that the appropriate department or project conduct this type of awareness. Similarly, emphasise that it would be preferable if some training could be arranged for this project to develop this component of the process. On the other hand, the HR department may receive external training at any time, and they will be notified of relevant projects, such as receiving information from this external party regarding this training program and asked to suggest eligible officers for this training to arrange training.

CA.2.R13 explained that *"Lean practices there, however, do not act this as a concept of lean, diverse ways that are in accordance with lean concept or practice*". R11 further recognised the HR department or the Project Manager as the organisation's principal custodian of lean learning. R12 reportedly revealed that employees have been sent to CPD and any other external courses linked to the lean concept through the HR department. After receiving the invitation for these programs, the HR department informs the appropriate department or project that this program is required. Further, selected workers were invited to participate in this program and were chosen by the divisional head under division and the project manager at the project level.

Additionally, R15 indicated that though the organisation implements a quality management system, continual improvement is possible for lean principles. This quality management system adheres to ISO standards and incorporates lean techniques such as 5S, PDCA, and others. As a result, training programmes and improvement for the lean concept are available throughout the organisation, which is linked to the quality management system. Nevertheless, the HR department is in charge of this training, with the help of the quality assurance department. The project engineer and quality engineer will work with them to give suitable training at the project level. The quality assurance department will provide this training regularly to the organisation's employees. Additionally, in certain cases, the HR division will contract with an outside party to give training to the organisation's employees. Consequently, this training will take place at the head office or a relevant project location. Furthermore, the head office and project-level senior management staff attended the training program. Following that, the project manager or quality engineer will provide the training on-site at a site meeting for the rest of the staff. Thereafter, it will be trained to labourers by the supervisor or project staff at a morning meeting or on the worksite. The quality assurance department and quality engineer on-site assess whether this concept is being implemented properly or not.

On the other hand, R14 emphasised that rather than quality-related lean tools, staff would acquire other common tools as contrasted with following the usual method. It does not implement it as a separate concept as it is part of the work. Moreover, it practices routine work. It means that practice it in general work, rather than doing it separately as a separate concept. It simply means that it is in normal project management tasks. Further, there are a few concepts that have been incorporated into the typical working procedure. Apart from the fact that this has not been established as a separate procedure, the project manager has no specific responsibilities in this area. The project manager is used to working, and his routine includes certain lean elements. According to their experience, the project manager and top-level people are knowledgeable of it; they will implement it and share their expertise with others through regular site practices; low-level individuals will implement it. There is no special training; rather, it is a common procedure that is based on the project manager's expertise and knowledge.

5. DISCUSSION

Rosli et al. (2023) stated that lean construction involves establishing clear priorities during the delivery process, with a focus on improving customer efficiency at the project level. This includes aligning product and process design and implementing production management across the product's lifecycle, from design to delivery. Further, Koskela (2020) highlighted that the goal of lean construction is to complete projects by enhancing value, minimising waste, and striving for perfection. Similarly, a study revealed that lean construction is defined as the process of eliminating non-value-adding activities and maximising value-adding activities throughout the project. Tezel et al. (2018) have highlighted the most often used lean tools in the construction industry, including Last Planner System (LPS), Value Stream Mapping (VSM), visual Management, Poka-Yoke, 5S, Just in Time (JIT), Kanban, supply chain integration, Jidoka, PDCA, and others. However, all respondents noted the presence of numerous lean practices within the organisation, yet they are implemented in an ad-hoc manner. Furthermore, the study revealed that as a result of the organisation's adoption of the ISO standard, its quality management system incorporates several lean approaches, including 5S, PDCA, and quality circles. The findings point out the significance of proper training and awareness across all levels of the organisation, from top management to labourers. Likewise, Albalkhy and Sweis (2021) underlined that encouraging labour participation in the adoption of lean construction entails supporting their education and training, as well as integrating them into the mindset transformation process. In addition to that, the study underscored the importance of structured training sessions organised by internal departments or external experts and further highlighted a more informal sharing of knowledge through routine site practices and interactions. Also, Bygballe (2014) and Ranadewa et al. (2021) point out that the firm used the strength of “experience-based learning” to help with the adoption of lean and the related culture shift, allowing site managers and workers to experience the benefits personally, and “learning-by-doing” is used to transform and translate the concept of lean construction. The study highlighted the necessity for ongoing improvement and the integration of lean practices to boost efficiency and minimise waste. Accordingly, the finding reveals that successful lean implementation depends on educating a culture of continuous improvement and ensuring that employees receive the essential training, support and resources to enhance their skills and knowledge in lean practices. Most of the existing lean learning practices research has focused on educational institutions rather than their application within construction projects or organisations (Rybkowski et al., 2018). As a result, there is a notable gap in investigating lean learning practices specifically within the Sri Lankan construction industry. Therefore, this study fills this gap by being the first to investigate lean learning practices in Sri Lankan construction.

6. CONCLUSIONS

This research aimed to investigate the state-of-the-art lean learning practices in the Sri Lankan construction industry. This is the first research to uncover lean learning practices in the Sri Lankan construction industry. Accordingly, the study revealed that lean construction is perceived as a strategic approach aimed at enhancing project efficiency by minimising non-value-adding activities and optimising value-adding activities throughout the project lifecycle. Further, the implementation of lean tools within the investigated organisations is notable, with respondents recognising various lean methodologies such as LPS, VSM, visual management, Poka-Yoke, 5S, JIT, Kanban systems, and others. Despite not always being labelled explicitly as "lean," these tools are employed to improve quality, productivity, and overall project performance. Furthermore, the study underscores the critical role of lean learning practices in fostering successful lean adoption within Sri Lankan construction firms. Respondents emphasised the importance of comprehensive training programs tailored to different organisational levels, from top management to site workers. Training initiatives encompass a variety of formats, including regular sessions, workshops, presentations, and hands-on exercises, designed to translate theoretical lean concepts into practical knowledge applicable to daily construction tasks. The organisational structure for lean learning is also remarkable, with departments responsible for overseeing lean initiatives, ensuring continuous improvement, and aligning practices with quality management systems, for example, ISO standards. This structured approach reflects a commitment to embedding lean principles into organisational culture and operations. While lean practices are being implemented, there is scope to enhance awareness and engagement across all levels of the organisation. Clear communication, ongoing training, and a culture of continuous improvement are essential to sustain lean transformation and drive clear benefits in terms of efficiency, waste reduction, and project outcomes.

This study addresses the growing importance of lean practices in the construction industry, particularly in the context of Sri Lanka, where the construction sector is experiencing rapid development and faces unique challenges. By focusing on lean learning practices, the topic acknowledges the continuous improvement aspect of lean methodologies, emphasising the need for ongoing education and skill development within construction teams. Additionally, the inclusion of a case study in Sri Lanka provides a specific and contextualised examination of how lean principles are being implemented and their impact on construction projects in the country. Overall, this study has the potential to contribute valuable insights to both academia and industry practitioners seeking to enhance efficiency, quality, and sustainability in construction projects. Further, the study provides the knowledge base by providing insights into the current state-of-the-art lean practices and learning initiatives in the Sri Lankan construction industry. Moreover, the study revealed the range of lean tools employed by organisations, their practical application and their impact on project performance. This study provides valuable insights for policymakers, particularly CIDA and relevant ministries, to enhance lean practices through structured training programs and lean awareness initiatives in the construction industry. Moreover, further research directions could delve into exploring the impact of technology and digitalisation on enhancing lean learning and implementation practices within the construction organisation. Additionally, data collection was restricted to three construction organisations that have adopted lean construction practices.

7. REFERENCES

Al-aomar, R. (2012). Analysis of lean construction practices at Abu Dhabi construction industry. *Lean Construction Journal,* 105–121. Retrieved from https://leanconstruction.org/wp-content/uploads/2022/08/LCJ_12_006.pdf

Albalkhy, W., & Sweis, R. (2021). Barriers to adopting lean construction in the construction industry: A literature review. *International Journal of Lean Six Sigma*, *12*(2), 210–236. https://doi.org/10.1108/IJLSS-12-2018-0144

Asri, M. A. N., & Nawi, M. N. M. (2015). Actualizing lean construction: Barriers toward the implementation. *Advances in Environmental Biology*, *9*(5), 172–174. https://doi.org/10.1108/IJLSS-12-2018-0144

Aziz, R. F., & Hafez, S. M. (2013). Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, *52*(4), 679–695. https://doi.org/10.1016/j.aej.2013.04.008

Biotto, C. N., Herrera, R. F., Salazar, L. A., Pérez, C. T., Luna, R. M., Rodrigheri, P. M., & Serra, S. M. B. (2021). Virtual parade game for lean teaching and learning in students from Brazil and Chile. Proc.

*29th Annual Conference of the International Group for Lean Construction (*pp. 340–349). doi.org/10.24928/2021/0203

Brioso, X. (2015). Teaching lean construction: Pontifical catholic university of Peru training course in lean project & construction management. *Procedia Engineering*, 123, 85–93. Retrieved from https://doi.org/10.1016/j.proeng.2015.10.062

Bygballe, L. E. (2014). Implementing lean construction: a practice perspective. *Proceedings 22nd Annual Conference of the International Group for Lean Construction* (pp. 3–14). https://iglc.net/papers/Details/1022

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D. and Walker, K. (2020), "Purposive sampling: complex or simple? Research case examples", *Journal of Research in Nursing, 25*(8), 652-661. doi: 10.1177/1744987120927206.

Cisterna, D., Hergl, M., Oprach, S., & Haghsheno, S. (2021). Digitalization of lean learning simulations: teaching lean principles and last planner® system. In L. F. Alarcon & V.González (Eds.), *Proc. 29th Annual Conference of the International Group for Lean Construction* (pp. 279–288). doi.org/10.24928/2021/0136

Dalkin, S., Forster, N., Hodgson, P., Lhussier, M., & Carr, S. M. (2021). Using computer assisted qualitative data analysis software (CAQDAS; NVivo) to assist in the complex process of realist theory generation, refinement and testing. I*nternational Journal of Social Research Methodology*, *24*(1), 123-134. https://doi.org/10.1080/13645579.2020.1803528

Deshpande, A. A., & Huang, S. H. (2011). Simulation games in engineering education: A state-of-the-art review. C*omputer Applications in Engineering Education, 19*(3), 399–410. https://doi.org/10.1002/cae.20323

Freitas, A. A. F. De, & Heineck, L. F. M. (2012). Technological capability: Evidence from building companies in a lean learning environment. *20th Annual Conference of the International Group for Lean Construction.* Retrieved from https://www.iglc.net/Papers/Details/771

Koskela, L. (1992). *Application of the new production philosophy to construction*. Retrieved from https://www.researchgate.net/profile/Lauri-Koskela-2/publication/243781224_Application_of_the_New_Production_Philosophy_to_Construction/links/5bcd97a792851cae21b8dd9a/Application-of-the-New-Production-Philosophy-to-Construction.pdf

Koskela, L. (2020). *"Theory of lean construction", in lean construction: Core concepts and new frontiers* (1st edition). Routledge. Retrieved from https://www.taylorfrancis.com/chapters/edit/10.1201/9780429203732-1/theory-lean-construction-lauri-koskela

Mano, A. P., Costa, S. E. G. da, & Lima, E. P. de. (2021). Criticality assessment of the barriers to lean construction. *International Journal of Productivity and Performance Management, 70*(1), 65–86. https://doi.org/10.1108/IJPPM-11-2018-0413

Mhetre, K., Konnur, B. A., & Landage, A. B. (2016). Risk Management in Construction Industry. *International Journal of Engineering Research,* 5(1), 153–155. doi: 10.17950/ijer/v5i1/035

Mossman, A. (2015). Bringing lean construction to life: Developing leaders, consultants, coaches, facilitators, trainers & instructors. *Proceedings of 23rd Annual Conference of the International Group for Lean Construction* (pp. 413–423). Retrieved from https://www.iglc.net/papers/details/1176

Mostafa, S., Chileshe, N., & Abdelhamid, T. (2016). Lean and agile integration within offsite construction using discrete event simulation: A systematic literature review. *Construction Innovation, 16*(4), 483–525. https://doi.org/10.1108/CI-09-2014-0043

Noor, K. B. M. (2008). Case study: A strategic research methodology. *American journal of applied sciences, 5*(11), 1602-1604.

Neeraj, A., Rybkowski, Z. K., Fernández-Solís, J. L., Hill, R. C., Tsao, C., Seed, B., & Heinemeier, D. (2016). Framework linking lean simulations to their applications on construction projects. *IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction* (pp. 3–12). Retrieved from https://iglc.net/Papers/Details/1295

Oey, E., & Lim, J. (2021). Challenges and action plans in construction sector owing to COVID-19 pandemic – a case in Indonesia real estates. *International Journal of Lean Six Sigma, 12*(4), 835-858. https://doi.org/10.1108/IJLSS-09-2020-0149

Ogunbiyi, O., Goulding, J. S., & Oladapo, A. (2014). An empirical study of the impact of lean construction techniques on sustainable construction in the UK. *Construction Innovation*, *14*(1), 88–107. https://doi.org/10.1108/CI-08-2012-0045

Parameswaran, A., & Ranadewa, K. A. T. O. (2023). Learning-to-learn sand cone model integrated lean learning framework for construction industry. *Smart and Sustainable Built Environment,* 13*(4)* , 852-886. https://doi.org/10.1108/SASBE-10-2022-0234.

Parameswaran, A., Ranadewa, K. A. T. O., & Rathnasinghe, A. P. (2024). Roles of lean learners for successful lean implementation in the construction industry: a force-directed graph. *International Journal of Productivity and Performance Management*. Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/IJPPM-07-2023-0346

Pasquire, C., & Court, P. (2013). An exploration of knowledge and understanding - The eighth flow. *21st Annual Conference of the International Group for Lean Construction 2013* (pp. 944–953). Retrieved from https://iglc.net/Papers/Details/938

Ranadewa, K. A. T. O., Y.G. Sandanayake, Y. G. S., & Siriwardena, M. (2021). Enabling lean through human capacity building: An investigation of small and medium contractors. *Built Environment Project and Asset Managemen*t, 11(4), 594-610. https://doi.org/https://doi.org/10.1108/BEPAM-03-2020-0045

Rosli, M. F., Muhammad Tamyez, P. F., & Zahari, A. R. (2023). The effects of suitability and acceptability of lean principles in the flow of waste management on construction project performance. *International Journal of Construction Management, 23*(1), 114-125. https://doi.org/10.1080/15623599.2020.1853006

Rybkowski, Z.K., Forbes, L.H. and Tsao, C. (2018), “The evolution of lean construction education (part 1 of 2): at US-based universities”, in Gonzalez, V.A. (Ed.), *26th Annual Conference of the International. Group for Lean Construction,* Chennai, India, (pp. 1013-1023). doi: 10.24928/2018/0447

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). The Interaction of Lean and Building Information Modeling in Construction. *Journal of Construction Engineering and Management, 136*(9), 1–29. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203

Salem, O., Solomon, J., Genaidy, A., & Luegring, M. (2005). Site implementation and assessment of lean construction techniques Work Performance Indicator Measurement for the Improvement of Productivity, Quality and Safety in the Workplace View project. *Lean Construction Journal*, 2(2), 1–21. www.leanconstructionjournal.org

Tezel, A., Koskela, L., & Aziz, Z. (2018). Lean thinking in the highways construction sector: motivation, implementation and barriers. *Production Planning & Control, 29*(3), 247–269. https://doi.org/10.1080/09537287.2017.1412522

Tezel, A., & Nielsen, Y. (2013). Lean Construction Conformance among Construction Contractors in Turkey. *Journal of Management in Engineering, 29*(3), 236–250. https://doi.org/10.1061/(asce)me.1943-5479.0000145

Tongco, M.D.C. (2007), “Purposive sampling as a tool for informant selection”. *Ethnobotany Research and Applications*, 5, pp. 147-158, http://hdl.handle.net/10125/227

Uhanovita A.C., N., K.A.T.O., R. and Parameswaran, A. (2023), "Poka-Yoke to minimise variations: a framework for building projects", *Construction Innovation*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/CI-12-2022-0343

Verschuren, P. (2003). Case study as a research strategy: Some ambiguities and opportunities. *International journal of social research methodology, 6*(2), 121-139. https://doi.org/10.1108/IJLSS-12-2018-0144

Zhang, L., & Chen, X. (2016). Role of Lean Tools in Supporting Knowledge Creation and Performance in Lean *Construction. Procedia Engineering, 145*, 1267–1274. https://doi.org/10.1016/j.proeng.2016.04.163

Nuwandhara, R.M.K.K., Perera, A.S. and De Silva, G.H.S.P., 2024. Survival challenges faced by the small-scale building contractors in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 961-973. DOI: https://doi.org/10.31705/WCS.2024.76. Available from: https://ciobwcs.com/papers/

SURVIVAL CHALLENGES FACED BY THE SMALL-SCALE BUILDING CONTRACTORS IN SRI LANKA

R.M.K.K. Nuwandhara[1], A.S. Perera[2] and G.H.S.P. De Silva[3]

ABSTRACT

The construction industry is a significant contributor to the socio-economic development of Sri Lanka, and small-scale contractors play a crucial role in this industry. However, their sustainability is a matter of concern. The vital contribution made by small-scale contractors in generating job opportunities and reducing poverty has been recognised in Sri Lanka and globally. The research study examines the significant challenges C7-C9 grade contractors face in surviving in the Sri Lankan construction industry. The study utilised a mixed-method approach. Stage one consists of, administering a questionnaire survey, distributed among C7 to C9 contractors and stage two consists of conducting a series of semi-structured interviews among five industry experts. The initial groundwork involved an extensive review of the existing literature, complemented by acquiring primary data. During the first stage, the study continued using thirty responses and to analyse the collected data, descriptive statistical tools such as percentage counts, weighted averages, etc used through a 5-point Likert Scale analysis. Among the key challenges that emerged, financial policies stand as a critical issue with higher governance. Semi-structured interviews were analysed using code-based content analysis. Among the solutions proposed, improving skills and efficiencies was a highly proposed solution to facing these challenges. This study will be useful for many struggling C7-C9 contractors in Sri Lanka to identify their least-performing areas in the trade and to improve their overall performance while nurturing the construction industry.

Keywords: *Building Construction Projects; Small-Scale Contractors; Survival Challenges.*

1. INTRODUCTION

The construction sector is a noteworthy contributor to the Sri Lankan economy (Manoharan et al., 2023; Pathirana, 2021; Somachandra et al., 2024). However, recent data reveals a significant decline in its contribution to the national Gross Domestic Product (GDP) (Jui et al., 2024). One of the main reasons for this diminished contribution is the dwindling presence of small-scale contractors within the industry (Liyanagamage & Fernando, 2023; Ramawickrama, 2016). The construction sector relies on contractors

[1] Student, Department of Life and Medical Sciences, University of Hertfordshire, United Kingdom, kulunu6789@gmail.com
[2] Student, Liverpool John Moores University, United Kingdom, amendaperera47@gmail.com
[3] Academic, Department of QS, SLIIT, Sri Lanka, priyanwadadesilva@gmail.com

to translate the design into a tangible built environment (Shan et al., 2020). In both developing and developed countries, the construction industry consists of small, medium and micro-sized enterprises (Chileshe, 2020; Liyanagamage & Fernando, 2023). A study conducted on critical success factors of Singaporean contractors by Shan et al. (2020) revealed that the majority of the contractors in the world are small contractors. They further highlighted that the majority of 99.8% of the small contractor population in the UK construction industry in the USA, 97% of speciality specialised contractors and 96% of home builders represent small contractors. Small-scale contractors are crucial in construction (Chileshe et al., 2020). These small-scale contractors significantly boost the economy and construction sector by creating job opportunities, aiding in poverty reduction and boosting the sector's growth. They also contribute to social development and economic advancement and lead to a country's economic growth (Amoah & Bikitsha, 2022). Even though a noticeable number of small firms exist in the construction sector, due to the competitiveness and toughness of the construction industry, today, these firms struggle a lot for their survival (Liyanagamage & Fernando, 2023). Regardless of their high capability to adapt to innovation (Jayalath, 2023), they experience significant restrictions in resources such as labour, capital and many more aspects compared with large-scale contractors (Liyanagamage & Fernando, 2023; Shan et al., 2020; Somachandra et al., 2024). This fact is further proven by a South African construction industry case study, which revealed that emergent contractors face financial issues due to delays in payments, poor management, lack of basic skills, contract negotiation, lack of finances, specialised activities, assets, poor procurement, business skills, failure to retain skilled workforce, and inadequate finance (Amoah & Bikitsha, 2022). Similarly, Shan et al. (2020) found that lack of continuation of jobs, pressure of the same level competitors from the same trade, different expectations of shareholders, high pressure on professionalism and integrity, poor level of technology, absence of skilled workers, and poor access to the international market as critical challenges experienced by the small-scale contractors. Another study conducted on the Jordanian Construction industry revealed the absence of expertise, resources (Amoah & Bikitsha, 2022) and managerial support to manage participant affairs as a common challenge for SMEs of developing countries (Alkilani& Loosemore, 2022), whilst inadequate financial management, availability of knowledge and investment, and insufficient skills are reported as the most challenging factors for Tanzanian Small-scale contractors (Chileshe et al., 2020). Corroborating these challenges (Shan et al., 2020) indicated that Singaporean small-scale contractors still depend on traditional construction methods, which hinders the possibility of enhancing their capacity.

Similar to the Singaporean, United Kingdom (UK), and United States of America (USA) construction industries, in the Sri Lankan construction sector, the majority of the population represents small and medium-scale contractors (Dodanwala & Santoso, 2024). They range from C4 to C9, according to the CIDA grading system. A study by Ranadewa et al. (2018) revealed that compared to the strengths and opportunities available for Small and Medium-scale (SME) contractors, the weaknesses and threats show a significant presence in the Sri Lankan construction industry. They further revealed that the Sri Lankan construction industry is plagued with challenges in access to finance, interest rates, global finance crisis, and cost of energy standards to every contractor regardless of their grade. However, the higher cost of construction, labour, material, equipment, availability of funds offered by the government and its competitiveness, availability of quality equipment, material and skilled workers, and investment in new technology precisely hit the small and medium scale contractors in the local context threatening their existence (Ranadewa et al., 2018). Due to these challenges, many of these firms disappear during their first couple of years without exhibiting any progress in development or even the skill to survive (De Silva et al., 2022). However, these challenges can manifest each grade of small-sized contractor differently, depending on their financial strength, demographic conditions, and capability to handle such challenges within the business environment. Nevertheless, it demonstrates that a substantial number of small-scale contractors experience critical challenges in the Sri Lankan construction industry, and those challenges need more attention and in-depth investigation (Dodanwala & Santoso, 2024). Though there are attempts to recognise the challenges faced by small-scale contractors, no such record explores the challenges faced specifically by C7-C9 small-scale contractors in the Sri Lankan Context. Therefore, this research aims to fill that gap and identify the challenges faced by the C7-C9 small-scale contractors in the Sri Lankan construction industry.

2. LITERATURE REVIEW

2.1 CONSTRUCTION INDUSTRY

The construction industry is vital in preserving the country's social and economic advancement (Jayalath, 2023; Omopariola et al., 2020). It brings more financial value to the government, securing and creating employment opportunities (Pathirana, 2021). Similar to other countries, The Sri Lankan construction industry also plays a significant role as a contributor to the Sri Lankan economy (Fernando et al., 2016; Liyanagamage & Fernando, 2023; Pathirana, 2021). However, recent studies indicate that the Sri Lankan construction industry is in a constant struggle with a notable surge in costs over the past few years due to political chaos and the economic catastrophe in the country; competition comes from overseas contestants, health and safety standards (Pathirana, 2021). The situation has significantly impacted Sri Lankan contractors, leading to increased survival struggles and disrupting the industry's growth despite being an essential national economy sector (Jayalath, 2023). Understanding this, many scholars worldwide made attempts to identify industry barriers to persistence and advancement, focusing on challenges faced by different contractors, including large-scale, small, medium, and micro-scale, contributing to the development and improvement of the construction industry (Amoah & Bikitsha, 2022).

2.2 SMALL-SCALE CONTRACTORS

According to the literature, different trades and countries use different perceptions when defining small-scale contractors (Shan et al., 2020). Therefore, still, there is no universal definition for the term "small-scale" contractors. However, with the changing economy, from time to time, scholars come up with different arguments for defining small-scale firms (Shan et al., 2020). One of the main arguments scholars presented is that, in determining the term, with the rapidly changing economy across industries, it cannot rely on single measures such as employment or resources, revenue or output, etc. (Ranadewa et al., 2018). By referring to Bolton (1971), Ranadewa et al. (2018) advocated that the definition of a small firm must depend only on the firm's market share, management style, and owners' independence in decision-making. Even though the worldwide construction industry consists of a high portion of small-scale contractors, according to the growing body of knowledge, the definition of small-scale contractors portrays a high dependence on national and industrial considerations (Shan et al., 2020). Regardless of this economic definition, most countries today rely on quantitative parameters to define small- and medium-scale enterprises (Ranadewa et al., 2018). Accordingly, different countries use different parameters and grading systems to classify small-scale contractors (Liyanagamage & Fernando, 2023; Shan et al., 2020). While the USA consider organisations with an annual income level of small companies of USD 36.5 million, European countries consider parameters such as organisations with below 50 workers, sales below EUR 50 million, or annual resources and obligations less than EUR 43 million to define small scale contractors (Shan et al., 2020). Similarly, the Construction Industry Development Authority (CIDA) of Sri Lanka defines small-scale contractors as those with an annual turnover of 16 – 250 Mn, mainly graded under C9 – C4. The grading system ranges from CS2 to C9 based on financial terms. However, Ranadewa et al. (2018) indicated that micro-enterprises also fall under this category regarding policy-related measures. This grading system of CIDA aims to determine the contractor's comprehensive capability in carrying out numerous development activities with diverse forms and sizes regardless of the precise contract. Nevertheless, there is yet to be a universally accepted definition. The CIDA system determines a company's ability and capability to undertake various projects (Perera et al., 2023). Currently, more than 2500 registrations exist under CIDA. Among these, the small and medium-sized contractors appear under the C4-C9 categories. Within that, C7 -C9 indicates the lowest gradings according to the financial strength. These categories show the minimum financial strength as, C9-grade: minimum financial limit of 2 million, C8 grade:2 million to 5 million and C7 grade: limit reaching from 5 million to 10 million. The CIDA grading system identifies the best contractor within the parameters of their financial and technical skills and instils confidence in the firm to make improvements while enhancing its capabilities. Ultimately, the business must meet project objectives, including deadlines and high-quality standards. Though they have deficient financial capacity, these small-scale contractors play an essential role worldwide in creating infrastructure regardless of demographic diversion (Jayalath, 2023; Liyanagamage & Fernando, 2023).

2.3 PROBLEMS AND CHALLENGES FACED BY SMALL-SCALE CONTRACTORS

The construction industry is a sector with critical problems (Jayalath, 2023; Jui et al., 2024) due to a range of internal and external factors that impact the corporate environment of the construction sector (Amoah & Bikitsha, 2022). A study by Rajakaruna et al. (2008) identified several factors that are crucial to any construction organisation or industry's success. These factors include state and monetary policies, research and development, administration skills, resource availability, safety requirements, training, technology, and social aspects. Previous research studies indicate that such problems cause unembellished concern about the economic status of countless nations (Jui et al., 2024; Somachandra et al., 2024). In developing countries like Sri Lanka, several issues are amassing together with the common difficulties that occur due to the country's economic turmoil, scarcity of possessions (Human and financial), poor management and investment matters in construction firms, and political constraints in the country are some of these issues that exist within the industry from a long time (Liyanagamage & Fernando, 2023). These problems cause severe complications, specifically with contractors, regardless of their scale (Jayalath, 2023). Commonly, small-scale contractors have inadequate monetary and capital strength, equipment, plant, low safety measures and limited resources (Liyanagamage & Fernando, 2023). Thus, these problems can hit small-scale contractors even more challenging than other grades. According to Rajakaruna et al. (2008), Small-scale contractors primarily encounter technical and financial management challenges. They further showed that these challenges are often due to insufficient resources, inadequate management skills, and poor business planning strategies. Consequently, many small-scale construction contractors struggle to overcome these obstacles. The following paragraph describe these factors in more detail.

Financial Policies: A company's financial strength is an essential aspect that facilitates the smooth running of a company and the timely completion of projects. According to Rajakaruna et al. (2008), the main challenge that small-scale construction companies in Sri Lanka face is the unreasonable rates of commercial borrowings compared to those in developed countries.

Government Policies: Construction companies also need proper government policies and more support from governmental bodies. Scholars such as Thwala and Mvubu (2008) and Raghavan and Kumar (2015), indicated this in their studies on Swaziland and the Indian construction industry. By highlighting a similar situation in the Sri Lankan context, Rajakaruna et al., (2008) indicated the country's political instability as another reason for such pressure on small-scale contractors, which resulted in them losing their contracts due to changing governments and revised decisions.

Technology: Many of the mega projects in Sri Lanka on irrigation works, power plants, and industrial works claim the involvement of foreign parties due to a need for more technology from local contractors (Rajakaruna et al., 2008). However, progress can be seen in utilising technology in construction works, considering that small-scale contractors have yet to show any progress in utilising such technology (Rajakaruna et al., 2008).

Management Skills: Management skills are crucial factors that affect a construction company's well-being. According to (Jayawardane & Gunawardena, 1998), many small-scale companies must be more successful due to poor administration and coordination. By studying further, Rajakaruna et al. (2008) indicated areas such as cost planning, schedule planning, labour handling, scope management and administrative issues as the areas affected by poor handling.

Resource Availability: In many developing nations, construction companies often rely on a pool of contracted workers for specific projects. This approach may lead to a need for more skills and technical knowledge, ultimately contributing to failures in small-scale construction businesses (Rajakaruna et al., 2008).

Safety: According to Rajakaruna et al. (2008), most small-scale construction companies in Sri Lanka lack safety measures and precautions. Therefore, the construction workforce must understand and be made aware of the importance of maintaining these safety measures. On top of that, they reported that these companies do not possess the funds and assets for suitable safety measures, which counts as the main barrier faced by small-scale companies.

Training and Development: The workmanship of labourers is another major challenge construction companies have faced in recent years. According to Madushanka (2003), though different industrial training institutions are established in Sri Lanka, more is needed to fulfil the requirements of the construction sector. Therefore, many small-scale organisations today need more quality.

Skills: according to Gangwar and Goodrum (2005), Small-scale construction companies need more professionals and fresh graduates with low skills. They pointed out the inability to retain professionals with high skills by offering them an attractive remuneration package as the reason. They identified it as a common problem across developing countries.

Social Factors: Gangwar and Goodrum (2005) pointed out that labourers' social issues directly impact construction companies. Moreover, the authors revealed that most need more financial strength and good health. Due to their lack of education, they lack welfare facilities in these organisations, display poor behaviour and irresponsible manners, making labour management challenging (Gangwar & Goodrum, 2005).

In the local context, the construction industry's capacity experiences rapid changes due to the competitive nature of the emergence of many infra-structure public projects. These projects require the collaboration of foreign contractors (Rajakaruna et al., 2008).

2.4 MITIGATORY MEASURES

To overcome such challenges, scholars related to the construction industry recommended different mechanisms (Jayalath, 2023; Rajakaruna et al., 2008). Among these mechanisms, Rajakaruna et al. (2008) identified five mechanisms that can be applied to the Sri Lankan construction industry. They are: ***enhancing skills and efficiency****:* enhancing employee skills (Liyanagamage & Fernando, 2023) and fostering a culture of innovation is necessary to improve industry efficiency and image (Rajakaruna et al., 2008). International collaboration can facilitate knowledge transfer and technological advancement, ultimately enhancing the industry's global competitiveness, ***adopting incentive awarding mechanisms****:* introducing incentives (Shan et al., 2020)and enhancing performance in the construction industry such as financial rewards, training opportunities (Liyanagamage & Fernando, 2023), and recognition for health and safety adherence can drive positive change, ***imposing quality practices***: enhancing construction quality requires improvements in workmanship (Shan et al., 2020), employee skills (Shan et al., 2020), and established quality standards, ***improving professionalism***: enhance expertise through improved knowledge, practices, and relationships by incorporating professionalism into education at all levels, from the preliminary stage to professional practice, to foster a culture of excellence and ***improve procurement strategies****:* within the local construction context, despite of continuing the conventional methods, adopting alternative approaches like joint ventures and partnerships could uplift the industry to international standards, increasing its global competitiveness (Rajakaruna et al., 2008).

3. RESEARCH METHODOLOGY

In setting up the background information, the study utilised a comprehensive literature review concerning the survival challenges encountered by contractors in the global construction industry using journal articles, books, conference papers, etc.; then to explore the challenges faced specifically by the C7-C9 small-sized contractors in Sri Lanka, the study used a mixed method approach. Since the challenges faced by small-scale contractors can differ from region to region and country to country, a questionnaire survey was administered to contextualise the literature findings. Out of the 55 questionnaires distributed, only 30 complete responses were returned and proceeded to the analysis. To analyse the collected data, the study used Descriptive statistical tools such as weighted average, percentage counts, mean, etc., by introducing a 5-point Likert

Scale; according to Kusmaryono et al. (2022), 90% of research contains Likert Scales and is a recognised tool in measuring attitudes, concepts and values. The following Likert Scale was employed to identify the critical issues among C7-C9 Contractors in Sri Lanka, as shown in Table 1. It consists of a range where "not critical" = 1 and "very critical" = 5 and is based on two assumptions. They are, the distance between "very critical" and "critical" is the same as "not critical" and "less critical". Thereby, the distance between "not critical" and "less critical" is five times less than the distance between "very critical" and "critical".

Table 1: Likert scale for the level of criticality of challenges faced by small-scale contractors

Value	Range	Scale
1	1.00-1.08	Not critical
2	1.81-2.60	Less critical
3	2.61-3.40	Moderate
4	3.41-4.20	Critical
5	4.21-5.00	Very Critical

As of the second phase of data collection, semi-structured interviews with five industry experts were conducted to find solutions for the challenges faced by C7-C9 contractors. The data were analysed through code-based content analysis with the help of transcripts of each interview. Data analysis and discussion

3.1 QUANTITATIVE ANALYSIS

3.1.1 Demographic Information of Respondents

The gathered data highlighted a significant difference in experience levels between contractor grades. The majority of C7 (50%) and C8 (55.5%), possess 5-10 years of experience, indicating a more established group. C8 contractors also have a concentration in the 5-10 years, the most concerning trend is with C9 contractors. A staggering 76.9% have less than 5 years of experience, and none have more than 15 years. This suggests a workforce dominated by relatively new companies in the C9 grade, which may lack the experience of their larger counterparts.

3.1.2 Upgrade Status of the CIDA Grading

The gathered data reflects the failure of the majority of more than 92% of the C9 contractors to upgrade their CIDA grading. Yet the C8 and C7 contractors portray an upward trend of improvement. The results indicate that only the C9 contractors show a reluctance to upgrade themselves.

3.1.3 Issues of the Contractors

Financial Challenges: The analysis indicated that all three grades share the same view on changes related to the national economy, lack of bank support, and high interest rates. However, C9 are the most impacted grade by cashflow issues (25%) and the COVID-19 pandemic (7.7%) compared to C8 and C9.

Government Policy Changes: All three grades consider showing the slightest concern for Government tax policy compared to the other two issues. However, the impact of Tax policy shows a reverse link with the grade. Over 44% of all grades consider Government instability a major issue while over 62.5% confirm that they lack Government support.

Technological Issues: The analysis revealed a significant gap in technological issues among all three grades except for the lack of software for teaching. However, among them, C9 is the most disadvantaged grade with the highest rates of challenges due to a lack of technological development, knowledge, and low IT usage. However, the C7 grade shows a substantially lower impact than the C8 grade on these three issues.

Management Skills Issues: The analysis revealed a trend of growing issues with the decrement of the size of the grade. while the C7 mainly faced poor cost planning and low administrative flexibility, they showed less impact with Documentation issues. However, C8 contractors struggle with all three problems, with 66.7% suffering from poor documentation, 55.6% and 33.3% facing poor cost planning and low administrative flexibility. C9 is the most deprived grade and shows the highest percentage.

Resource Availability Issues: The C7-C9 contractors face significant challenges due to resource availability issues. According to survey results, over 66% of respondents deal with high labour turnover (76.7%) and a lack of high technical construction equipment (66.7%). When broken down by company grade, high labour turnover has a more significant impact on all C7-C9 contractors compared to the lack of high technological construction equipment. These resource availability issues are mainly causing delays in work procedures, significant cost overruns and deviations from planned schedules.

Safety Issues: the analysis indicates that C9 is the most exposed grade to safety issues due to limited resources and knowledge. While every grade gets stressed with poor safety precautions and for its funding C9 does not portray problems due to the unresponsiveness of employees**.**

Training and Development Issues: Among the respondent contractors of C7-C9 grade companies 80% face limited funds for employee training and 50% face a lack of support from institutional organisations. However, compared to the lack of institutional support, all three grades indicated they need more funds for employee training. The statistical data gathered from the survey indicated that 80% of contractors from C7 to C9 grade companies reported facing limited funds for employee training. In comparison, 50% showed a lack of support from institutional organisations. The analysis by company grade revealed that small-scale contractors need financial stability to train new employees.

Skilled Professional Issues: The analysis indicated that a substantial portion of 60% struggle with a lack of skilled workers and the absence of skills development programs and 50% of the population confirmed they face difficulties availability of professionals. However, compared to C7 and C9, C8 reported the lowest percentage of finding skilled workers. The most vulnerable group of these grades is C9 in all three issues.

Social Issues: The most prevailing issue among all grades is the lack of on-site facilities (70%), while high environmental impact affected 66.7%, and the mentality of the labourers is the least affected, accounting for less than 7% of the respondent contractors. C9 is the most affected grade by social issues with over 90% experiencing a lack of on-site facilities and over 80% by environmental issues. However, C7 and C8 grades show a lower impact on social issues, averaging around 50%.

According to the data analysis, all the contractors under C7-C9 confirmed that all these five solutions to overcome challenges faced by small-scale contractors are significant.

Among them, the majority agreed that improving skills and efficiency, enhancing procurement strategies and introducing incentive awarding mechanisms are also critical. However, there is a dialogue on improving the quality procedures, and the participants responded by improving the outcome by enhancing professionalism throughout the hierarchy.

3.2 QUALITATIVE ANALYSIS

Under the qualitative analysis, the study employed semi-structured interviews with industry experts who possess experience between 5 to 30 years of experience. The interviewees represented the administrative levels. The respondents represented a Project Manager with over 30 years of experience, a Deputy General Manager with over 30 years of experience, two Civil engineers with over 35 and 8 years of experience and a Quantity Surveyor with over 8 years of experience. The majority of the interviewees possess high experience in the construction industry and therefore the insights provided by them is more realistic and comprehensive.

3.2.1 Interview Data

According to the data, the interviewees agreed that all five suggestions could be utilised to overcome the challenges of C7-C9 contractors. However, among them, improving skills and efficiency was identified as the main fact. Apert from that, enhancing quality practices, professionalism and procurement strategies were identified as crucial. The finding also proposed that improving skills and efficiency is substantial among other solutions as it minimises critical issues faced by C7-C9 small-scale contractors. Another recommendation is to adopt innovative construction methods to stand among the competitors and adopt new technologies to achieve efficiency. However, there is a dialogue on improving the quality procedures, and the participants responded by improving the outcome by enhancing professionalism throughout the hierarchy.

3.3 DISCUSSION

The study examined the challenges confronted by the contractors concerning nine critical issues identified through the literature review. These issues include financial policies, government policies, technological challenges, management skills, resource availability, safety concerns, training and development, skilled professional workforce, and social issues. According to the data analysis, around 40% of contractors in each grade are affected by all nine issues. It confirms the high level of criticality and sensitivity of all nine matters considered for each group of contractors. The results confirmed that changes in the national economy, lack of support from the banking sector, and high interest rates showed a considerable challenge on all three grades of contractors. The situation is same with the Nigerian and South African small-scale contractors as they suffer from lack of access to finance and high interest rate (Mafimidiwo & Iyagba, 2015). Considering government policy challenges, C9 confirmed a higher effect than the other two grades. However, every grade reported challenges related to policy issues. Moreover, over 50% of all grades reported a lack of technological development and knowledge, and over 76% needed proper IT usage, similar to the Ghanaian small-scale contractors (Asante et al., 2018). Appropriate management is crucial for a successful enterprise, but small-scale companies need more cost planning, better documentation, and administrative flexibility. Pathirana (2021) emphasises the importance of proper finance, line management, and administrative approaches for smooth processes and survival in a competitive business landscape. The results revealed that all three grades suffer from resource availability and safety issues. However, C9 reported the highest impact. Similarly, Pathirana (2021) and Somachandra et al. (2024) claimed that facilitating the workforce with the latest safety measures can ensure more workforce. The study investigated the need for more support from institutional organisations and limited funds for employee training under the training and development issues. The results indicated that C9 is the group most highly impacted by the lack of training and development. However, compared to C9, C7 and C8 reported a more stable position.

Pathirana (2021) argued that facilitating training and development would enable the industry to complete international projects with the help of the local workforce, which creates recognition for contractors in the regional context and the global market. The skilled professional issues investigated are the availability of professionals, lack of qualified workers and lack of skill development programs. All three matters showed equal significance and effect over all three grades. These findings validate the argument that Pathirana (2021) made that private companies must facilitate and conduct training programs and workshops to educate their staff and keep them updated about the latest technology, processes, methods and knowledge. The study identified three social issues: lack of on-site facilities, high environmental impacts, and the mentality of the labourers. However, the mindset of the labourers indicates a considerably low impact as a social issue. However, the other two matters showed considerable significance over the mentality of labourers. Moreover, Pathirana (2021) recommended providing incentives, increasing job security, enhancing occupational health and safety, and adhering to labour laws will enable a country to retain the workforce. Similarly, Somachandra et al. (2024) recommended that providing training opportunities can enhance the skills and capabilities of the workforce. Among the solutions proposed by the experts to enhance the standards and quality of the construction, the highly recommended solution is to improve the efficiency and skills of the workforce. Similarly, Pathirana (2021) claimed that poor skills and inefficiency may lead to problems related to quality standards. However, proposing incentives can subdue such quality matters. Quality is an essential factor that small-scale contractors should concentrate on to survive in the industry.

4. CONCLUSIONS

Small-scale contractors are crucial in every construction industry, particularly in developing countries. Despite their significant contribution, small-scale contractors face numerous limitations over resources, such as human and mechanical access to finance, compared to other large-scale contractors. Regardless of these challenges, the growing body of knowledge indicates they are flexible in adapting to innovation. However, the literature does not provide an exact definition of small-scale contractors. Depending on the national and industrial considerations, the nature of the business and the rapidly changing economic conditions of different industries and countries define small-scale contractors on subjective and objective grounds. Countries like the USA, the UK, and Singapore and their construction-related governing bodies use their definitions with different grading systems. These industries use other parameters such as sales, annual income, number of employees, yearly resources, and obligations to define their grades for small-scale contractors.

Similarly, the CIDA, Sri Lanka, defined small-scale contractors using a grading system from C4 to C9. These small-scale contractors experience high insecurities due to various issues they face. Accordingly, De Silva (2022) identified nine main issues small-scale contractors face within the Sri Lankan construction arena. These are financial policies, government policies, technological issues, management skill issues, resource availability issues, safety issues, training and development issues, skilled professional issues, and social issues. Each issue contains different perspectives depending on its grade and potential impact. As possible solutions for identified challenges of C7-C9 contractors of Sri Lanka, professionals highly recommended introducing an incentive awarding mechanism, improving competence and professionalism of the workforce, improvements in quality practices, and proper procurement arrangements to overcome and minimise such challenges. These findings may be helpful for C7-C9 small-scale contractors of Sri Lanka to identify their strengths and weaknesses by recognising their performance gaps and what mechanisms to overcome them. Improving their potential may help them to enhance their overall performance while contributing to the development of the Sri Lankan construction industry.

5. RECOMMENDATIONS

In Sri Lanka, there are over 2000 small-scale contractors registered under CIDA. Therefore, research findings, indicate the necessity of forming a regulatory body to attend to the promotion of lower-grade contractors to uplift the construction industry. Also, it necessitates the need to maintain the professionalism and quality of such contractors while concentrating on their competencies and efficiency. Since they can easily adopt innovation, these small-scale contractors must concentrate on innovation and accordingly enhance their competency level and try to compete in the industry.

6. FURTHER RESEARCH AREAS

The study only concentrates on the C7-C9 contractors engaged in building construction projects, the study can also extend to small-scale contractors in the Infrastructure and Industrial Construction Industry in Sri Lanka

7. ACKNOWLEDGEMENTS

the authors would like to express our sincere gratitude to the Department of Quantity Surveying at SLIIT for their unwavering support and invaluable contributions to our research. Their guidance, resources, and encouragement were instrumental in the completion of this study.

8. REFERENCES

Alkilani, S., & Loosemore, M. (2022). An investigation of how stakeholders influence construction project performance: A small and medium sized contractor's perspective in the Jordanian construction industry. *Engineering, Construction and Architectural Management*, *31*(3), 1272-1297. https://doi.org/10.1108/ECAM-06-2022-0539

Amoah, C., & Bikitsha, L. (2022). Business sustenance strategies in the competitive construction industry: Emerging contractor's perspective. *IOP Conference Series: Earth and Environmental Science,* 1101*(4),* 042036. https://doi.org/10.1088/1755-1315/1101/4/042036

Asante, J., Kissi, E., & Badu, E. (2018). Factorial analysis of capacity-building needs of small-and medium-scale building contractors in developing countries: Ghana as a case study. *Benchmarking: An International Journal, 25*(1), 357-372. https://doi.org/10.1108/BIJ-07-2016-0117

Chileshe, N., Kavishe, N., & Edwards, D. (2021). Critical factors influencing the bid or no-bid decision of the indigenous small building contractors in Tanzania. *Construction Innovation*, *21*(2), 182–202. https://doi.org/10.1108/CI-09-2019-0098

Construction Industry Development Authority. (n.d.). *National registration and grading scheme for construction contractors*. Retrieved May 21, 2024, from https://www.cida.gov.lk/sea_con/pages_e.php?id=124

De Silva, S., Wijekoon, W., & Kalugala, C. (2022). Impact Of Economic Crisis on Employees of Contractors' organisations in The Sri Lankan Construction Industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ramachandra, T. and Ranadewa, K.A.T.O. (eds). *Proceedings of the 11th World Construction* (pp. 557-568). Ceylon Institute of Builders - Sri Lanka. https://doi.org/10.31705/WCS.2023.46

Dodanwala, T. C., & Santoso, D. S. (2024). Critical factors influencing the bid/no-bid decisions of small and medium-sized contractors in Sri Lanka. *International Journal of Construction Education and Research*., 1-26. https://doi.org/10.1080/15578771.2024.2332237.

Fernando, P., Fernando, N., & Gunarathna, M. (2016). Skills developments of labourers to achieve the successful project delivery in the Sri Lankan construction industry. *Civil and Environmental Research*, *8*(5), 86-99. Retrieved from https://www.iiste.org/Journals/index.php/CER/article/view/30376/31208

Gangwar, M., & Goodrum, P. (2005). The effect of time on safety incentive programs in the US construction industry. *Construction Management and Economics*, *23*(8), 851-859. https://doi.org/10.1080/01446190500184527

Jayalath, C. (2023). Survival strategies in the economic recession at firm level: The case of large-scale construction companies in Sri Lanka. *Journal of Economics, Management and Trade*, *29*(10), 67–76. https://doi.org/10.9734/jemt/2023/v29i101143.

Jayawardane, A. K. W., & Gunawardena, N. B. (1998). Construction workers in developing countries: A case study of Sri Lanka. *Construction Management and Economics*, *16*(5), 521–530. https://doi.org/10.1080/014461998372060.

Jui, F. N., Hossain, M. J., Das, A., Sultana, N., & Islam, M. K. (2024). Analyzing the impact of remittance, FDI and inflation rate on GDP: A comparative study of Bangladesh, Pakistan and Sri-Lanka using VAR and BEKK-GARCH approach, *Heliyon*, *10*(11), e31381. https://doi.org/10.1016/j.heliyon.2024.e31381.

Kusmaryono, I., Wijayanti, D., & Maharani, H. R. (2022). Number of response options, reliability, validity, and potential bias in the use of the Likert scale education and social science research: A literature review. *International Journal of Educational Methodology*, *8*(4), 625–637. Eurasian https://doi.org/10.12973/ijem.8.4.625.

Liyanagamage, N., & Fernando, M. (2023). Sensemaking in the construction industry: What is small-business social responsibility? *Social Responsibility Journal*, *19*(9), 1613–1631. https://doi.org/10.1108/SRJ-06-2022-0243.

Mafimidiwo, B., & Iyagba, R. (2016). Comparative study of problems facing small building contractors in Nigeria and South Africa. *Journal of Emerging Trends in Economics and Management Sciences*, *7*(2), 101-109. Retrieved from https://hdl.handle.net/10520/EJC190048.

Madushanka, U. (2003). *A survey of construction safety in Sri Lankan sites* [Unpublished B.Sc. (Quantity Surveying) dissertation]. University of Moratuwa, Sri Lanka.

Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2023). Assessment of critical factors influencing the performance of labour in Sri Lankan construction industry. International *Journal of Construction Management*, *23*(1), 144–155. https://doi.org/10.1080/15623599.2020.1854042.

Jayalath, C. (2023). Survival strategies in the economic recession at firm level: The case of large-scale construction companies in Sri Lanka. *Journal of Economics, Management and Trade*, *29*(10), 67–76. https://doi.org/10.9734/jemt/2023/v29i101143.

Jui, F. N., Hossain, M. J., Das, A., Sultana, N., & Islam, M. K. (2024). Analyzing the impact of remittance, FDI and inflation rate on GDP: A comparative study of Bangladesh, Pakistan and Sri-Lanka using VAR and BEKK-GARCH approach, *Heliyon*, *10*(11), e31381. https://doi.org/10.1016/j.heliyon.2024.e31381.

Kusmaryono, I., Wijayanti, D., & Maharani, H. R. (2022). Number of response options, reliability, validity, and potential bias in the use of the Likert scale education and social science research: A literature review. *International Journal of Educational Methodology*, *8*(4), 625–637. Eurasian https://doi.org/10.12973/ijem.8.4.625.

Liyanagamage, N., & Fernando, M. (2023). Sensemaking in the construction industry: What is small-business social responsibility? *Social Responsibility Journal*, *19*(9), 1613–1631. https://doi.org/10.1108/SRJ-06-2022-0243.

Mafimidiwo, B., & Iyagba, R. (2016). Comparative study of problems facing small building contractors in Nigeria and South Africa. *Journal of Emerging Trends in Economics and Management Sciences*, *7*(2), 101-109. Retrieved from https://hdl.handle.net/10520/EJC190048

Omopariola, E. D., Windapo, A., Edwards, D. J., & Thwala, W. D. (2020). Contractors' perceptions of the effects of cash flow on construction projects. *Journal of Engineering, Design and Technology, 18(2),* 308–325. https://doi.org/10.1108/JEDT-04-2019-0099

Pathirana, L. P. D. (2021). Construction industry and factor condition prospective of Sri Lanka: a special reference to skill labour shortage. *Journal of Business and Management, 23(2)*, 35–41. https://doi.org/http://dx.doi.org/10.9790/487X-2302073541

Perera, M., Gunarathna, K., & Karunaratne, B. (2023). *Effects of current economic crisis on construction contractors in Sri Lanka: An exploratory study on small scale contractors*. The 14th international conference on Sustainable Build Environment, Kandy, Sri Lanka. Retrieved from https://www.researchgate.net/publication/380401958_EFFECT_OF_CURRENT_ECONOMIC_CRISIS_ON_CONSTRUCTION_CONTRACTORS_IN_SRI_LANKA_AN_EXPLORATORY_STUDY_ON_SMALL-_SCALE_CONTRACTORS

Raghavan, S., & Kumar, K. (2015). Problems faced by small scale construction contractors in India. *International Research Journal of Engineering and Technology*, *2*(2), 105-107. Retrieved from https://www.irjet.net/archives/V2/i2/Irjet-v2i220.pdf

Rajakaruna, R., Bandara, K., & Silva, N. De. (2008). *Challenges faced by the construction industry in Sri Lanka: Perspective of clients and contractors.* Proceedings from International Conference on Building Education and Research (BEAR), Salford, United Kingdom. Retrieved from https://api.semanticscholar.org/CorpusID:67816942

Ranadewa, T., Sandanayake, Y. G., Siriwardena, M., & Ranadewa, K. A. T. O. (2018). *A SWOT analysis for Sri Lankan construction SMEs*. The 7th World Construction Symposium 2018: Built Asset Sustainability: Rethinking Design, Construction and Operations, Colombo, Sri Lanka. Retrieved from https://www.researchgate.net/publication/353767145

Ramawickrama, G. (2016). *Barriers on small scale contractors to enter and survive competitive construction industry in Sri Lanka.* [Unpublished MBA (Project Management) dissertation]. University of Moratuwa, Sri Lanka.

Shan, M., Liu, W., Hwang, B., & Lye, J. (2020). Critical success factors for small contractors to conduct green building construction projects in Singapore: Identification and comparison with large contractors. *Environmental Science and Pollution Research*, *27*(8), 8310–8322. https://doi.org/10.1007/s11356-019-06646-1.

Somachandra, V., Sylva, K., Bandara, C., & Dissanayake, R. (2024). Corporate social entrepreneurship (CSE) model for the construction industry of Sri Lanka. *Green and Low-Carbon Economy*. https://doi.org/10.47852/bonviewglce42022122.

Thwala, W.D., & Mvubu, M. (2008). Current challenges and problems facing small and medium size contractors in Swaziland. *African Journal of Business Management*, *2*(5), 93-98. Retrieved from https://www.researchgate.net/publication/228424137_Current_challenges_and_problems_facing_small_and_medium_size_contractors_in_Swaziland

Kanakan, K. and Gurmu, A., 2024. Sustaining concrete structural integrity: A framework for defect identification and rectification methods. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 974-984. DOI: https://doi.org/10.31705/WCS.2024.77. Available from: https://ciobwcs.com/papers/

SUSTAINING CONCRETE STRUCTURAL INTEGRITY: A FRAMEWORK FOR DEFECT IDENTIFICATION AND RECTIFICATION METHODS

Kripal Kanakan[1] and Argaw Gurmu[2]

ABSTRACT

One of the key issues that requires substantial attention in existing residential buildings is the occurrence of defects in their concrete structures. Flaws in the structural concrete of these types of buildings are frequently reported in numerous studies. If not rectified early, defects in concrete structures can lead to the collapse of these buildings. This study aims to develop a framework for understanding the identification and rectification methods of concrete defects in existing residential buildings. Thirty-three academic texts generated through a systematic literature review were utilised to collect qualitative data, and content analysis was carried out to meet the research objectives. The findings revealed that cracks are the most prevalent defect in concrete structures. Further, the review explored the most common non-destructive techniques such as the use of Schmidt hammer and ultrasonic for concrete defect detection. Moreover, rectification methods including epoxy treatment and concrete jacketing were identified. Finally, a framework that maps concrete defects with their identification and rectification techniques has been developed. The framework can help building inspectors, property managers, and other stakeholders involved in building maintenance to understand the alternative techniques for the identification and rectification of concrete defects.

Keywords: *Buildings; Concrete Defect; Rectification Techniques; Retrofitting.*

1. INTRODUCTION

Concrete plays a crucial role in residential construction, providing structural support and foundation. However, over time, concrete structures may develop flaws due to various factors such as subpar building techniques, environmental conditions, and ageing (Mehta, 2004). These flaws or defects can compromise the quality, service life, and structural integrity of buildings, posing safety risks to occupants and necessitating costly repairs for building owners (Gurmu et al., 2023). Previous studies revealed the impact of concrete defects on health and safety. For instance, a study conducted by Grillone et al. (2020) showed 26 accidents per 1000 workers due to the collapse of the beam, column, slabs, or other weak parts of the building which may be a result of poor construction or lack of retrofitting on those parts. To prevent impending failures of concrete structures during

[1] School of Architecture and Built Environment, Deakin University, Australia, kripalkkanakan@gmail.com
[2] School of Architecture and Built Environment, Deakin University, Australia, argaw.gurmu@deakin.edu.au

their service life, continuous surveying, monitoring, and rectifying the defects are needed (Obiora et al., 2022).

Various rectification methods have been proposed to strengthen and restore existing concrete structures, involving the addition of new components or structural pieces to enhance functionality and extend lifespan. However, the complexity of concrete flaws and the multitude of available retrofitting options make it challenging to select the most suitable strategy for each specific issue (Austin et al., 2022). Therefore, frameworks or tools for quickly examining concrete faults, pinpointing their origins, and figuring out the best rectification techniques must be developed. To the best of the authors' knowledge, no research has yet developed a framework linking concrete defects, detection techniques, and rectification processes. Additionally, Georgiou (2010) noted that there is a lack of studies guiding the selection of the most suitable and efficient retrofitting method to address generated defects. Therefore, the purpose of this study is to develop a system for figuring out several approaches to recognising concrete defects and comprehending how to correct the flaws in existing residential buildings. The specific objectives of this research are to (i) identify the most typical defects in the concrete structure of the existing buildings, (ii) explore the suitable methods of defect identification and rectification, and (iii) develop a framework that includes defects, causes, method of identification and the rectification process.

2. RESEARCH METHODOLOGY

As essential components of the study technique, a systematic literature review and qualitative analysis of secondary data are employed in the creation of a framework for rectifying concrete defects in existing residential buildings. Gathering, analysing, and summarising all pertinent materials (including articles, journals, case studies, websites, and process evaluations) is the goal of the systematic literature review (Nathan et al., 2023). A pre-planned search strategy is used to guarantee the thorough evaluation of relevant sources, and the procedure is documented to improve openness and repeatability (Nathan et al., 2023). This method entails a thorough examination of case studies, literature, and other relevant sources to develop a framework for fixing concrete flaws in residential buildings.

Data collection is a crucial component of secondary research, necessitating the collection of various theories and research papers to effectively conduct the study. This process involves browsing multiple websites and sources to gather the requisite data. The information-gathering endeavour encompasses retrieving relevant journal articles, conference papers, and other relevant resources from diverse outlets, including academic databases such as Scopus and Web of Science, business reports, government publications, and other online resources. A comprehensive analysis of secondary sources about concrete flaws in existing residential structures was conducted during the data collection phase of this research (Ullrich et al., 2020).

A thematic analysis, which involves identifying patterns and themes within the data, was employed first. Thereafter, content analysis was carried out to extract detailed information regarding the concrete defects, methods of identifying concrete flaws, and techniques for fixing the defects. The PRISMA framework was adopted to extract articles using keywords such as defect, concrete, retrofitting, and rectification (refer to Figure 1). The most popular databases such as Web of Science, Scopus, and Google Scholar were used to retrieve relevant articles (Gurmu et al., 2022). Initially, 223 articles were retrieved and then reduced to 171 articles after excluding articles published in languages other than English. Further screening was carried out to exclude studies addressing defects in non-residential building structures. Finally, the full texts of 33 articles were downloaded and analysed.

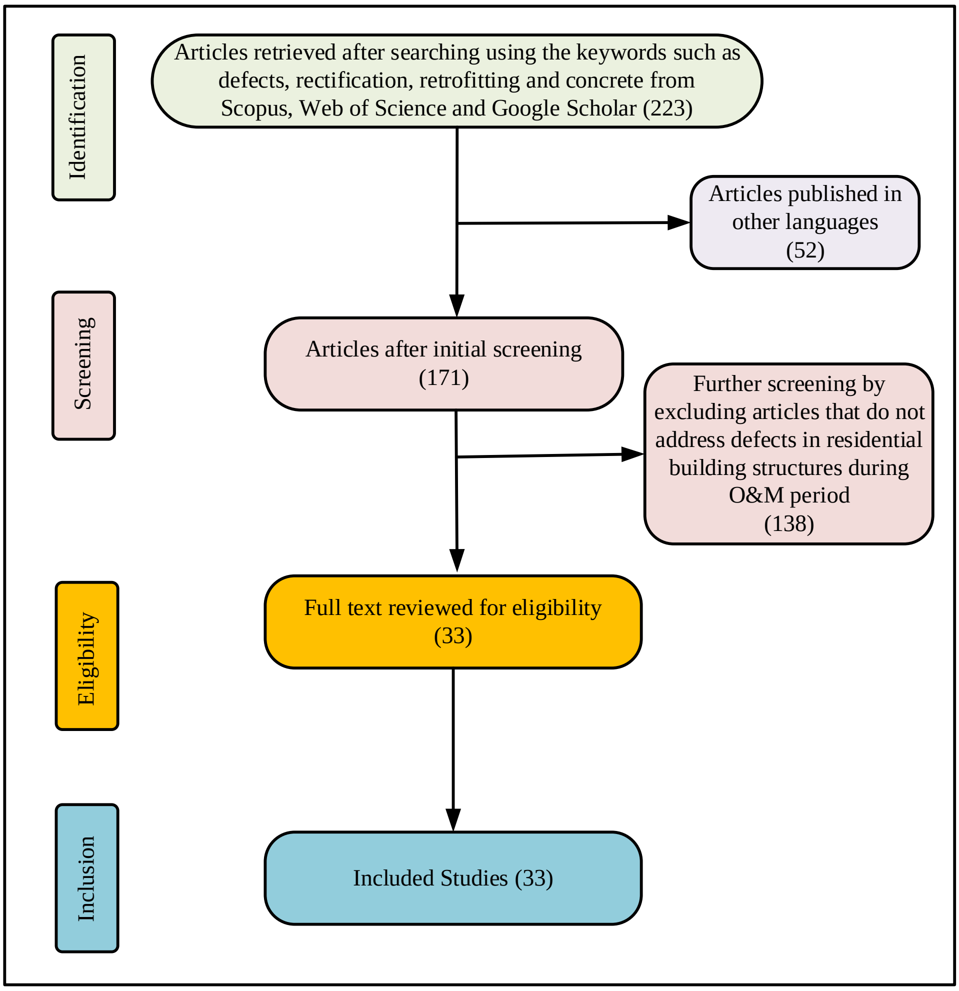


Figure 1: PRISMA framework

3. FINDINGS

3.1 BREAKDOWN OF SYSTEMATICALLY REVIEWED LITERATURE

The findings obtained in this paper are based on qualitative data which were obtained from the 33 academic studies that were selected using the PRISMA framework. As shown in Figure 2, most articles obtained through the systematic literature review were from 2021, comprising seven papers, followed by five papers from 2020, and four each from 2019, 2022, and 2023. These articles employed various research methods, including case studies, literature reviews, questionnaires/surveys, statistical analysis, and qualitative content analysis, to address the research aims and objectives.

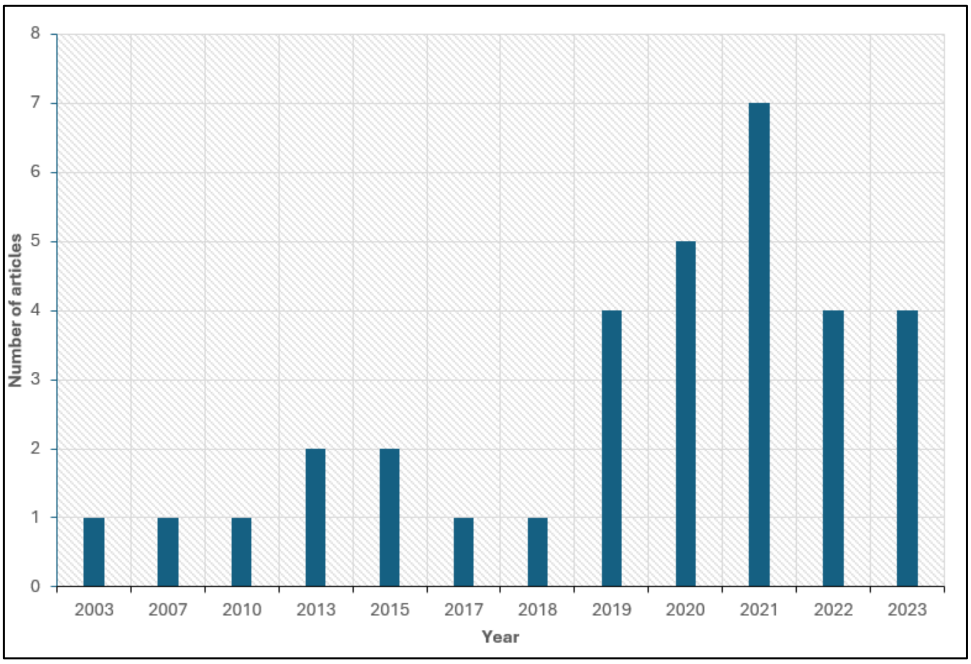


Figure 2: Yearly distribution of the studies

As shown in Figure 3, most of the selected articles were from the Journal of Construction and Building Materials, reflecting the study's focus on concrete. Other texts include the Journal of Applied Science, Journal of Building Engineering, and Journal of Civil Engineering, among others. In total, there are 14 different sources of the texts, providing a diverse range of perspectives relevant to this study.

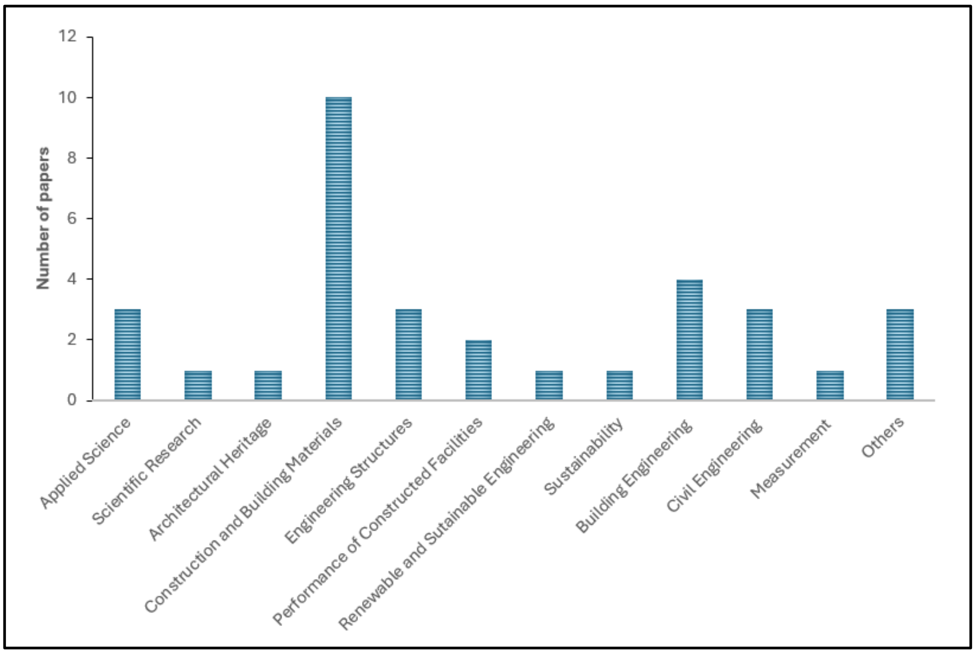


Figure 3: Distribution of articles based on their sources

3.2 DEFECTS IN CONCRETE STRUCTURES

As summarised in Table 1, blisters, cracking, crazing, curling, delamination, discolouration, dusting, efflorescence, low spots, pop-outs, scaling, and spalling were found to be some of the common defects in concrete structures. Among the various types of defects listed in Table 1, cracks have been identified as the predominant defect observed in numerous research papers.

Table 1: Summary of defects in concrete structures

Category	Description	Author
Cracks in concrete	Cracks can develop due to several causes, including drying shrinkage, temperature variations, incorrect curing, overloading, or subgrade settling.	Li et al. (2018)
	Insufficient depth of concrete overbends in reinforcement and lack of expansion joints may cause cracks.	Shaikh (2018)
Curling of concrete structure	This can become worse due to inadequate curing, inadequate subgrade preparation, or the use of inferior-quality materials.	Oh et al. (2016)
Scaling of concrete	This flaw may be due to poor finishing, repeated freeze-thaw cycles, or contact with chemicals such as dicing salts.	Yang et al. (2021)
Spalling of concrete	Occur due to overloading, freeze-thaw cycles, chemical actions, inadequate curing, poor finishing, or the use of poor-quality materials.	Shannag and Higazey (2020)
Delamination	Inadequate surface preparation, insufficient bonding, or the use of inferior materials.	Oh et. al. (2016)
Pop-out and discoloration	Poor quality control during the manufacture	Yang et al. (2021)
	Placing concrete can also cause popouts.	Shannag and Higazey (2020)
	Variations in the aggregate, fluctuations in the quantity of water used during mixing, or exposure to sunshine can all contribute	Shaikh (2018)

3.3 DEFECT IDENTIFICATION TECHNIQUES

Through a systematic review of the literature, four different categories of Non-Destructive Testing (NDT) i.e. (i) ultrasonic testing, (ii) GPR technique, (iii) IE, and (iv) Schmidt hammer were identified (refer to Table 2).

Table 2: Data summary obtained in the study.

Category	Description	Author
Ultrasonic testing	To identify the thickness and state of the concrete structure.	Gupta et al. (2022)
Ground Penetrating Radar (GPR) technique	To find changes in the concrete's material composition	Metwaly (2015)
Impact Echo (IE) test	To find cracks, delamination, thickness, and other flaws	Baggens and Ryden (2015)

Category	Description	Author
Schmidt Hammer	To assess the compressive strength	Kumavat et al. (2021)
Visual Inspection	Provides valuable initial information and serves as the first step in evaluating the overall condition of concrete structures	Shannag and Higazey (2020)

3.4 RECTIFICATION PROCESS OF CONCRETE DEFECTS

The most common rectification methods for flaws in concrete are outlined in Table 3. A review of relevant studies revealed that epoxy treatment and Carbon fibre reinforcement are the most suitable methods to be applied to fix concrete flaws.

Table 3: Rectification methods for concrete defects

Category	Description	Author
Epoxy treatment	Epoxy injection is used to repair and reinforce concrete structures with cracks or cavities. The epoxy injection assists in stopping additional deterioration and extends the life of the structure.	Kaarthik and Mandurachalam (2022)
Carbon fibre reinforcement	Carbon fibre strips or sheets to the surface of the concrete structure provide additional strength and stiffness. It provides strength and rigidity to the structure while reducing the extra weight or thickness.	Liu et al. (2020)
Grout Injection	By injecting a particular resin into the fractures, the crack injection technique may fix cracks in concrete.	Kim et al. (2013), Jiang et al. (2019)
Steel and concrete jacketing	Provide additional support and thickness to members to carry more load.	Mahmoud (2022)

4. DISCUSSION

4.1 DEFECTS IN CONCRETE

Concrete structures are susceptible to cracking over time, which can compromise their structural integrity and longevity. Cracks affect the load-carrying capacity and overall performance of the structures. Moisture and aggressive chemicals can penetrate concrete through cracks, further deteriorating it and reducing its durability. Depending on their size, orientation, and location, cracks can affect the behaviour of structures. Cracks can be divided into several categories, including structural cracks, thermal fractures, settlement cracks, and plastic cracks. Several factors can cause concrete cracking, including shrinkage, thermal stresses, excessive loading, and inadequate reinforcement. Moreover, faulty design or construction methods including inadequate joint spacing, and incorrect control joint placement can cause cracks (Li et al., 2018).

Besides cracks, delamination, which is the separation of a thin surface layer of concrete from an existing concrete surface, was identified as another defect in concrete structures. Concrete paste separates along a plane parallel to the surface of the concrete in the case of delamination. This type of concrete flaw typically forms because of concrete properties, daily temperature increases, and the finishing procedure used (Lacroix et al., 2021). Variations in the aggregate, fluctuations in the quantity of water used during mixing, or exposure to sunshine can all contribute to this. Inadequate curing, poor finishing, or the use of contaminated materials can also cause it.

In concrete, curling refers to the lifting or curling of the corners or edges of a slab, typically for a flat surface. Concrete structures can be adversely affected by this deformation. Moisture gradients or differences in moisture content are one of the major causes of concrete curling. When concrete cures and dries, the top surface dries faster than the bottom, causing shrinkage. This differential shrinking causes the slab edges to curl upward. Curling can be caused by temperature changes, restricted mobility at joints, and poor building practices (Oh et al., 2016). Moreover, pop-out is another defect found in structural elements in this review. In concrete, pop-out occurs when small cone-shaped or circular fragments break away from the surface. The size of these pop-outs can vary from a few millimetres to a few centimetres, and they can affect the appearance, durability, and functionality of concrete structures. Pop-outs, from an aesthetic perspective, form unattractive craters or depressions on the surface of concrete, reducing its visual attractiveness. In terms of durability, pop-outs can undermine the concrete surface's integrity, resulting in increased permeability, probable moisture infiltration, and decreased resistance to freeze-thaw cycles.

4.2 DEFECT IDENTIFICATION TECHNIQUES

The concrete surface can be visually examined to identify visible defects. It can detect apparent cracks, spalling, scaling, pop-outs, crazing, discolouration, honeycombing, and other surface abnormalities that could suggest a problem. In addition to detecting surface defects, the visual inspection also helps to assess concrete uniformity, inspect reinforcement conditions, detect surface contamination, ensure proper surface preparation, and provide documentation for future reference.

The Non-Destructive Testing (NDT) method does not damage materials, components, or structures while identifying defects or assessing potential failures. To examine the properties of an object, these methods typically involve specialised equipment and techniques. One of the most useful NDT techniques is ultrasonic testing. In this technique, ultrasonic pulses are transmitted through concrete and their travel time is measured. The test analyses the velocity of sound waves to determine the concrete's quality, uniformity, and potential defects. Concrete is exposed to sound waves via a transducer that is positioned on the concrete's surface. The transducer analyses the waves after they bounce off the material surfaces to identify the thickness and state of the structure.

Another commonly used technique in concrete defect identification is the use of the Schmidt hammer (rebound hammer) which measures the rebound of a spring-loaded mass striking a sample's surface. The test hammer strikes the concrete with a predetermined amount of force. Its rebound is determined by the hardness of the concrete and assessed by test equipment. The rebound value may be used to calculate the compressive strength of concrete using a conversion chart. The rebound value is then connected to the compressive strength of the concrete, indicating its total strength.

Furthermore, Ground Penetrating Radar (GPR) is another NDT method commonly employed for inspections. It is used in concrete testing to assess the condition of concrete structures by providing information about reinforcement bars, voids, cracks, and delamination. Typically, GPR antennas are moved over concrete surfaces and reflected signals are recorded and analysed in real-time or during post-processing. Radar waves are used in the GPR technique to find changes in the concrete's material composition. An image of the inside of the slab is produced by sending waves into the material and then analysing the signals that reflect.

Additionally, the impact echo test, as an NDT technique, is employed for identifying defects in concrete structures. This method detects voids, honeycombing, cracks, and delamination. A mechanical impact or impulse is applied to the surface of the concrete structure using a specialised impact device, (Baggens & Ryden, 2015). The impact can be generated by striking the surface with a hammer or using a mechanical excitation device. A concrete thickness gauge is typically used to measure concrete elements from one side.

4.3 RECTIFICATION METHODS FOR CONCRETE STRUCTURE DEFECTS

One of the dominant and efficient rectification methods is the use of carbon fibre reinforcement. It is a popular retrofitting technique for strengthening and reinforcing concrete buildings that have been damaged owing to cracking, settling, or other types of damage. Carbon fibre strips or sheets are used on the surface of the concrete structure to offer extra strength and stiffness (Draganic et al., 2021). Carbon fibre reinforcement can help to increase the structure's strength and stiffness while decreasing the reinforcement's excess weight or thickness, making it a long-lasting and efficient method of retrofitting concrete structures (Liu et al., 2020). Grout injection was also highlighted as another important technique. Concrete cracks, voids, and porous areas are injected with grouts, resins, or other materials to improve performance and restore integrity. Epoxy injection has been identified as another important method. It is frequently employed as a retrofitting procedure to repair and reinforce concrete structures afflicted with cracks or voids (Kaarthik & Mandurachalam, 2022). Many advantages can be gained from epoxy treatments, including high strength, excellent adhesion, chemical resistance, durability, and ease of maintenance. Concrete surfaces can be significantly improved in terms of performance, appearance, and longevity with these treatments.

The application of steel or concrete jacketing is another NDT method. Using epoxy adhesive or mechanical fasteners, steel plates are affixed to existing concrete structures. This integration of steel plates enhances both strength and stiffness, effectively serving as external reinforcement (Kim et al., 2013). A steel jacket provides additional strength and stability by covering columns and beams with steel angles, channels, or bands. By forming a new reinforced concrete section around the existing member, concrete jacketing adds a new layer of concrete to it. Shotcrete is more often used than cast-in-place concrete. In addition to improving load-carrying capacity, the jacketed section provides additional resistance against seismic forces. As part of this method, a layer of reinforced concrete is added outside the perimeter of the existing member using longitudinal steel reinforcements and transverse steel ties. By using reinforced concrete jackets, the member's strength, both flexural and shear, as well as its vertical bearing capacity, can be substantially increased. Through the confinement and anti-buckling action of the new stirrups, the member's ductility and deformation capacity can also be increased significantly. By adding longitudinal reinforcement, the member's bearing capacity and flexural strength are enhanced, while the addition of transverse reinforcement improves its shear strength and ductility.

4.4 DEVELOPMENT OF THE FRAMEWORK

By linking the defects, their identification methods, and rectification techniques discussed in previous subsections, a framework shown in Figure 4 is developed. The framework provides the link between each defect, its identification techniques, and the remediation process. For instance, from the findings discussed above, one of the major defects in concrete is crack, and the techniques to identify are visual inspection, ultrasonic testing, impact echo, and Schmidt hammer. The methods that can be utilised to remedy the cracks are Carbon fibre reinforcement, epoxy treatment, and grout injection. Using a similar procedure, the methods for identification and rectification processes for other defect types can be easily obtained from the framework.

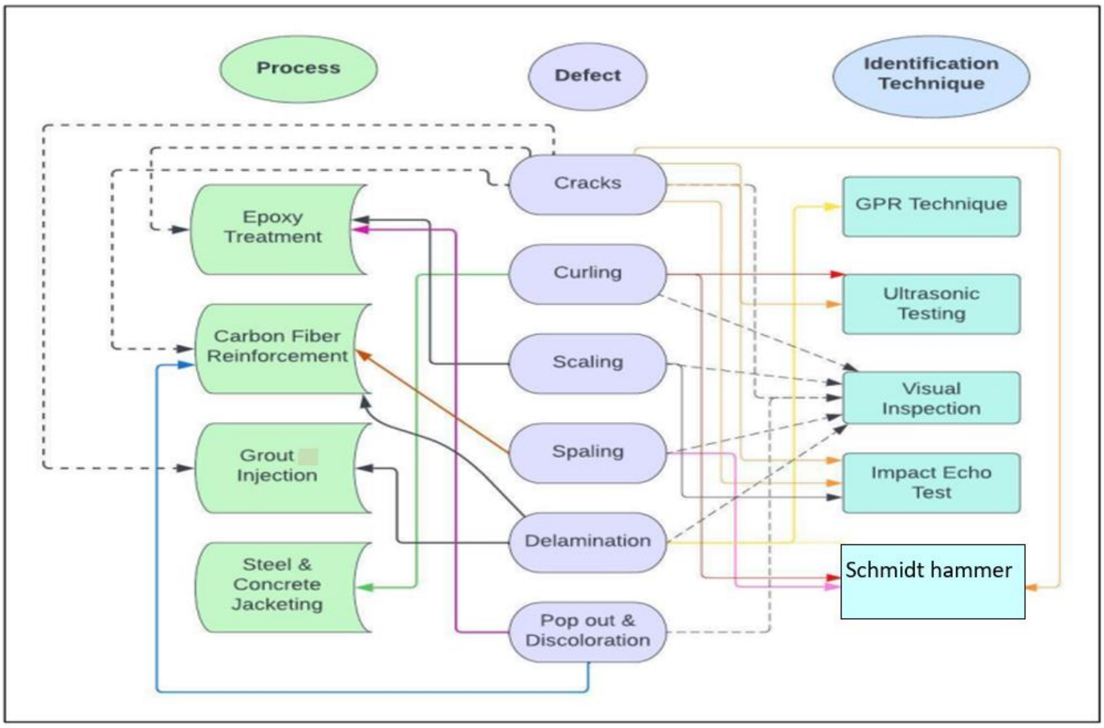


Figure 4: Framework to detect defects, identification techniques, and rectification process

5. CONCLUSIONS

This study aimed to analyse defects in the concrete structures of residential buildings via a systematic review of the literature. The findings obtained in this research revealed several defects associated with concrete structures; however, cracks are the most dominant and severe problem. Additionally, the study has shown that while several techniques were used for the identification of defects in concrete, the Schmidt hammer and ultrasonic methods are the most widely used. The means to rectify these identified flaws can be done through epoxy treatment, fibre-reinforced treatment, grout injection, and jacketing. It was found that epoxy and fibre-reinforced treatment are capable of remedying most of the defects.

This research has managed to establish a framework that provides links between defects, identification techniques, and rectification processes. Various stakeholders involved in the building maintenance and operation can benefit from the output of this research. By retrofitting using the suggested techniques, owners or property managers of residential buildings can maintain the structural integrity of their concrete structures. Moreover, the framework can be used by future researchers interested in investigating defects in other structures and materials such as steel or masonry for comparison purposes. Despite its contributions, there were certain limitations associated with this research. The study used secondary data only and field tests were not carried out to verify the proposed framework. Further, due to the complexity of building defects, the developed framework may not capture all the causes and their interrelationships. Hence, it is suggested that future researchers should conduct field tests and employ triangulation methods to verify the proposed techniques. Additionally, separate frameworks for low-rise and high-rise buildings can be developed by future researchers since the causes of defects may vary based on the types of buildings.

6. REFERENCES

Austin, M. C., Carpino, C., Mora, D., & Arcuri, N. (2022). A Methodology to identify appropriate refurbishment strategies towards zero energy buildings in a hot and humid climate. *Journal of Physics. Conference Series*, *2385*(1), 1–13. https://doi.org/10.1088/1742-6596/2385/1/012020

Baggens, O., & Ryden, N. (2015). Systematic errors in Impact-Echo thickness estimation due to near-field effects. *NDT & E International*, *69*, 16–27. https://doi.org/10.1016/j.ndteint.2014.09.003

Draganić, H., Gazić, G., Lukić, S., & Jeleč, M. (2021). Experimental investigation on blast load resistance of reinforced concrete slabs retrofitted with epoxy resin-impregnated glass fiber textiles. *Composite Structures*, *274*, 114349. https://doi.org/10.1016/j.compstruct.2021.114349

Georgiou, J. (2010). Verification of a building defect classification system for housing. *Structural Survey*, *28*(5), 370-383. https://doi.org/10.1108/02630801011089164

Grillone, B., Danov, S., Sumper, A., Cipriano, J., & Mor, G. (2020). A review of deterministic and data-driven methods to quantify energy efficiency savings and to predict retrofitting scenarios in buildings. *Renewable and Sustainable Energy Reviews*, *131*, 110027. https://doi.org/10.1016/j.rser.2020.110027

Gupta, M., Khan, M. A., Butola, R., & Singari, R. M. (2022). Advances in applications of Non-Destructive Testing (NDT): A review. *Advances in Materials and Processing Technologies*, *8*(2), 2286-2307. https://doi.org/10.1080/2374068X.2021.1909332

Gurmu, A. T., Krezel, A., & Mahmood, M. N. (2023). Analysis of the causes of defects in ground floor systems of residential buildings. *International Journal of Construction Management*, *23*(2), 268-275. https://doi.org/10.1080/15623599.2020.1860636

Gurmu, A. T., Shooshtarian, S., & Mahmood, M. N. (2022). Critical evaluation of building defects research: A scientometric analysis. *Journal of Performance of Constructed Facilities*, 36(3), 03122001. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001727

Jiang, B., Oh, K. H., Kim, S. Y., He, X., & Oh, S. K. (2019). Technical evaluation method for physical property changes due to environmental degradation of grout-injection repair materials for water-leakage cracks. *Applied Sciences*, *9*(9), 1740. https://doi.org/10.3390/app9091740

Kaarthik, M., Mandurachalam, R. (2022). A State-of-the-Art review on methods of retrofitting in building structural members: A comprehensive review. In: S. Kolathayar, C. Ghosh, B. R. Adhikari, I. Pal, A. Mondal (Eds.) *Resilient infrastructure. Lecture notes in Civil Engineering*, (1st ed., pp. 175-185). Springer, Singapore. https://doi.org/10.1007/978-981-16-6978-1_13

Kumavat, H. R., Chandak, N. R., & Patil, I. T. (2021). Factors influencing the performance of rebound hammer used for non-destructive testing of concrete members: A review. *Case Studies in Construction Materials*, *14*, e00491. https://doi.org/10.1016/j.cscm.2021.e00491

Kim, D., Jung, S., & Cha, K. (2013). Evaluation of the performance of grouting materials for saturated riprap. *Materials*, *6*(12), 5713-5725. https://doi.org/10.3390/ma6125713

Lacroix, F., Noël, M., Moradi, F., Layssi, H., & Tingson, T. (2021). Nondestructive condition assessment of concrete slabs with artificial defects using wireless impact echo. *Journal of Performance of*

Constructed Facilities, *35*(6), 04021072. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001651

Li, L., Wang, Q., Zhang, G., Shi, L., Dong, J., & Jia, P. (2018). A method of detecting the cracks of concrete undergo high temperature. *Construction and Building Materials*, *162*, 345-358. https://doi.org/10.1016/j.conbuildmat.2017.12.010

Liu, B., Guo, J., Wen, X.-Y., Zhou, J., & Deng, Z. (2020). *Study on flexural behavior of carbon fibers reinforced coral concrete using digital image correlation*. *Construction and Building Materials*, *242*, 117968. https://doi.org/10.1016/j.conbuildmat.2019.117968

Mahmoud, K. M., Sallam, E. A., & Ibrahim, H. M. H. (2022). Behavior of partially strengthened reinforced concrete columns from two or three sides of the perimeter. *Case studies in Construction Materials*, *17*, e01180. https://doi.org/10.1016/j.cscm.2022.e01180

Mehta, P. K. (2004). High-performance, high-volume fly ash concrete for sustainable development. In K. Wang (Eds.), *Proceedings of the International Workshop on Sustainable Development and Concrete Technology* (pp. 3-14). Iowa State University Ames, IA, USA. https://core.ac.uk/download/pdf/11346106.pdf#page=14

Metwaly, M. (2015). Application of GPR technique for subsurface utility mapping: A case study from urban area of Holy Mecca, Saudi Arabia. *Measurement*, *60*, 139-145. https://doi.org/10.1016/j.measurement.2014.09.064

Nathan, B. A., Love, R., & Carlson, L. A. (2023). An autoethnographic reflection from two black women Ph. D.'s and their white woman advisor on the use of sista circle methodology in the dissertation process. *The Qualitative Report*, *28*(1), 323-339. https://doi.org/10.46743/2160-3715/2023.5577

Obiora, C. O., Ezeokoli, F. O., Belonwu, C. C., & Okeke, F. N. (2022). Defects in concrete elements: A study of residential buildings of 30 years and above in Onitsha Metropolis, Anambra State, Nigeria. *Journal of Building Construction and Planning Research*, *10*(03), 102–123. Https://doi.org/10.4236/jbcpr.2022.103005

Oh, H. J., Cho, Y. K., Seo, Y., & Kim, S. M. (2016). Experimental analysis of curling behavior of continuously reinforced concrete pavement. *Construction and Building Materials*, *128*, 57-66. https://doi.org/10.1016/j.conbuildmat.2016.10.079

Shaikh, F. U. A. (2018). Effect of Cracking on corrosion of steel in concrete. *International Journal of Concrete Structures and Materials*, *12*(1), 112-115. https://doi.org/10.1186/s40069-018-0234-y

Shannag, M. J., & Higazey, M. (2020). Strengthening and repair of a precast reinforced concrete residential building. *Civil Engineering Journal*, *6*, 2457-2473. https://doi.org/10.28991/cej-2020-03091630

Ullrich, C., Stürmlinger, A., Wensing, M., & Krug, K. (2020). Qualitative research methods in medical dissertations: an observational methodological study on prevalence and reporting quality of dissertation abstracts in a German university. *BMC Medical Research Methodology*, *20*, 301. https://doi.org/10.1186/s12874-020-01186-6

Yang, Y., Chen, B., Zeng, W., Li, Y., Chen, Q., Guo, W., Wang, H., & Chen, Y. (2021). Utilization of completely recycled fine aggregate for preparation of lightweight concrete partition panels. *International Journal of Concrete Structures and Materials*, *15*, 32. https://doi.org/10.1186/s40069-021-00470-z

Yang, G., Fan, Y., Wang, G., Cui, X., Li, Q., Leng, Z., & Deng, K. (2023). Mitigation effects of air-backed RC slabs retrofitted with CFRP subjected to underwater contact explosions. *Ocean Engineering*, *267*, 113261. https://doi.org/10.1016/j.oceaneng.2022.113261

Gunasekara, K.A., Perera, B.A.K.S. and Ranadewa, K.A.T.O., 2024. Symptoms of occupational stress in construction professionals: A systematic literature review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 985-997. DOI: https://doi.org/10.31705/WCS.2024.78. Available from: https://ciobwcs.com/papers/

SYMPTOMS OF OCCUPATIONAL STRESS IN CONSTRUCTION PROFESSIONALS: A SYSTEMATIC LITERATURE REVIEW

Gunasekara, K.A.[1], Perera, B.A.K.S.[2], and Ranadewa, K.A.T.O.[3]

ABSTRACT

Construction professionals are particularly vulnerable to stress due to the demanding and high-risk nature of their work. However, they often remain unaware of their elevated stress levels, which can lead to negative consequences for both their personal well-being and overall job performance. Despite the significance, there has been limited research on stress among construction professionals. This study aims to conduct a Systematic Literature Review (SLR) to identify stress symptoms among construction professionals. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method filtered the search from 216 articles to 22. The studies were screened based on inclusion criteria, and relevant data were categorised into psychological, behavioural, and physical/physiological symptoms. The analysis identified 41 psychological symptoms (such as anxiety, depression, and irritability), 44 individual behavioural symptoms (including changes in eating and sleeping patterns and increased substance use), nine organisational behavioural symptoms (such as absenteeism and high turnover rates), and 20 physical/physiological symptoms (including headaches, muscle tension, and fatigue). The findings highlight the extensive impact of stress on construction professionals' mental, emotional, and physical health. The paper contributes to the existing body of knowledge by categorising stress symptoms and emphasising the need for holistic stress management strategies. It offers practical insights for employers, policymakers, and healthcare providers to develop targeted interventions to enhance the well-being and productivity of construction professionals. The findings also provide a foundation for future research to explore the long-term effects of stress and evaluate the efficacy of interventions in this high-risk population.

Keywords: *Construction Professionals; PRISMA; Stress; Symptoms.*

1. INTRODUCTION

Work-related stress is a phenomenon that constantly increases in severity (Vlăduţ & Kállay, 2010). According to a study by the Chartered Institute of Building (CIOB, 2006), 68.2% of Construction Professionals (CPs) had suffered from stress, anxiety, or depression as a direct result of working in the construction industry, and 84% of the CPs felt that stress in the construction industry was one factor responsible for the poor

[1] Research Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, gunasekaraka.21@uom.lk

[2] Professor in Quantity Surveying, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk

[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, tharushar@uom.lk

retention of CPs in the sector (Kumar & Jeswani, 2018). Moreover, construction is a dynamic, complicated, and crisis-ridden industry that works quickly (Chan et al., 2012), and construction-related occupations are most vulnerable to stress (Ojo et al., 2019).

A 2020 global survey of 2,081 construction industry professionals found high incidents of stress (97%), anxiety (87%), depression (70%), fatigue (96%), poor concentration (95%), feeling over- whelmed (91%), and low self-confidence (86%), experienced at least once within the last twelve months (van Heerden et al., 2024). Further, several studies on stress management concerning professionals working in different fields, such as education (Bakhuys Roozeboom et al., 2020) and healthcare (Salam, 2016), have been conducted. However, there are few studies conducted on directing stress and stress management of CPs such as Project managers (Naoum et al., 2018), Engineers (Hazeen & Umarani, 2022), Architects and CPs (Saikala & Selvarani, 2015) and as common for CPs (De Silva et al., 2017; Dodanwala & Santoso, 2022; Kamardeen, 2022). Workplace accidents can be connected to workers' mental health, with factors such as age, physical demands, and particularly the long working hours of construction professionals contributing significantly to stress, anxiety, and fear (Gómez-Salgado et al., 2023). Further, the unawareness of CPs about their stress is a common problem (Bowen et al., 2013). This unawareness will aggravate their stress levels (Chan, 2011). In addition, unawareness will delay taking necessary precautions (Sousa et al., 2014). Hence, identifying stress symptoms is the first step in stress management. Even though studies are identifying the symptoms of CPs stress, very few SLRs have been conducted to synthesise the findings in the literature and get a holistic idea. Therefore, this paper aims to systematically review existing literature on the symptoms of stress of construction workers. This paper introduces work-related stress and stress management construction, directing to the research objectives. Next, a literature review on stress and stress management will be discussed. Subsequently, the research method, results and discussion will be presented.

2. LITERATURE REVIEW

2.1 STRESS AND STRESS MANAGEMENT

The word ‘stress’ is derived from the Latin word ‘stringere’, which means to draw tight (Oladinrin et al., 2014; Ross, 2020). Further, Ross (2020) mentions that in the 14th century, “stress” was associated with adversity, hardship, or some affliction. In the 17th century, stress was described as hardship, strain, adversity, or affliction (Oladinrin et al., 2014). Fontana (1989), as cited in Chow (2009), defines stress as those challenges that excite us and keep us on our toes, and without stress, life for many people would ultimately become dull and not worth living. This study focussed on the harmful effects of stress, which could be overcome by managing it. Jeffrey (2006) defined stress as a state of cognitive, emotional, and physical arousal (Oladinrin et al., 2014), which links up with the perspective of the human body. Kalia (2002) and Spielberger et al. (2003) identified stress as an epidemic (Ajayi et al., 2019). Thus, its management deserves attention. Greenberg (2017) mentions that the goal of stress management should not be to eliminate stress but to learn how to manage and use it effectively.

2.2 SYMPTOMS OF STRESS OF CONSTRUCTION PROFESSIONALS

The Health and Safety Executive (2004) states that around half a million people in the UK experience work-related stress at a level that they believe is making them ill, and up to five million people feel "very" or "extremely" stressed by their work and work-related stress costs society about £3.7 billion every year (Donald et al., 2005). Hence, how stress will make a person ill is worthwhile to study. A person who is under stress will show some signs and symptoms. According to Lehrer et al. (2007), as cited by Kushwaha (2014), the first signs that indicate individuals may suffer from excessive pressure or stress are changes in behaviour or appearance. In research, Sommerville and Langford (1994) further categorised stress symptoms into three aspects as Oladinrin et al. (2014), as presented below in Table 1.

Table 1: Three aspects of stress symptoms

Definition	Description	Reference
Psychological Symptoms	Include lack of concentration, tenseness and other symptoms that can be regarded as possible illnesses, such as depression and paranoia.	Oladinrin et al., (2014)
Behavioural Symptoms	Include irritability, lack of effort, excessive consumption of food and beverages, and withdrawal from the work environment that is trying to retreat from commitments.	
Physical Symptoms	Include cardio-bronchial pains, weight loss from under-eating, and sleeping at abnormal times.	

Accordingly, stress symptoms have been categorised as Psychological, Behavioural and Physical.

2.3 IMPORTANCE OF IDENTIFYING SYMPTOMS OF STRESS FOR CONSTRUCTION PROFESSIONALS

As many global and local researchers have outlined, identifying stress symptoms among CPs is imperative for several reasons. Table 2 presents the summary of identified factors.

Table 2: Importance of identification of stress symptoms

Aspect	Description	Reference
Impact on Physical Health	The physical demands of construction work, including heavy lifting, prolonged standing, and exposure to hazardous environments, significantly contribute to stress among workers. Identifying stress symptoms early is crucial because prolonged stress can exacerbate physical health issues such as cardiovascular diseases, musculoskeletal disorders, and chronic pain.	Enshassi et al. (2016)
Mental Health Consequences	Construction workers face high risks of anxiety, depression, and burnout due to job insecurity and high-performance demands. Recognising symptoms like persistent sadness, irritability, and concentration	Love et al. (2010; Tijani et al. (2021); Torres et al. (2023)

Aspect	Description	Reference
	difficulties enables timely mental health support and intervention.	
Safety and Productivity	Stress negatively impacts workplace safety and productivity. Stressed workers are prone to errors and accidents. Identifying symptoms such as insomnia and impaired judgment helps implement strategies to enhance safety and maintain productivity.	(Koulinas et al., 2023; Wong et al., 2023)
Economic Implications	Stress in the construction sector leads to costs associated with lost productivity, absenteeism, and healthcare. Early identification of stress symptoms allows for proactive measures, reducing these economic burdens.	Chan et al. (2018)
Improving Workplace Culture	Addressing stress fosters a positive workplace culture, leading to higher job satisfaction, better team cohesion, and enhanced morale. Recognising stress symptoms is essential for building a supportive work environment.	Peterson & Wilson, (2015); Wei et al., (2020)
Legal and Ethical Considerations	Employers have a legal and ethical obligation to ensure employee well-being. Addressing stress symptoms demonstrates a commitment to health and safety, enhancing organisational trust and compliance with occupational health regulations.	Allen et al. (2014); Chin et al. (2018); Lockwood et al. (2017)

Accordingly, identifying stress symptoms is vital in several aspects, such as impact on physical health, mental health consequences, safety and productivity, economic implications, improving workplace culture, and legal and ethical considerations.

By recognising and addressing these symptoms early, stakeholders in the construction industry can implement effective strategies to support worker well-being and foster a healthier, more productive workforce. Therefore, a thriving need arises to investigate the symptoms of stress in the early stages and minimise the stress of construction workers in the construction industry.

3. METHODOLOGY

In this study, the literature search was conducted using the systematic review technique, a widely adopted method in research. To enhance the quality of the study, the authors utilised the PRISMA approach instead of selecting literature randomly. As Benachio et al. (2020) highlighted, the PRISMA guidelines feature a four-phase flow diagram encompassing the stages of identification, screening, eligibility, and inclusion.

Research synthesis is essential for literature reviews with extensive samples, offering evidence-based insights for specific research questions (Lock & Giani, 2021). SLRs are more effective than bibliometric or narrative reviews, requiring an unbiased and transparent approach (Rowley & Paul, 2021). PRISMA is a widely recognised reporting guideline that addresses issues in systematic reviews, ensuring rigour and reducing bias (Page et al., 2021). Due to the complex nature of this study, PRISMA's comprehensive guidelines were deemed suitable, aiding transparent reporting. Consequently, Figure 1 illustrates the development of the PRISMA four-phase flow diagram utilised in this research.

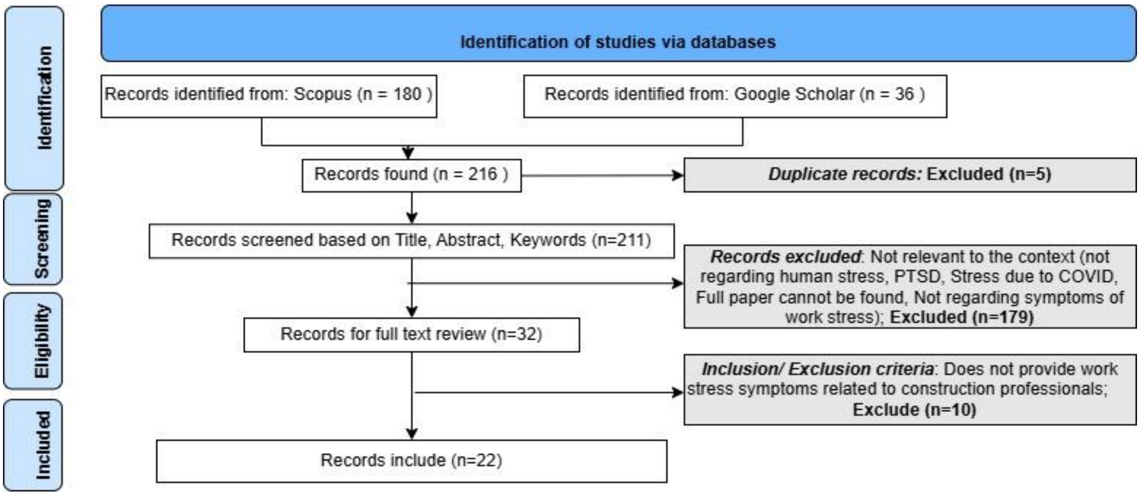


Figure 1: PRISMA Flow diagram of the study selection

Accordingly, Figure 1 demonstrates the process of literature identification from Scopus and Google Scholar, followed by the screening procedures conducted following the eligibility criteria, ultimately resulting in the final records included in this study.

3.1 SEARCH WORDS AND STRINGS

Background knowledge of occupational stress and stress management is essential to develop an effective search string. This understanding is enhanced through an extensive review of relevant literature. Formulating the research aim and objectives is the foundation for developing the search string. Subsequently, relevant databases were identified, and Scopus and Google Scholar were selected for this study. Accordingly, the search string used in this literature review is as follows:

("job stress*" OR "work* stress*" OR "workplace* stress*" OR "occupation* stress*" OR "job* stressor*" OR "work* stressor*" OR "workplace* stressor*" OR "occupation* stressor*" OR "job* stress* symptom*" OR "work* stress* symptom*" OR "workplace* stress* symptom*" OR "occupation* stress* symptom*" OR "job* stress* manage*" OR "work* stress* manage*" OR "workplace* stress* manage*" OR "occupation* stress* manage*" AND "construction*" AND NOT "trauma*" AND NOT "burnout" AND NOT "worker*" OR "labourer*" OR "labor*")*

Given the long-standing nature of the occupational stress concept, the timeline was not restricted. The search was limited to peer-reviewed articles in the English language, excluding major clinical studies, as they focus on the medical aspects of stress rather than the social dimensions of occupational stress relevant to the research participants. During the abstract and full-text review, articles were excluded if they were not pertinent to the context (e.g., unrelated to human stress, PTSD-Post Traumatic Stress Disorder, stress due to COVID-19, inaccessible full papers, or not concerning work stress symptoms). Articles that did not address work stress symptoms related to construction professionals were excluded. As shown in Figure 1, 22 papers were included in this study.

4. RESEARCH FINDINGS AND DISCUSSION

4.1 STRESS SYMPTOMS OF CONSTRUCTION PROFESSIONALS

When considering the literature on stress symptoms, there is a considerable lack of literature focusing on separate professional groups in the construction industry. However, the authors identified 22 articles for content analysis after conducting the SLR. After conducting the content analysis, the identified stress symptoms were categorised into three categories i.e. (i) psychological/state of mind, (ii) behavioural, and (iii) physical/physiological, as discussed in the sections below.

4.1.1 Psychological/State of Mind

The researchers with a psychological orientation emphasised micro-level characteristics as factors affecting work stress. In contrast, stress-orientated epidemiologists turned to studying specific occupational stress to identify new risks and experiences occurring in work life (Väänänen et al., 2012). Psychological symptoms of stress pertain to the mental and emotional well-being of construction professionals and affect how individuals think, feel, and process information, often leading to emotional disturbances and cognitive impairments (Love et al., 2010). These symptoms can severely impact a worker's ability to focus, make decisions, and maintain emotional stability, ultimately affecting their overall mental health and job performance (Adhikari et al., 2023). Accordingly, 41 factors were identified as the psychological symptoms of stress for construction professionals, as shown in Figure 2.

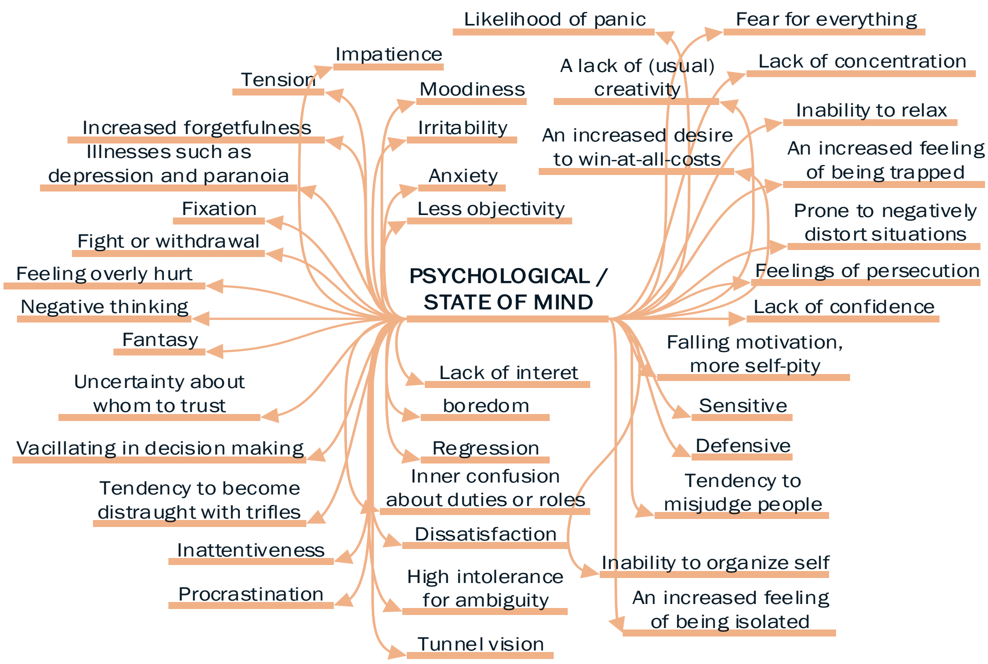


Figure 2: Psychological stress symptoms of construction professionals

Chan et al. (2016), Haydam and Smallwood (2016) and Rosen et al. (2010) have identified a range of psychological symptoms that are prevalent among construction professionals, such as an inability to relax, tunnel vision, a tendency to misjudge people, and irritability. Similarly, common psychological symptoms reported in the literature include anxiety, depression, mood swings, and a sense of being overwhelmed (Patching, 2022). Figure 2 summarises the psychological symptoms reported in 22 relevant studies focused on construction professionals.

4.1.2 Behavioural

Behavioural symptoms of stress are reflected in the actions and habits of construction workers, encompassing both individual and organisational behaviours (Brenda & Steve, 2006). Recognising these behavioural changes is crucial for addressing stress at both personal and organisational levels.

4.1.2.1 Individual

On an individual level, these symptoms include changes in eating and sleeping patterns, increased use of alcohol or drugs, withdrawal from social interactions, and decreased productivity. The SLR revealed 44 individual behavioural symptoms of stress of construction professionals as presented in Figure 3. These symptoms range from emotional responses such as irritability and anxiety to physical manifestations including headaches and fatigue. Construction professionals often face significant stress due to the demanding nature of their work, which can lead to both mental and physical health issues. Recognising these symptoms is imperative for implementing effective stress management strategies. However, in the construction industry, identifying stress symptoms among professionals remains challenging. Many researchers including Adhikari et al. (2023) argued that many individuals attempt to conceal their stress symptoms, making accurate identification difficult. This reluctance to acknowledge stress can hinder efforts to address and manage these issues effectively, exacerbating the problem within the industry.

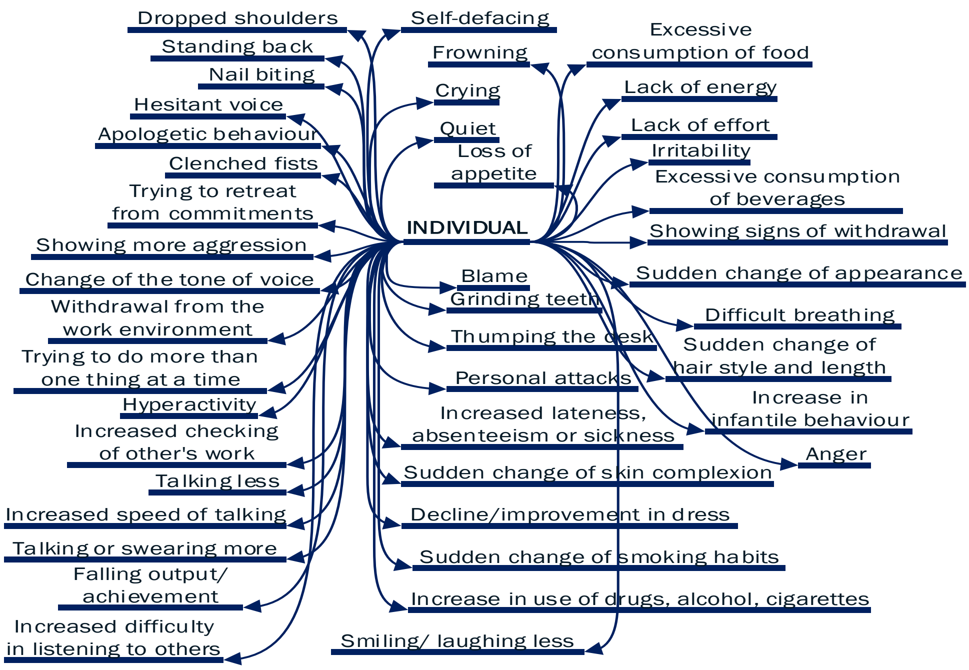


Figure 3: Behavioural (individual) stress symptoms of construction professionals

Figure 3 provides a summary of individual behavioural stress symptoms. As identified by (Zhou et al., 2022), these symptoms can manifest visibly to others through signs such as frowning, crying, changes in hairstyle, and even reduced smiling.

4.1.2.2 Organisational

Organisational behavioural symptoms involve broader patterns within the workplace, such as increased absenteeism, high turnover rates, reduced team collaboration, and conflicts among workers. The SLR revealed 09 organisational behavioural symptoms of stress as presented in Figure 4.

Figure 4: Behavioural (organizational) stress symptoms of construction professionals

As illustrated in Figure 4, organisational behavioural stress symptoms include absenteeism and voluntary turnover, as documented by Glasscock et al. (2006) and Jung et al. (2020).

4.1.3 Physical/Physiological

Physical or physiological symptoms of stress manifest in the body and can significantly impair a construction worker's physical health (Abbe et al., 2011). These symptoms include headaches, muscle tension, fatigue, gastrointestinal issues, and cardiovascular problems. Chronic stress can weaken the immune system, making workers more susceptible to illnesses and injuries. Identifying and addressing these physical symptoms is vital for maintaining the health and safety of construction workers, ensuring they can perform their physically demanding tasks effectively. The SLR revealed 20 physical symptoms of stress.

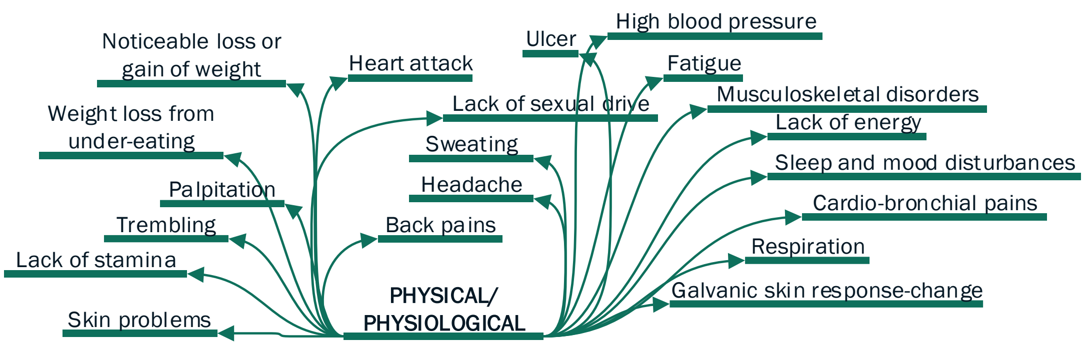


Figure 5: Physical/ Physiological stress symptoms of construction professionals

Authors Abbe et al. (2011), Nixona et al. (2011) and Wei et al. (2020) emphasise physical stress symptoms, including headaches, back pain, and noticeable weight changes. These symptoms are illustrated in Figure 5.

5. CONCLUSIONS

This systematic literature review has highlighted the multifaceted nature of stress experienced by construction professionals, categorizing the identified symptoms into psychological/state of mind, behavioural, and physical/physiological domains. The psychological symptoms, encompassing anxiety, depression, and irritability, underscore the significant mental health challenges faced by these workers. Behavioural symptoms, both individual and organisational, reflect the impact of stress on daily routines, productivity, and workplace dynamics. Physical/physiological symptoms such as headaches, muscle tension, and fatigue further illustrate stress's toll on the body.

Understanding these symptoms is crucial for developing comprehensive strategies to address and mitigate stress in the construction industry. By recognising and categorising these symptoms, this review provides a foundation for targeted interventions to improve construction professionals' overall well-being and safety. The findings emphasise the need for holistic approaches considering mental, behavioural, and physical health aspects to manage stress and enhance job performance effectively.

5.1 CONTRIBUTION OF THIS PAPER

This paper makes several significant contributions to the construction industry's existing knowledge of occupational stress. By systematically categorising stress symptoms into psychological, behavioural, and physical/physiological domains, this paper provides a clear framework for understanding the diverse manifestations of stress among construction professionals. This categorisation aids in identifying specific areas where interventions are needed. The review underscores the importance of a holistic approach to managing stress. Stakeholders can develop more effective and comprehensive stress management programs by collectively addressing psychological, behavioural, and physical health. The detailed identification and analysis of stress symptoms offer valuable insights for employers, policymakers, and healthcare providers. These insights can guide the design and implementation of targeted interventions, such as mental health support services, stress management training, and workplace safety enhancements. This paper lays the groundwork for future research by highlighting gaps in the current literature and suggesting areas for further investigation. Future studies can build on these findings to explore the long-term effects of stress in construction workers and evaluate the efficacy of various intervention strategies. For construction companies and industry stakeholders, the findings provide practical implications for improving worker well-being and productivity. Implementing the recommended strategies can lead to a healthier, more motivated workforce, ultimately enhancing overall industry performance. This paper advances our understanding of stress symptoms in construction professionals and serves as a valuable resource for developing effective stress management interventions. By addressing the identified symptoms through targeted strategies, the construction industry can create a safer and more supportive work environment, promoting the health and well-being of its workers.

6. ACKNOWLEDGEMENT

The authors greatly acknowledge the financial support provided by the Senate Research Committee of the University of Moratuwa under the Grant SRC/LT/2021/17.

7. REFERENCES

Abbe, O. O., Harvey, C. M., Ikuma, L. H., & Aghazadeh, F. (2011). Modeling the relationship between occupational stressors, psychosocial/physical symptoms and injuries in the construction industry.

International Journal of Industrial Ergonomics, *41*(2), 106–117. https://doi.org/10.1016/j.ergon.2010.12.002.

Adhikari, B., Poudel, L., Bhandari, N., Adhikari, N., Shrestha, B., Poudel, B., Bishwokarma, A., Kuikel, B. S., Timalsena, D., Paneru, B., & Gurung, M. (2023). *Prevalence and factors associated with depression, anxiety and stress symptoms among construction workers in Nepal*. PLoS ONE, *18*(5), e0284696. https://doi.org/10.1371/journal.pone.0284696.

Ajayi, S. O., Jones, W., & Unuigbe, M. (2019). Occupational stress management for UK construction professionals: Understanding the causes and strategies for improvement. *Journal of Engineering, Design and Technology*, *17*(4), 819–832. https://doi.org/10.1108/JEDT-09-2018-0162.

Allen, M., Alleyne, D., Farmer, C., McRae, A., Turner, C., Garg, P., Agarwal, D., Doskocil, R., Yang, L.-R., Kloppenborg, T. J., Tesch, D., Müller, R., Martinsuo, M., Machado, F. J., Martens, C. D. P., Rolstadås, A., Tommelein, I., Morten Schiefloe, P., Ballard, G., Pheng Low, S. (2014). A framework for project success. *Journal of IT and Economic Development*, *5*(2), 1-17. Retrieved from https://www.academia.edu/35399386/A_Framework_for_Project_Success

Bakhuys Roozeboom, M. C., Schelvis, R. M. C., Houtman, I. L. D., Wiezer, N. M., & Bongers, P. M. (2020). Decreasing employees' work stress by a participatory, organizational level work stress prevention approach: A multiple-case study in primary education. *BMC Public Health*, *20*, 676. https://doi.org/10.1186/s12889-020-08698-2.

Benachio, G. L. F., Freitas, M. do C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *260*, 121046. https://doi.org/10.1016/j.jclepro.2020.121046.

Bowen, P., Edwards, P., & Lingard, H. (2013). Workplace stress experienced by construction professionals in South Africa. *Journal of Construction Engineering and Management*, *139*(4), 393–403. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000625.

Brenda, Y., & Steve, R. (2006). Coping strategies among construction professionals: Cognitive and behavioural efforts to manage job stressors. *Journal for Education in the Built Environment*, *1*(2), 70–79. https://doi.org/10.11120/jebe.2006.01020070.

Chan, I. Y. S., Leung, M. Y., & Liu, A. M. M. (2016). Occupational health management system: A study of expatriate construction professionals. *Accident Analysis and Prevention*, *93*, 280–290. https://doi.org/10.1016/j.aap.2015.11.003.

Chan, I. Y. S., Leung, M., & Yu, S. S. W. (2012). Managing the stress of Hong Kong expatriate construction professionals in Mainland China: Focus group study exploring individual coping strategies and organizational support. *Journal of Construction Engineering and Management*, *138*(10), 1150–1160. https://doi.org/10.1061/(asce)co.1943-7862.0000533.

Chan, I. Y. S., Leung, M.-Y., & Liang, Q. (2018). The roles of motivation and coping behaviours in managing stress: Qualitative interview study of Hong Kong expatriate construction professionals in Mainland China. *International Journal of Environmental Research and Public Health*, *15*(3). 561. https://doi.org/10.3390/ijerph15030561.

Chan, M. (2011). Fatigue: The most critical accident risk in oil and gas construction. *Construction Management and Economics*, *29*(4), 341–353. https://doi.org/10.1080/01446193.2010.545993.

Chin, C., Lee, T., & Cullen, D. (2018). An empirical comparison of ethical perception among the consultant's quantity surveyor and contractor's quantity surveyor in the UK construction industry. In *Proceedings of the construction and building research conference (COBRA)* (pp 64-74). UWE Bristol Research Repository. Retrieved from **Error! Hyperlink reference not valid.**

Chow, H. T. D. (2009). *A study on the effects of stress level on working performance of construction project managers in Hong Kong*. [Doctoral dissertation, University of Hong Kong]. Retrieved from http://hdl.handle.net/10722/131075

CIOB. (2006). *Occupational stress in the construction industry; Survey*, https://www.ciob.org/sites/default/files/Occuptaional%20Stress%20in%20Construction.pdf

De Silva, N., Samanmali, R., & De Silva, H. L. (2017). Managing occupational stress of professionals in large construction projects. *Journal of Engineering, Design and Technology*, *15*(4), 488–504. https://doi.org/10.1108/JEDT-09-2016-0066.

Dodanwala, T. C., & Santoso, D. S. (2022). The mediating role of job stress on the relationship between job satisfaction facets and turnover intention of the construction professionals. *Engineering,* *Construction and Architectural Management*, *29*(4), 1777–1796. https://doi.org/10.1108/ECAM-12-2020-1048.

Donald, I., Taylor, P., Johnson, S., Cooper, C., Cartwright, S., & Robertson, S. (2005). Work environments, stress, and productivity: An examination using ASSET. *International Journal of Stress Management*, *12*(4), 409–423. https://doi.org/10.1037/1072-5245.12.4.409.

Dubey, M. K., & Jeswani, H. (2018). Qualitative study on stressors-stresses-absenteeism pattern among Indian construction professionals. *International Journal of Engineering Technology Science and Research*, (5)4, 76-81. Retrieved from https://www.researchgate.net/publication/348563498_Qualitative_study_on_Stressors-Stresses-Absenteeism_pattern_among_Indian_construction_professionals

Enshassi, A., Al Swaity, E., & Arain, F. (2016). Investigating common causes of burnout in the construction industry. *International Journal of Construction Project Management*, *8(1)*, 43-56. Retrieved from https://www.proquest.com/docview/1842450396?pq-origsite=gscholar&fromopenview=true&sourcetype=Scholarly%20Journals

Glasscock, D. J., Rasmussen, K., Carstensen, O., & Hansen, O. N. (2006). Psychosocial factors and safety behaviour as predictors of accidental work injuries in farming. *Work and Stress*, *20*(2), 173–189. https://doi.org/10.1080/02678370600879724.

Gómez-Salgado, C., Camacho-Vega, J. C., Gómez-Salgado, J., García-Iglesias, J. J., Fagundo-Rivera, J., Allande-Cussó, R., Martín-Pereira, J., & Ruiz-Frutos, C. (2023). Stress, fear, and anxiety among construction workers: A systematic review. *Frontiers in Public Health*, *11*. https://doi.org/10.3389/fpubh.2023.1226914.

Greenberg, J. S. (2017). *Comprehensive stress management* (14th ed.). McGraw-Hill Education.

Haydam, E., & Smallwood, J. (2016). Mental stress among civil engineering construction site agents and formen in the Nelson Mandela Bay Metropoe. *Journal of Construction Project Management and Innovation*, *6*(1), 1375-1390. https://journals.co.za/doi/pdf/10.10520/EJC196307.

Hazeen, M. F., Umarani, C. A study on the impact of role stress on engineer intention to leave in Indian construction firms. *Sci Rep*, *12*(1), 17576. https://doi.org/10.1038/s41598-022-21730-2.

Health and Safety Executive (HSE) (2004). *Health and safety statistics 2004/05.* https://qhse.support/public/media/uk-health-and-safety-statistics-2004-05.pdf

Jung, M., Lim, S., & Chi, S. (2020). Impact of work environment and occupational stress on safety behavior of individual construction workers. *International Journal of Environmental Research and Public Health*, *17*(22), 8304. https://doi.org/10.3390/ijerph17228304.

Kalia, M. (2002). Assessing the economic impact of stress: The modern day hidden epidemic. *Metabolism-clinical and experimental*, *51*(6), 49-53. https://doi.org/10.1053/meta.2002.33193.

Kamardeen, I. (2022). Work stress related cardiovascular diseases among construction professionals. *Built Environment Project and Asset Management*, *12*(2). 223-242. https://doi.org/10.1108/BEPAM-06-2021-0081.

Koulinas, G. K., Demesouka, O. E., Marhavilas, P. K., Orfanos, N. I., & Koulouriotis, D. E. (2023). Multicriteria health and safety risk assessments in highway construction projects. *Sustainability (Switzerland)*, *15(12*), 9241. https://doi.org/10.3390/su15129241.

Kushwaha, S. (2014). Stress management at workplace. *Global Journal of Finance and Management (6)5*, 469-472 Retrieved from https://www.ripublication.com/gjfm-spl/gjfmv6n5_13.pdf

Lock, I., & Giani, S. (2021). *Finding more needles in more haystacks: Rigorous literature searching for systematic reviews and meta-analyses in management and organization studies*, University of Amsterdam. https://doi.org/10.21942/uva.c.4992662.v1.

Lockwood, G., Henderson, C., & Stansfeld, S. (2017). An assessment of employer liability for workplace stress. *International Journal of Law and Management*, *59*(2), 202–216. https://doi.org/10.1108/IJLMA-10-2015-0053.

Love, P. E. D., Edwards, D. J., & Irani, Z. (2010). Work stress, support, and mental health in construction. *Journal of Construction Engineering and Management*, *136*(6), 650–658. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000165.

Naoum, S. G., Herrero, C., Egbu, C., & Fong, D. (2018). Integrated model for the stressors, stress, stress-coping behaviour of construction project managers in the UK. *International Journal of Managing Projects in Business*, *11*(3), 761–782. https://doi.org/10.1108/IJMPB-07-2017-0071.

Nixona, A. E., Mazzolab, J. J., Bauera, J., Kruegerc, J. R., & Spectora, P. E. (2011). Can work make you sick? A meta-analysis of the relationships between job stressors and physical symptoms. *Work and Stress*, *25*(1), 1–22. https://doi.org/10.1080/02678373.2011.569175.

Ojo, G. K., Adeyeye, G. M., Opawole, A., & Kajimo-Shakantu, K. (2019). Gender differences in workplace stress response strategies of quantity surveyors in Southwestern Nigeria. *International Journal of Building Pathology and Adaptation*, *37*(5), 718–732. https://doi.org/10.1108/IJBPA-10-2018-0084.

Oladinrin, T. O., Adeniyi, O., & Udi, M. O. (2014). Analysis of stress management among professionals in the Nigerian Construction Industry. *International Journal of Multidisciplinary and Current Research. (2)*2, 22-33. Retrieved from http://ijmcr.com/wp-content/uploads/2013/12/Paper522-331.pdf

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. n71. http://dx.doi.org/10.1136/bmj.n71

Panojan, P., Perera, B. A. K. S., & Dilakshan, R. (2019). Work-life balance of professional quantity surveyors engaged in the construction industry. *International Journal of Construction Management*, *22*(5), 751–768. https://doi.org/10.1080/15623599.2019.1644759.

Patching, A. (2022). *Attitudes to psychological stress among construction professionals*. Springer International Publishing AG. https://doi.org/10.1007/978-3-030-93776-8.

Peterson, M., & Wilson, J. F. (2015). The culture-work-health model and work stress. *American Journal of Health Behavior, (26)*1,16-24. https://doi.org/10.5993/AJHB.26.1.2.

Rosen, C. C., Chang, C. H., Djurdjevic, E., & Eatough, E. (2010). Occupational stressors and job performance: An updated review and recommendations. *Research in Occupational Stress and Well Being*, (*8)*1, 1–60. https://doi.org/10.1108/S1479-3555(2010)0000008004.

Ross, S. M. (2020). Resistance for strength: The role of phytomedicine adaptogens in stress management. *Holistic Nursing Practice*, *34*(5), 314–317. https://doi.org/10.1097/HNP.0000000000000408.

Rowley, C., & Paul, J. (2021). Introduction: The role and relevance of literature reviews and research in the Asia Pacific. *Asia Pacific Business Review*, *27*(2), 145-149. https://doi.org/10.1080/13602381.2021.1894839.

Saikala, L., & Selvarani, A. (2015). A study on work stress among Architects and construction professionals in Indian construction industry. *International Journal of Management*, *6*(1), 585–593. Retrieved from https://iaeme.com/MasterAdmin/Journal_uploads/IJM/VOLUME_6_ISSUE_1/10120140601062.pdf

Salam, A. (2016). Job stress and job satisfaction among health care professionals. *European Scientific Journal*, 10(32), 156-173. Retrieved from https://core.ac.uk/download/pdf/236417895.pdf

Sommerville, J., & Langford, V. (1994). Multivariate influences on the people side of projects: Stress and conflict. *International Journal of Project Management*, *12*(4), 234–243. https://doi.org/10.1016/0263-7863(94)90048-5.

Sousa, V., Almeida, N. M., & Dias, L. A. (2014). Risk-based management of occupational safety and health in the construction industry - Part 1: Background knowledge. *Safety Science*, *66*, 75–86. https://doi.org/10.1016/j.ssci.2014.02.008.

Spielberger, C. D., Vagg, P. R., & Wasala, C. F. (2003). Occupational stress: Job pressures and lack of support. In J. C. Quick & L. E. Tetrick (Eds.), *Handbook of occupational health psychology* (pp. 185–200). American Psychological Association. https://doi.org/10.1037/10474-009.

Tijani, B., Xiaohua, J., & Osei-Kyei, R. (2021). Critical analysis of mental health research among construction project professionals. In *Journal of Engineering, Design and Technology, (19)*2.467-496. https://doi.org/10.1108/JEDT-04-2020-0119.

Torres, G. M. S., Backstrom, J., & Duffy, V. G. (2023). A systematic review of workplace stress and its impact on mental health and safety. In Q. Gao, J. Zhou, V. G. Duffy, M. Antona, & C. Stephanidis (Eds.), *HCI International 2023 – Late Breaking Papers. HCII 2023. Lecture Notes in Computer Science* (pp.610-627). Springer, Cham. https://doi.org/10.1007/978-3-031-48041-6_41.

Väänänen, A., Anttila, E., Turtiainen, J., & Varje, P. (2012). Formulation of work stress in 1960-2000: Analysis of scientific works from the perspective of historical sociology. *Social Science and Medicine*, *75*(5).784-794. https://doi.org/10.1016/j.socscimed.2012.04.014.

van Heerden, A., Boulic, M., McDonald, B. W., & Chawynski, G. (2024). Gender-perceived workplace stressors by New Zealand construction professionals. *International Journal of Construction Management*. 1-12. https://doi.org/10.1080/15623599.2024.2317039.

Vlăduţ, C. I., & Kállay, É. (2010). Brief report work stress, personal life, and burnout. Causes, consequences, possible remedies - A theoretical review. *Brain, Behavior. An Interdisciplinary Journal*, *XIV*(3), 261–280. Retrieved from https://www.researchgate.net/publication/281633700_BRIEF_REPORT_WORK_STRESS_PERSONAL_LIFE_AND_BURNOUT_CAUSES_CONSEQUENCES_POSSIBLE_REMEDIES_-A_theoretical_review

Wei, L., Yang, R., Chen, Y., Shahi, A., Safa, M., Hanna, A., & McCabe, B. (2020). Comparison of safety cultures and performances between the construction industries in the United States and Canada: A case study of Texas and Ontario. *Construction Research Congress 2020* (pp. 346–355). Construction Research Congress 2020: Safety, Workforce, and Education. https://doi.org/10.1061/9780784482872.038.

Wong, Q., Sapuan, N. M., & Ali Khan, M. W. (2023). The impact of safety and health towards construction workforce productivity. *Journal of Governance and Integrity*, *6*(1), 504–514. https://doi.org/10.15282/jgi.6.1.2023.9114.

Zhou, J., Hu, F., Xing, Y., & Gao, J. (2022). Influence of job stress and burnout on unsafe behaviors of construction workers. *China Safety Science Journal*, *32*(11),14-22. https://doi.org/10.16265/j.cnki.issn1003-3033.2022.11.2539.

Senaratne, S., Gamage, I., Jayakodi, S. and Perera, S., 2024. Taxonomy of circular economy terminologies. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 998-1010. DOI: https://doi.org/10.31705/WCS.2024.79. Available from: https://ciobwcs.com/papers/

TAXONOMY OF CIRCULAR ECONOMY TERMINOLOGIES

Sepani Senaratne[1], Iresha Gamage[2], Shashini Jayakodi[3], and Srinath Perera[4]

ABSTRACT

The construction sector predominantly follows a linear economic model, which necessitates a shift towards embracing the Circular Economy (CE) principles. Even though several CE approaches have been introduced for the construction context, numerous barriers have hindered their implementation. Confusion of CE terminologies with a lack of awareness is identified as one of the main barriers to the successful implementation of CE in the construction industry. Hence, this research focuses on differentiating the CE terminologies based on their academic definitions to establish a consolidated and comprehensive understanding and thereby, aims to develop a taxonomy for CE terminologies for the construction industry. This research adopted qualitative comparative literature analysis research methodology and selected individualising comparison as a suitable comparison method. To carry out the comparison, the academic definitions from Oxford and Cambridge dictionaries were compared with the definitions from CE-related construction articles. Subsequently, the consolidated definitions were established for selected terminologies by differentiating their ideas. Consequently, the hierarchy of the terminologies was identified to develop a CE taxonomy. This research provides significant guidance for CE researchers for appropriate CE terminology usage in their research, while industry practitioners can gain a wider understanding of CE for its successful implementation in the industry.

Keywords: *Circular Economy; Construction Industry; Definitions; Taxonomy; Terminologies.*

1. INTRODUCTION

CE is a trending concept in many industries, which consists of an opposing approach to the prevailing linear economy approach. The linear economy's 'take-make-dispose' approach has been transformed in the circular economy by minimising the 'take' and 'dispose' steps through closed-loop methods such as reusing, recycling, and regeneration (Velenturf & Purnell, 2021). The Ellen MacArthur Foundation (EMF), Wautelet (2018) and Rodríguez et al. (2020) have identified a few different schools of thought that the CE concept has been nourished from.

[1] Associate Professor, Centre for Smart Modern Construction (c4SMC), School of Engineering, Design and Built Environment, Western Sydney University, Australia, s.senaratne@westernsydney.edu.au
[2] Doctoral researcher, c4SMC, School of Engineering, Design and Built Environment, Western Sydney University, Australia, iggamageiresha@gmail.com
[3] Doctoral researcher, c4SMC, School of Engineering, Design and Built Environment, Western Sydney University, Australia, jayakodishashini@gmail.com
[4] Professor, c4SMC, School of Engineering, Design and Built Environment, Western Sydney University, Australia, srinath.perera@westernsydney.edu.au

The first instance of CE appearing in the literature was the study entitled 'The Economics of the Coming Spaceship Earth' by Boulding (1966). In his study, Boulding (1966) explained the idea of the **'spaceman economy'**, comparing Earth with a resource-constrained spaceship, where humans must live and meet their needs within a 'cyclical ecological system'. According to the argument of Stahel (1982), product life extension activities are more labour-intensive than energy intensive. There can be employment opportunities for people, as the product goes in a cycle between the consumer and the manufacturer in which energy can be substituted by manpower. This argument is the basis for a '**performance economy'** which can be considered as another school of thought associated with CE. CE was also influenced by the concept of **'industrial ecology'**, where waste from one industrial activity is incorporated as raw materials for another industrial activity, which ultimately results in reducing adverse effects on the environment through industrial activities (Frosch & Gallopoulos, 1989). The concept of **'regenerative design'** which was initialised by Lyle (1996) is also considered as a baseline concept for CE. According to the author, it simply means altering the current linear output flows with cyclical flows. Another concept that supports CE is **biomimicry**. The underlying concept of biomimicry has placed a higher value on nature than other concepts. It promotes the idea that humans can observe patterns and strategies of nature to find answers to manmade challenges in a better way, as nature has already dealt successfully with many problems people are handling now (Benyus, 1997). Lovins et al. (1999) proposed another concept related to CE as '**natural capitalism'** which is a system that allows companies to meet customer needs and improve profits, while also providing solutions to conflicts of interest between business and the environment. A well-known concept that heavily influenced CE is **'Cradle to Cradle (C2C)'**. The C2C concept explains the way of designing products considering both metabolic types, biological aspects and engineering, to keep the value of materials and ingredients at the highest possible level for the next cycle of use. According to Rodríguez et al. (2020), the latest concept called **'blue economy'** is the concept that has created the highest influence on CE so far. The blue economy suggests an innovative business model that facilitates local communities to come up with competitive products and services targeting different markets from what they have while encouraging social well-being and environmentally friendly lifestyle (Rodríguez et al., 2020).

The concept of CE is still evolving and incorporates elements from the other schools of thought mentioned earlier. Furthermore, the multi-disciplinary nature of the CE concept makes it difficult to come up with a solid definition for CE (Kirchherr et al., 2017). The most employed definition is given by EMF (Geissdoerfer et al., 2017), which defines CE as an industrial system that is *'restorative or regenerative by intention and design'* (Ellen MacArthur Foundation, 2012). Elaborating further, Geissdoerfer et al. (2017) highlighted that within such a regenerative system resource intake, waste, emission and energy outflows are controlled by slowing, closing and narrowing loops.

Notable attention has been given towards the CE concept in recent decades. Multiple government and non-government organisations have further investigated the CE concept and developed several CE principles and CE frameworks to facilitate the implementation of the concept. EMF has developed three principles to wrap up the basic idea of CE and to direct how CE would be implemented within different contexts. EMF's three CE principles are; (i) Conserve and improve natural capital through better management of scarce resources and sustainable energy flows; (ii) Improve the use of resources through circulating those at the highest value at all times in both technical and biological cycles; and, (iii) Substitute system through designs which eliminates negative outwardness (EMF, 2012). As a result of EMF's continuous efforts in the development of the CE concept, the 'ReSOLVE' framework was developed jointly with Arup, which has defined six action areas i.e. (i) regenerate, (ii) share, (iii) optimise, (iv) loop, (v) virtualise, and (vi) exchange, that can consider in transitioning towards CE. The British Standard Institute (BSI) has also developed six CE principles and published a guideline for CE named BS 8001:2017, which is recognised as the first guideline related to CE. The six principles defined in BS 8001:2017 are; i) Systems thinking; ii) Stewardship; iii) Transparency; iv) Collaboration; v) Innovation; and vi) Value optimisation. According to BSI (2017), these principles would assist organisations and governments in their decision-making. Furthermore, Papageorgiou et al. (2021) have carried out a study on available CE principles in the literature and found that 'R' principles have gained wide attention among different types of CE principles. There are many variants of R- principles available in the literature ranging from 3Rs to 10Rs since different authors have expanded the basic 3Rs with new attributes based on their perceptions.

Given the significant depletion of resources, wastage, and ecological footprint associated with the construction industry, the transition to the CE model has become a top priority (Munaro et al., 2020; Senaratne et al., 2021; Jayakodi et al., 2023). However, the construction industry is notoriously resistant to change, and its complexity creates unprecedented barriers to CE adoption (Buyle et al., 2019; Ossio et al., 2023). Consequently, the transition to CE in the construction sector is complex and necessitates a comprehensive effort to acquire the necessary knowledge for implementation in the industry (Illankoon & Vithanage, 2023). As a result, studies that facilitate the transformation towards the circular built environment have been in a rapid progression within the last few years and remarkable attention has been given to practical implementation and assessment.

In the circular economy, the 'take-make-dispose' approach is minimised through closed-loop methods such as reusing, recycling, and regeneration (Velenturf & Purnell, 2021). Furthermore, there are commonly used terminologies in assessing CE implementation as 'dimensions', 'indicators', 'indices', 'measures' and 'metrics' (Corona et al., 2019; de Oliveira et al., 2021; Khadim et al., 2022). Bocken et al. (2016) and Ababio and Lu (2022) identified that most CE-associated terminologies have been used differently by researchers in the construction context. The underlying cause of this confusion is that CE is still an evolving idea, which lacks precise boundaries. Ababio and Lu (2022) identified this confusion of terminologies as a barrier to the successful implementation of CE in the construction industry and suggested that further research should be conducted to overcome this barrier. Consequently, this study aims to propose a taxonomy for CE terminologies for the construction industry. Accordingly, each term is discussed separately considering their dictionary definition and how those have been applied for CE implementation within the construction industry to derive a consolidated definition for each term and to develop a hierarchical taxonomy. The upcoming sections of this paper describe the research methodology, and research findings followed up with a proposed taxonomy and finally conclusions and recommendations.

2. METHODOLOGY

The above-mentioned aim of this research leads to two key objectives i.e., (i) to establish consolidated definitions for CE terminologies, and (ii) to identify the hierarchy of the selected terminologies to develop a CE taxonomy for the construction industry. This research adopts a qualitative comparative literature analysis research methodology to achieve the aim of the research. A comparative study is a method that analyses phenomena and then puts them together to find the points of differentiation and similarity (Miri & Shahrokh, 2019). According to Esser and Vliegenthart (2017), comparative research focuses on understanding how the surrounding context influences communication outcomes, emphasising the explanatory significance of the environment and its role in shaping communication phenomena across diverse settings. According to Pickvance (2001), there are four types of comparative analysis: i.e., (i) individualising comparison, (ii) universalising comparison, (iii) variation-finding comparison, and (iv) encompassing comparison. Among the identified types, this research is more focused on individualising comparison as it compares a small number of definitions to grasp the peculiarities of each definition. The research process followed in the current study is depicted in Figure 1.

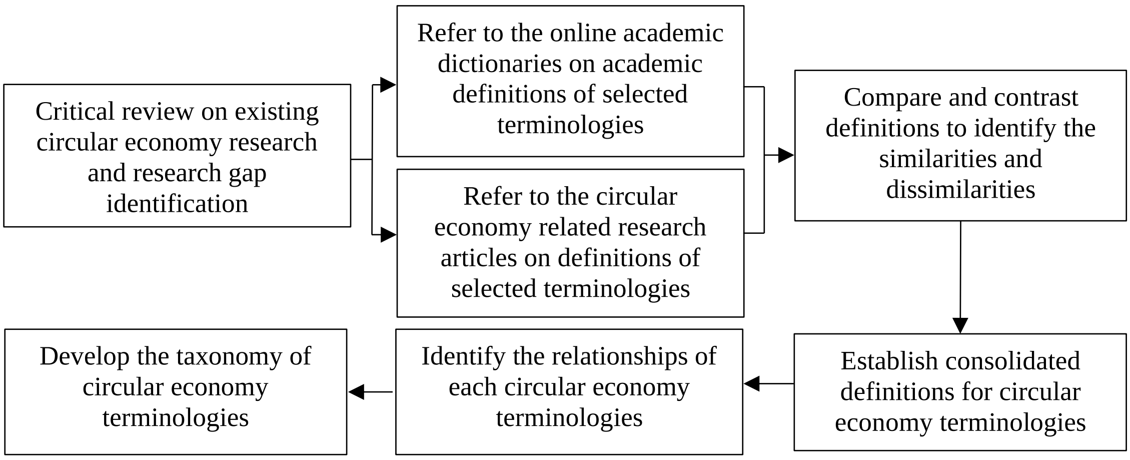


Figure 1: Research process

To achieve the first objective, the study referred to online academic dictionaries (Oxford and Cambridge) to find the general academic definition of selected CE terminologies. Online specialised free dictionaries aid everybody in need of information while facilitating immediate responses (Caruso et al., 2011). Authors further defined dictionaries as the best terminological resources. Subsequently, the research articles published in construction industry-specific CE literature were critically reviewed to identify the definitions of the selected terminologies in the CE context. In the instances that definitions were not available, it was mainly focused on the examples and background explanations of the selected CE terminologies to set the definition scope.

Then, the identified definitions were compared to identify the similarities and dissimilarities of the definitions to establish consolidated definitions for selected CE terminologies. After the establishment of the consolidated definitions for CE terminologies, the relationships of terminologies were mapped to identify and establish the hierarchy of the terminologies to achieve the second objective. Based on the identified relationship between the terminologies, a CE taxonomy was developed.

3. ANALYSIS AND DISCUSSION

This section discusses terminologies that frequently appeared in CE-related literature in the construction context. Accordingly, definitions of the CE concept, CE principle, CE framework, CE strategy, CE practice and CE assessment-related terminologies are compared to derive a new definition for each. Meanwhile, occasional misuse of CE terminologies in literature is critically discussed here under three subheadings and an acceptable hierarchy has been proposed.

Oxford Dictionary defines a ‘concept’ as “an idea that is connected with something existing in thought but not having a physical reality and often relates to something new”. Section 1 of the current study describes the evolution of the CE concept in a detailed manner concerning all prior concepts that impacted shaping the CE concept. During the discussion in Section 1, it was observed that there is no contradiction in the dictionary meaning of the term ‘concept’ and how it appears in the CE-related literature. On the other hand, it was noted that the definition given by EMF is widely used to define the ‘circular economy’. Thus, combining both dictionary definitions of the term ‘concept’ and EMF’s definition of CE, the current study defines the ‘CE concept’ as *“an idea about a system that is restorative or regenerative by intention and design”.* CE concept is broader and at the highest level, which should be studied further and narrowed down until real implementation is possible. The upcoming sections will discuss the terminologies that are commonly used when implementing the CE concept in the construction context.

3.1 CIRCULAR ECONOMY PRINCIPLES AND FRAMEWORKS

Along with the development of the CE concept, different entities and individuals have developed CE principles and frameworks, which have been briefly discussed in Section 1. The two terminologies have been utilised interchangeably on some occasions to refer to the same information in the literature. For instance, Papageorgiou et al. (2021) propose ‘R’s as CE principles, whereas some authors define those as CE frameworks (Chizaryfard et al., 2020). According to the Cambridge Dictionary, a ‘principle’ is “a basic idea or rule that explains or controls how something happens or works” and a ‘framework’ is “a system of rules, ideas, or beliefs that is used to plan or decide something”. The dictionary definitions depict that the principles are established to inform and shape concepts whereas, frameworks can be a set of principles rolled together along with relationships and probable actions, which aid in planning something. Within the CE context, CE principles shape the CE concept providing the foundation for CE implementation. Thus, a CE principle can be defined as “*a fundamental rule or belief on which CE implementation is based”*. The CE principles developed by the EMF can be identified as examples, which comply with the characteristics of the derived definition. Besides, a CE framework can be defined *as “a system which is developed from CE principles and outlines a set of ideas to facilitate CE implementation within a particular context”*. The ‘ReSOLVE’ framework described in Section 1 is an example of a CE framework at a higher level. During practical implementation, different entities such as organizations, institutes, and the government may develop more detailed frameworks based on high-level frameworks to meet their specific requirements. For instance, Iyer-Raniga (2019) has customised the ReSOLVE framework considering the emerging markets in the construction industry. Furthermore, it can be noted that the 'R's do not comply with the definition of CE principles, as Rs help adopt CE rather than rule the concept. Since Rs exhibit the characteristics of a CE framework, it is appropriate to name them as frameworks.

3.2 CIRCULAR ECONOMY STRATEGIES AND PRACTICES

Circular economy strategies and practices are vital for the transition towards CE in the construction industry (Guerra et al., 2021). These two terminologies have been used interchangeably in CE literature to indicate the same content (Gamage et al., 2024). For instance, design for disassembling building components is indicated as a 'practice' (Adams et al., 2017; Benachio et al., 2020; Ishan et al., 2023) and as a 'strategy' (Ghobadi & Sepasgozar, 2023; Lee et al., 2023). Besides, the same fact has been identified as a CE principle by Cheshire (2019). However, as per the derived definitions in Section 3.1, the term 'principle' is at a high level in the hierarchy of CE-related terminologies, thus, it is not appropriate to use the term 'principle' to refer to aspects such as 'design for disassembling building components.' According to the Oxford Dictionary, 'strategy' means "a plan, scheme, or course of action designed to achieve an overall aim" and 'practice' means "an activity or action considered as being the realisation of a theory". Quoted definitions exhibit a clear difference between these two terminologies. Strategies are more from the managerial level, and they refer to an overall plan to achieve CE, which may contain practices as part of it. According to van Bueren et al. (2019), strategies refer to the theoretical picture, whereas practices refer to the practical picture of CE implementation. Moreover, van Bueren et al. (2019) identified the lack of existing standard practices as a barrier to adopting circular strategies in construction. From the construction industry's point of view, a strategy can be formed by the government, relevant institutions, or top management of the construction organisations, whereas a practice can occur in a construction project context. A strategy implemented by an organisation can be achieved through multiple practices at the project level and applying practices may differ according to the project context. Thus, a CE strategy should be in a higher place than a CE practice within the construction context.

New definitions were derived considering the need for a clear distinction between the two terminologies in the construction industry to avoid confusion and overcome theoretical obstacles in CE implementation. Accordingly, a CE strategy can be defined as "*a plan to achieve a circular economy-related goal established in the construction industry*", while a CE practice can be defined "*as an activity that contributes to the implementation of a CE strategy in the construction industry*". Various CE principals and frameworks discussed in Section 1 could help in setting CE-related goals within a specific context. For example, a construction organisation would set a CE-related goal to reduce the natural material extraction for manufacturing construction materials by a certain percentage within the next five years. To achieve that goal, 'the use of second-hand materials/components in construction projects' can be considered as a strategy, whereas activities such as 'assessing the reusability of the materials in existing buildings', 'continuing preventive maintenance throughout the operation phase', 'disassembling building components at the end of life' and, 'designing new buildings with reusable materials and components' can be identified as practices to successfully realise the aforementioned strategy at the project level.

3.3 CIRCULAR ECONOMY INDICATORS AND RELATED TERMINOLOGIES

CE practices can be assessed using CE indicators. The terminologies such as 'indicators', 'dimensions', 'measures', 'metrics', 'index', or 'indices' have been often used in the literature, when referring to 'CE indicators' (Khadim et al. 2022). This variety of terminologies used to refer to CE indicators creates ambiguity. However, a deeper analysis of the relevant literature revealed that all these variations refer to the same phenomenon, which is to assess the progress toward achieving CE goals (de Oliveira et al., 2021). Although these terminologies refer to a similar phenomenon, each has a different definition.

CE indicators can be used to assess the CE adoption of any entity (Ellen MacArthur Foundation, 2015). An indicator is "a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor" (Organisation for Economic Co-operation and Development 2014, p 13). According to the Oxford dictionary, an indicator refers to "something that shows what a situation is like or how it is changing". For instance, González et al. (2021) have defined five CE indicators to assess the CE implementation of a construction project, i.e., (i) energy, (ii) material, (iii) water, (iv) social value, and (v) economic value. This explains that CE implementation of a construction project has been divided into five factors to simplify CE assessment to monitor the CE transition of the construction project. CE indicators can provide a standardised language to simplify information exchange and understanding and ease this transition (Verberne, 2016). Besides, Nuñez-Cacho et al. (2018a) identified material, water, waste, energy and 3R as CE dimensions. According to the Cambridge Dictionary, "a dimension is a measurement of something in a particular direction". Smith and Thomas (2021) explain that economy, environment, and society are three dimensions of CE in the construction context. Furthermore, Martinho (2021) elaborated that sustainability analysis, from a circular perspective, should also consider several dimensions such as environmental, economic, social and technical. Based on the preceding definitions and examples, a clear distinction can be established between CE indicators and CE dimensions, which will help to avoid the conflict between the two terminologies and establish a consolidated definition. Hence, "*a CE dimension represents a key measurable cluster/pillar, which contributes to the transition towards a more sustainable and circular built environment*". The definition of CE indicator can be derived as "*a factor used to measure the CE adoption and transition of some construction entity*". For instance, in a construction project, material, waste, energy and emission indicators are considered under the environmental dimension.

According to the Cambridge dictionary, "a measure refers to a way of achieving something, or a method for dealing with a situation", while "a metric referred to using or relating to a system of measurement that uses metres, centimetres, litres, etc". The study conducted by Torgautov et al. (2022) on the CE performance assessment of construction companies elaborated on 52 CE measures. Some of them are Construction and Demolition Waste (CDW) transportation costs, landfilling fees, administrative costs of CDW management, etc. These measures are mainly focused on the economic aspect. Hence, the metrics are identified as total expenditure, cost per unit, cost-to-income ratio, and cost savings. Furthermore, Núñez-Cacho et al. (2018b) explain that design for deconstruction, waste collected for reuse and waste collected for recycling etc are some CE measures to assess the CE. As the metrics of the identified measures, the authors have defined percentages as suitable metrics. Considering the definitions above and examples, it explains that measures and metrics have different definitions that cannot be used to refer to the same aspect. Hence, CE measures are identified as "*specific actions implemented to assess, monitor, and promote the transition towards a CE at a more focused and granular level*". These measures are more focused on achieving respective CE indicators. The metrics are "*units that are used to measure the CE measures*". For instance, under the waste CE indicator, waste collected for recycling is identified as the relevant measure. The percentage of collected waste to the total waste is identified as the suitable metric for the identified measure. Crucially, measures can be quantitative and qualitative, and respectively their metrics can vary.

According to the Oxford Dictionary, an index refers to "a number giving a measurement of something compared with a particular standard", while indices refer to the plural form of the term index. González et al. (2021) developed the material circularity index, energy circularity index, water circularity index, and social circularity index for construction projects. For instance, the energy circularity index is an equation, which explains the renewable energy coming from on-site generation or nearby sources and energy saving from active or passive energy-saving mechanisms to the total thermal energy and electricity consumption. Further, the water circularity index refers to the cycled water coming from different water re-utilisation or wastewater sources; water comes from the own building or upstream to the total water utilisation of the construction project. Besides, Smith and Thomas (2021) developed the index for construction materials using the multi-criteria decision-making method by considering the multiple attributes that define the circularity of the material by a number. However, these two studies have not compared with any standard, when developing the index. Considering these points, the CE index can be defined as "*a quantitative measure that typically incorporates a range of indicators or measures to assess CE performance and progress, facilitating comparisons over time and across different entities*". There are several other related terminologies such as meter, scale, parameters, and assessment frameworks occasionally used along with CE indicators, which are not discussed here.

4. CIRCULAR ECONOMY TAXONOMY

The term 'Taxonomy' is derived from the Greek words 'taxis', meaning 'arrangement or division', and nomos, meaning 'law' (Enghoff, 2009). Moreover, Enghoff (2009) stated that taxonomies are compiled with taxonomic units known as 'taxa', frequently arranged in a hierarchical structure. Thus, simply a taxonomy is a methodology that involves systematically classifying elements in a defined hierarchical form. According to Xueqing Liu et al. (2012), taxonomies are crucial for systematically organising knowledge within a specific domain, enabling users to easily access and analyse relevant information. As explained in Section 1, there is an ongoing issue with misusing CE-related terminologies in the literature, which creates confusion among researchers and industry practitioners, when studying and implementing the CE concept. To answer this issue, this study developed a taxonomy of CE terminologies, which is shown in Figure 2.

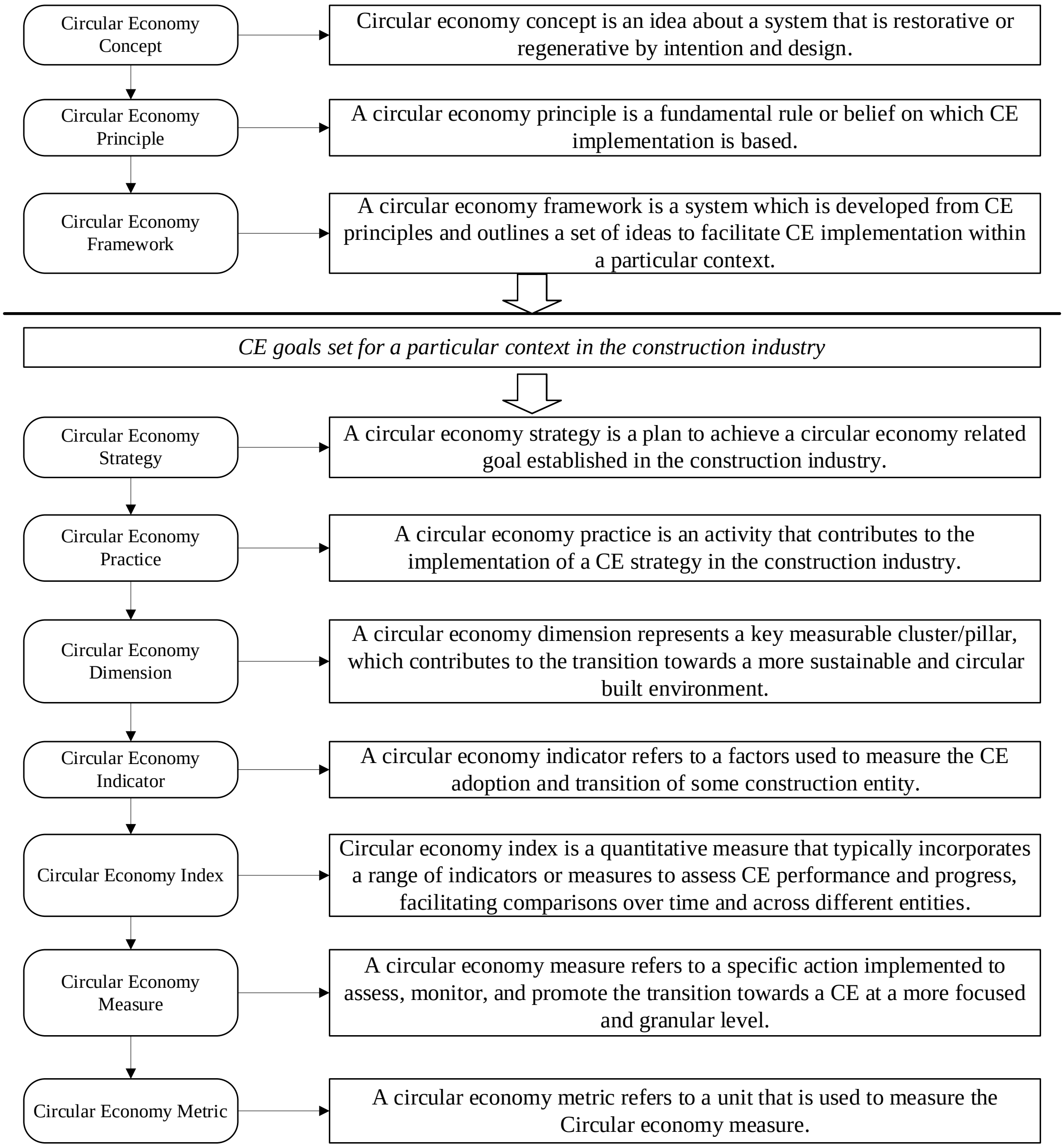


Figure 2: Proposed taxonomy of circular economy terminologies

The proposed taxonomy includes ten frequently used terminologies in implementing and assessing CE within the construction industry and follows a hierarchical arrangement. It starts with the broader concept of 'CE' and then delves into fundamental terms such as CE principles and CE frameworks. Thereafter, the taxonomy is diverted towards CE implementation within a particular context in the construction industry and followed up by the assessment of CE implementation. In addition to the hierarchical arrangement, the definitions for each term, which were derived from the above discussions are provided. An example scenario is elaborated below considering the hierarchy of the CE taxonomy.

Assume that a construction organisation has developed CE-related long-term and short-term goals considering the available CE principles and CE frameworks, which may align with their overall strategic planning process. If the construction organisation set a CE related goal to ‘reduce demolition waste at the end-of-life stage of their projects’, a strategy to achieve this goal would be ‘efficiently managing demolished material.’ A practice to realise this strategy could be ‘identifying and recycling possible demolished materials.' Moving into the assessment of the CE practice, the 'environmental' dimension could be identified as more appropriate for the scenario, since the plan is to reduce the demolition waste. Accordingly, the CE indicator can be 'waste', the CE measure can be 'the recyclability of the demolished material' and the metric can be 'the percentage.' According to the proposed taxonomy, the CE index of the given scenario can be identified as 'the recyclability value (%) of the material', which could be obtained from the ratio between total mass and the recyclable mass of the material expressed as a fraction of 100. Similarly, the taxonomy can be applied in different contexts and for different examples.

5. CONCLUSIONS

The study aimed to propose a taxonomy of circular economy terminologies for the construction sector. To compare dictionary definitions of various CE-related terminologies and their appearance in the literature on this subject, the study used a comparative analysis methodology. Accordingly, consolidated definitions were derived for each term and the hierarchical arrangement of the terminologies was identified to develop the Circular Economy Taxonomy. The findings of the study revealed that most CE terminologies are inappropriately used in the literature with regards to their dictionary meaning and many occasions were identified with misuse of these terminologies. The developed taxonomy would directly contribute to the existing body of knowledge and answer the prevailing issue of misusing terminologies in the CE literature. In addition, the taxonomy would assist in the proper implementation of CE within the construction industry as it demarcates each step that needs to be considered during implementation and assessment. It is recommended to follow the hierarchical order given in the taxonomy to gather information and properly plan the CE implementation process within the construction industry. Further research can be carried out to validate the proposed taxonomy with empirical data collected from experts' opinions and case studies and assess its applicability to other industries.

6. REFERENCES

Ababio, B. K., & Lu, W. (2022). Barriers and enablers of circular economy in construction: a multi-system perspective towards the development of a practical framework. *Construction Management and Economics*, *41*(1), 3-21. Retrieved from https://doi.org/10.1080/01446193.2022.2135750

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. In *Proceedings of the institution of civil engineers-waste and resource management*, (Volume 170, Issue WR1, pp. 15-24). ICE Publishing. https://doi.org/10.1680/jwarm.16.00011

Benachio, G. L. F., Freitas, M. d. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *260*, 121046. Retrieved from https://doi.org/10.1016/j.jclepro.2020.121046

Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature*. New York: William Morrow & Co.

Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of industrial and production engineering*, *33*(5), 308-320. Retrieved from https://www.tandfonline.com/doi/epdf/10.1080/21681015.2016.1172124?needAccess=true

Boulding, K. E. (1966). The economics of the coming spaceship earth. In H. Jarrett (Ed.), *Environmental Quality in a Growing Economy* (pp. 3-14). Johns Hopkins University Press.

British Standards Institution. (2017). *Framework for implementing the principles of the circular economy in organizations – Guide*(BS 8001:2017). BSI Standards Publication.

Buyle, M., Galle, W., Debacker, W., & Audenaert, A. (2019). Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *Journal of Cleaner Production*, *218*, 141-156.

Caruso, V., Kosem, I., & Kosem, K. (2011). Online specialised dictionaries: A critical survey. In *Proceedings of eLex*, (pp. 66-75).
Cheshire, D. (2019). *Building revolutions: Applying the circular economy to the built environment* (1 ed.). RIBA Publishing.
Chizaryfard, A., Trucco, P., & Nuur, C. (2020). The transformation to a circular economy: framing an evolutionary view. *Journal of Evolutionary Economics*, *31*(2), 475-504. Retrieved from https://doi.org/10.1007/s00191-020-00709-0
Corona, B., Shen, L., Reike, D., Rosales Carreón, J., & Worrell, E. (2019). Towards sustainable development through the circular economy: A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, *151*. Retrieved from https://doi.org/10.1016/j.resconrec.2019.104498
de Oliveira, C. T., Dantas, T. E. T., & Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. *Sustainable Production and Consumption*, *26*, 455-468. Retrieved from https://doi.org/10.1016/j.spc.2020.11.024
Ellen MacArthur Foundation. (2012). *Towards the circular economy - an economic and business rationale for an accelerated transition*.(Volume 1), Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an
Ellen MacArthur Foundation. (2015). *Delivering the circular economy: A toolkit for policymakers*. Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/a-toolkit-for-policymakers
Enghoff, H. (2009). What is taxonomy? : An overview with myriapodological examples. *Soil Organisms*, *81*(3). 441-451.
Esser, F., & Vliegenthart, R. (2017). Comparative research methods. In *The international encyclopedia of communication research methods*, (pp 1-22). John Wiley & Sons, Inc. doi:10.1002/9781118901731.iecrm0035
Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for manufacturing. *Scientific American*, *261*(3), 144-153.
Gamage, I., Senaratne, S., Perera, S., & Jin, X. (2024). Implementing circular economy throughout the construction project life cycle: A review on potential practices and relationships. *Buildings*, *14*(3). 653.
Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy : A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757-768. Retrieved from https://doi.org/10.1016/j.jclepro.2016.12.048
Ghobadi, M., & Sepasgozar, S. M. E. (2023). Circular economy strategies in modern timber construction as a potential response to climate change. *Journal of Building Engineering*,*77*, 107229. Retrieved from https://doi.org/10.1016/j.jobe.2023.107229
González, A., Sendra, C., Herena, A., Rosquillas, M., & Vaz, D. (2021). Methodology to assess the circularity in building construction and refurbishment activities. *Resources, Conservation & Recycling Advances*, *12*, 200051.
Guerra, B. C., Shahi, S., Mollaei, A., Skaf, N., Weber, O., Leite, F., & Haas, C. (2021). Circular economy applications in the construction industry: A global scan of trends and opportunities. *Journal of Cleaner Production*, *324*, 129125.
Illankoon, C., & Vithanage, S. C. (2023). Closing the loop in the construction industry: A systematic literature review on the development of circular economy [Review]. *Journal of Building Engineering*, *76*, 107362. Retrieved from https://doi.org/10.1016/j.jobe.2023.107362
Ishan, M., Gamage, I., & Lingasabesan, V. (2023). Highly effective circular economic practices for the life cycle of a construction project. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ramachandra, T. and Ranadewa, K.A.T.O. (Eds). *Proceedings of the 11th world construction symposium*, *Sri Lanka*, 21-22 July 2023, (pp. 532-544). Retrieved from https://doi.org/10.31705/WCS.2023.44
Iyer-Raniga, U. (2019). Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets. In *IOP conference series: Earth and environmental science*, (Vol. 294, No. 1, p. 012002). IOP Publishing. doi:10.1088/1755-1315/294/1/012002
Jayakodi, S., Senaratne, S., Perera, S., & Bamdad, K. (2023). Digital technology enabled circularity in the construction industry: a bibliometric study. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ramachandra, T. and Ranadewa, K.A.T.O. (eds). *Proceedings of the 11th world construction symposium Sri Lanka*, 21-22 July 2023, (pp. 460-470). doi: 10.31705/WCS.2023.38

Khadim, N., Agliata, R., Marino, A., Thaheem, M. J., & Mollo, L. (2022). Critical review of nano and micro-level building circularity indicators and frameworks. *Journal of Cleaner Production*, *357*. 131859. Retrieved from https://doi.org/10.1016/j.jclepro.2022.131859

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221-232.

Klein, N., Ramos, T., & Deutz, P. (2020). Circular Economy Practices and Strategies in Public Sector Organizations: An Integrative Review. *Sustainability*, *12*(10), 4181. Retrieved from https://doi.org/10.3390/su12104181

Lee, P.-H., Juan, Y.-K., Han, Q., & Vries, B. D. (2023). An investigation on construction companies' attitudes towards importance and adoption of circular economy strategies. *Ain Shams Engineering Journal*, *14,(*12), 102219. Retrieved from https://doi.org/10.1016/j.asej.2023.102219

Liu, X., Song, Y., Liu, S., & Wang, H. (2012). Automatic taxonomy construction from keywords. In *Proceedings of the 18th ACM SIGKDD international conference on knowledge discovery and data mining*, New York (pp. 1433-1441). https://doi.org/10.1145/2339530.2339754

Lovins, A. B., Lovins, L. H., & Hawken, P. (1999). A road map for natural capitalism. In *Understanding business environments*, (1st ed, pp. 250-263). Routledge

Lyle, J. T. (1996). *Regenerative design for sustainable development* (1st ed.) John Wiley & Sons.

Martinho, V. J. P. D. (2021). Insights into circular economy indicators: Emphasizing dimensions of sustainability. *Environmental and Sustainability Indicators*, *10*, 100119.

Miri, S. M., & Shahrokh, Z.D (2019). *A short introduction to comparative research*. [Doctoral dissertation, Allameh Tabataba'i University], https://www.researchgate.net/publication/336278925_A_Short_Introduction_to_Comparative_Research

Munaro, M. R., Tavares, S. F., & Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production*, *260*, 121134.

Nuñez-Cacho, P., Górecki, J., Molina-Moreno, V., & Corpas-Iglesias, F. (2018a). What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry. *Sustainability*, *10*(7). 2340.Retrieved from https://doi.org/10.3390/su10072340

Núñez-Cacho, P., Górecki, J., Molina, V., & Corpas-Iglesias, F. A. (2018b). New measures of circular economy thinking in construction companies. *Journal of EU Research in Business*, *2018*(2018), 909360

Organisation for Economic Co-operation and Development (OECD). (2014). *Education at a Glance 2014 OECD indicators*. OECD Publishing. https://www.oecd.org/education/Education-at-a-Glance-2014.pdf

Ossio, F., Salinas, C., & Hernández, H. (2023). Circular economy in the built environment: A systematic literature review and definition of the circular construction concept. *Journal of Cleaner Production*, *41,* 137738. Retrieved from https://doi.org/10.1016/j.jclepro.2023.137738

Papageorgiou, A., Henrysson, M., Nuur, C., Sinha, R., Sundberg, C., & Vanhuyse, F. (2021). Mapping and assessing indicator-based frameworks for monitoring circular economy development at the city-level. *Sustainable Cities and Society*, *75*, 103378. Retrieved from https://doi.org/10.1016/j.scs.2021.103378

Pickvance, C. G. (2001). Four varieties of comparative analysis. *Journal of Housing and the Built Environment*, *16*, 7-28.

Rodríguez, R. W., Pomponi, F., Webster, K., & D'Amico, B. (2020). The future of the circular economy and the circular economy of the future. *Built Environment Project and Asset Management*, *10*(4), 529-546. Retrieved from https://doi.org/10.1108/bepam-07-2019-0063

Senaratne, S., Kc, A., Perera, S., & Almeida, L. (2021). Promoting stakeholder collaboration in adopting circular economy principles for sustainable construction. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (eds). *Proceedings of the 9th world construction symposium*, *Sri Lanka*, 9-10 July 2021,(pp. 471-482). https://doi.org/10.31705/WCS.2021.41.

Smith, J., & Thomas, A. (2021). Integrated model and index for circular economy in the built environment in the Indian context. *Construction economics and building*, *21*(3), 198-220.

Stahel, W. R. (1982). The product life factor. In S.G. Orr (Ed.), *An Inquiry into the Nature of Sustainable Societies: The Role of the Private Sector*, (1st ed., pp. 72-150) Houston Area Research Center.

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Borucki, C., & Karaca, F. (2022). Performance assessment of construction companies for the circular economy: A balanced scorecard approach. *Sustainable Production and Consumption*, *33,* 991-1004.

van Bueren, B. J. A., Leenders, M. A. A. M., & Nordling, T. E. M. (2019). Case study: Taiwan's pathway into a circular future for buildings. *IOP conference series: earth and environmental science*, (Vol. 225, No. 1, p. 012060) IOP Publishing. https://doi.org/10.1088/1755-1315/225/1/012060

Velenturf, A. P. M., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption*, *27*, 1437-1457.Retrieved from https://doi.org/10.1016/j.spc.2021.02.018

Verberne, J. (2016). *Building circularity indicators:An approach for measuring circularity of a building* [Masters thesis, Eindhoven University of Technology]. *https://pure.tue.nl/ws/portalfiles/portal/46934924/846733-1.pdf*

Wautelet, T. (2018). *The concept of circular economy: its origins and its evolution*. https://doi.org/10.13140/RG.2.2.17021.87523

Sithumina, N.A.R., Perera, B.K.C., Wijesinghe, T. and Hettiarachchi, D.D., 2024. The impact of design changes on apartment projects' feasibility and project performances in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1011-1023. DOI: https://doi.org/10.31705/WCS.2024.80. Available from: https://ciobwcs.com/papers/

THE IMPACT OF DESIGN CHANGES ON APARTMENT PROJECTS' FEASIBILITY AND PROJECT PERFORMANCES IN SRI LANKA

N.A.R. Sithumina[1], B.K.C. Perera[2], T. Wijesinghe[3], and D.D. Hettiarachchi[4]

ABSTRACT

Design changes are inevitable in the construction industry. Among all, the consequences of design changes in apartment buildings are more crucial and evident with the existing salient nature of commercial aspects unlike in other building constructions. While the impacts of design changes on project performance have been investigated in usual building construction, there is a lack of focus on apartment construction projects and their reflections towards commercial behaviour. Therefore, this study aims to investigate the impact of design changes on project performance in terms of time, cost and feasibility in the case of apartment building construction in Sri Lanka. The research aim was achieved through the mixed-method approach. A questionnaire survey and expert interviews were conducted as data collection techniques. The impacts of design changes on project performance in apartment projects were identified by the questionnaire survey. Six experts were selected, who had experience in apartment construction projects for the semi-structured interview to investigate the reflections on financial feasibility. The quantitative data were analysed statistically and qualitative data from expert interviews were analysed using the code-based content analysis method. The findings of the research revealed that there is a significant impact of design changes on financial feasibility in apartment projects. Furthermore, ten strategies were proposed to minimise the impact of design changes on project performance and project feasibility, optimising both project performances and the feasibility of the apartment building projects for its whole life cycle.

Keywords: Apartment Building Construction; Design Changes; Financial Feasibility; Project Performance; Sri Lanka.

1. INTRODUCTION

The Sri Lankan construction sector is crucial for the country's development due to its forward and backward linkage with other industries. However, design changes pose significant challenges during project implementation (Perera et al., 2020). Such alterations, inherent in construction projects, impact overall project performance. These alterations, inherent in construction, adversely affect overall project performance

[1]Student, Department of Quantity Surveying, SLIIT, Malabe, Sri Lanka, sithum.ravishan99@gmail.com
[2]Lecturer, Department of Quantity Surveying, SLIIT, Malabe, Sri Lanka, kavinya.p@sliit.lk
[3]Senior Lecturer, Department of Quantity Surveying, SLIIT, Malabe, Sri Lanka, tilanka.w@sliit.lk
[4]Quantity Surveyor, Mynott Bowers (Private) Limited, Colombo, Sri Lanka, divanjanadisala@gmail.com

(Olawale & Sun, 2010; Jaffar et al., 2011), contributing to time and cost overruns and necessitating costly rework (Enrica et al., 2021). Research by Aslam et al. (2019) indicates that design changes can account for potential cost escalations ranging from 5% to 40% of total construction costs. Hence it becomes clear that achieving financial feasibility in such conditions becomes challenging (Hau et al., 2018).

Over the past decade, Sri Lanka has witnessed numerous luxury high-rise apartment projects, with many more underway (Mayes, 2018). The dominance of apartment buildings in South Korea's construction industry, as highlighted by Sack and Goldin (2007), underscores the importance of the real estate sector in shaping the economy. However, construction and design errors often lead to substantial losses, necessitating expensive re-work and redesigns (Sack & Goldin, 2007). The frequency and extent of design changes in apartment buildings depend on various internal and external factors, such as project size, client preferences, participant expertise, construction costs, and project complexity. Apartment construction, characterised by uniform floor plans and interconnected buildings, magnifies the risk of design changes, as alterations in one area can trigger a chain reaction affecting multiple components such as public facilities, underground structures, parking lots, balconies, and rooftops (Lee, 2018). While design changes significantly impact project performance globally (Olawale & Sun, 2010; James et al., 2014), the Sri Lankan construction industry faces challenges in effective project management readiness (Perera et al., 2020). Timely completion, adherence to budget, and maintaining quality are crucial for apartment project success. Unlike other types of construction, the profitability and sustainability of apartment building projects depend heavily on how well project performance and project feasibility coincide with each other (Ndihokubwayo, 2008).

Previous literature has mainly focused on exploring the broader implications of design changes in apartment projects within the construction sector worldwide. However, there is a noticeable gap in the literature specifically addressing apartment projects in Sri Lanka. These projects, often high-rise and large-scale constructions, pose potential risks in terms of time, cost, and overall feasibility. Nevertheless, this raises the question of whether the impacts of design changes on project performance in apartment constructions worldwide are similar to those in Sri Lanka. Additionally, the relationship between the effect of design changes and the financial aspects of apartment projects has not yet been thoroughly explored. Thus, this study is aimed to investigate the impact of design changes on project performance and feasibility in Sri Lankan apartment construction. It is achieved via identifying the effects of design changes on project performance in construction and secondly by investigating the level of impact of design changes on time and cost performances and its' reflection on the project feasibility in apartment projects. Later, strategies are proposed to enhance apartment project performances. Initially, this study was conducted on time and cost project performance parameters whereas quality was not considered due to resource limitations.

2. LITERATURE REVIEW

The construction industry, with its myriad stakeholders and numerous variables including design changes, variations, and regulations, poses challenges in project management (Gharaibeh, et al., 2020). The following sections present the existing scientific knowledge within the domain of design changes in construction projects.

2.1 CONTRIBUTORY FACTORS FOR DESIGN CHANGES

Design changes in a construction project can occur at various stages and due to various factors. According to Alnuaimi et al. (2009), there are 31 factors affecting design changes in construction projects. Client adjustments and design changes were ranked as the utmost primary sources of variation orders in Omani public construction projects. Design changes are resulted from internal and external factors. Internal factors involve project stakeholders such as owners, design consultants, construction management consultants, and contractors. External factors included political, economic, and environmental issues, technological advancements, and the involvement of third parties outside the project's internal system (Yana, et al., 2015). Apart from the main factors mentioned above, problems on-site, design errors, and omissions are common causes of design changes in construction projects. These alterations stem from various sources, including owners altering plans, consultants' lack of collaboration, and contractors facing financial constraints or labour shortages. Additionally, shifts in regulations and economic conditions prompt design changes. Bassa et al. (2019) identified the main causes: lack of review, design errors, client plan changes, incomplete contracts, differing site conditions, design evaluator inexperience, and decision-making delays. Yap and Skitmore (2017) added drivers such as team shortcomings, poor workmanship, site constraints, safety issues, regulatory challenges, reworks, communication gaps, evolving end-user needs, and risk management flaws. Altogether, it is evident that the causes of design changes in apartment projects are rarely explored yet discussed in overall building construction.

2.2 EFFECTS OF DESIGN CHANGES ON PROJECT PERFORMANCE

Olawale and Sun (2015), and Ibbs et al. (2005) highlight that design changes significantly affect construction project performance across all stages, leading to potential adjustments in contract durations, cost, and scope of work. Design changes often necessitate rework (Sun & Meng, 2009), resulting in time delays and cost overruns which adversely affect the project performance (Ekambaram et al., 2014; Hui Yap et al., 2015). Despite their acceptance in the construction industry, design changes are seen as detrimental to project performance, primarily assessed through time and cost considerations. This study focuses specifically on identifying the impact of design changes on time and cost in apartment projects.

2.2.1 Impact on Project Duration Due to Design Changes

Design changes have emerged as a significant factor contributing to construction project delays, as highlighted in various studies. Memon et al. (2014) categorised delays into excusable and non-excusable, with excusable delays often attributed to design changes. In California, for example, design changes increased construction project durations by 69% across four tested projects (Chang, 2002). Similarly, delays in design approvals were found to impede project progress (Williams et al., 1995). According to Dosumu and Aigbavboa (2018), construction delays were identified as a major issue stemming from design changes. These findings underscore the substantial negative impact of design changes on project schedules, a consistent trend observed across studies worldwide.

2.2.2 Impact on Project Cost Due to Design Changes

The financial implications of design changes vary across projects and countries. Aslam et al. (2019), revealed that virtually every project undergoes a transition from design to construction. Studies have consistently shown that design changes inevitably lead to cost overruns and specifically found that design changes are a primary cause of cost overruns, accounting for up to 40% of total project costs (Aslam et al., 2019). Chang (2002) reported direct cost impacts ranging from 2.1% to 21.5% of overall construction costs due to design changes. These findings underscore the universal challenge of cost overruns resulting from design changes, affecting projects worldwide (Aslam et al., 2019).

Likewise, past research extensively studies factors affecting design changes and project performance in overall construction whereas less attention is paid specific to apartment projects. This gap risks misleading generalisations when applying findings from broader construction studies.

3. METHODOLOGY

After considering the characteristics of this research and identified knowledge in the literature review, the data were collected using a mixed-method approach. The mixed methodology approach provides a comprehensive understanding of the research topic which allows the author to logically resolve the research problem. As there are wide range of attributes such as causes and impact of the design changes in Sri Lankan Apartment projects, a mixed methodology is required to fully capture the intricacy, interrelationships, and in-depth analysis of these variables both quantitatively and qualitatively. It is necessary to understand the financial aspects of apartment projects, the effect of design changes on project performance in terms of cost and time, and the feasibility aspects. Quantitative data provide measurable insights, while qualitative data offer in-depth understanding, making both essential for a comprehensive analysis. The general causes and impacts were identified through a comprehensive literature review and tested the applicability of those causes and impacts of the Sri Lankan apartment projects. Based on the findings of the literature review, a questionnaire survey was conducted to assess the impact of design changes on the project performance of apartment building construction in Sri Lanka in terms of time and cost. From the questionnaire survey, the literature review findings were validated. The survey included insights into procurement types, frequency of changes, and their effects on project performance, targeting professionals with apartment project experience. Data analysis highlighted the influential factors for project performance and viability. Identified causes and effects were further explored in expert interviews, leading to proposed strategies to mitigate design change impacts. Apart from that, different implications over financial feasibility owing to design changes were revealed. Quantitative data was analysed using the Chi-square method with adjustments made using Yates' theory for the 2x2 contingency table and Relative Important Index (RII). Subsequently, qualitative data were gathered from semi-structured interviews and analysed to assess the impact on project feasibility and performance in Sri Lankan apartment construction. Suggestions for overcoming the negative impact of design changes on project performance and feasibility were proposed. Qualitative data from semi-structured interviews were examined by the manual content analysis method, a qualitative research method that involves systematic coding and identifying patterns (White & Marsh, 2006). Finally, the conclusion of the study derived from inductive theory. Since the study was not committed merely from a single paradigm the believed philosophy is pragmatism.

4. DATA ANALYSIS

In this section, both the findings from the quantitative and qualitative analysis are presented. A total of 51 responses were received from a questionnaire survey with non-probability sampling method. Ten survey responses were rejected due to no experience in apartment projects. Interviews were conducted with six industry experts. Among the questionnaire respondents, 56% had over six years of experience in apartment construction, while all experts in the semi-structured interviews had at least seven years of industry experience.

4.1 QUESTIONNAIRE SURVEY ANALYSIS

The questionnaire survey involved Quantity Surveyors, Engineers, Building Information Modelling (BIM) Managers, Architects, and other relevant professionals with extensive experience in Sri Lankan apartment building projects. Their insights contribute significantly to analysing the data and addressing the research questions, particularly in identifying the impacts of design changes on project performance in this section.

4.1.1 Frequency of Design Changes

The survey delved into the frequency of design changes in projects by gathering insights from participants. Results revealed that 44% of respondents experienced four to six revisions per drawing, followed by one to three revisions as the second-highest frequency. Notably, a minority reported over six revisions per drawing. Remarkably, none of the participants reported encountering an apartment project without any drawing revisions. On average, drawings were altered between four to six times.

4.1.2 Causes of Design Changes

According to the diagram, the most common cause of design changes, cited by 32 out of 41 participants, was site conditions which is about 78% of the total, making it the most significant factor. Studies have shown that inadequate site conditions are major factors causing delays and cost overruns in construction projects. Errors and omissions in design, and scope changes by owners were the second and third most frequent causes indicating 25 and 26 out of 41 respectively. Surprisingly, only five respondents (about 12%) identified legislation and regulations as a factor. While these factors may be beyond the parties' control, they warrant attention for future predictions. Figure 1 illustrates the root causes of design changes in Sri Lankan apartment projects. Having said that, other causes that were listed in the literature were not selected.

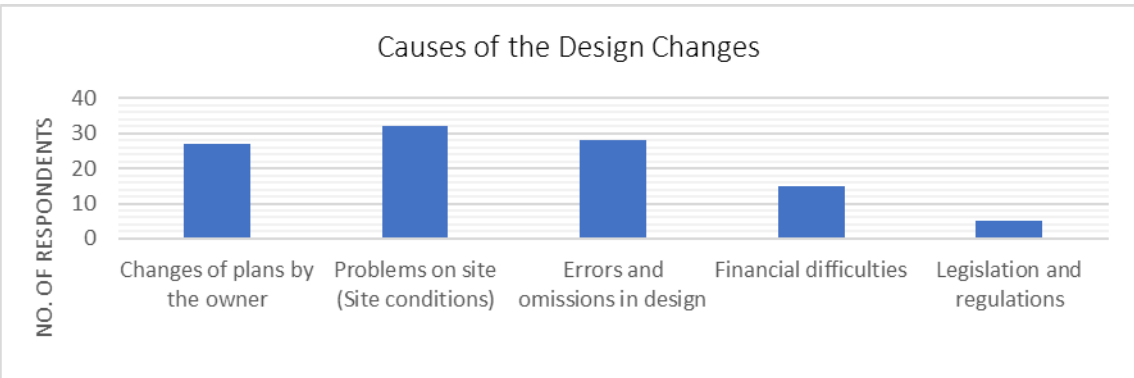


Figure 1: Causes of design changes

4.1.3 Impact Caused to the Time and Cost of the Project

Our research focuses on the effects of design changes in apartment projects, specifically on project performance in terms of time and cost. Figure 2 and Figure 3 illustrate the impact of design changes on time and cost in apartment projects in Sri Lanka. Analysis of questionnaire responses revealed that 24 respondents reported potential delays of 1-100 days in project completion due to design changes, accounting for 59% of total respondents. The second most common response indicated delays of 101-200 days, with 16 out of 41 respondents reporting this. According to the literature, design changes can significantly affect project costs (Aslam et al., 2019). To verify this in the context of Sri Lankan apartment construction projects, participants were specifically asked about the cost impacts caused by design changes. Regarding project cost, 21 respondents (51% of total participants) noted a 1% to 10% increase due to design changes. Additionally, 17 respondents reported cost impacts ranging from 11% to 20% in their apartment projects. Only three participants (7% of total participants) stated that costs were impacted by 21% to 30%, and none have experienced impacts exceeding 30% of the total project cost. This analysis highlights significant concerns regarding design changes in Sri Lankan apartment projects, which often lead to delays and cost escalations for developers. Figures 2 and 3 visually depict these impacts on project time and cost, respectively.

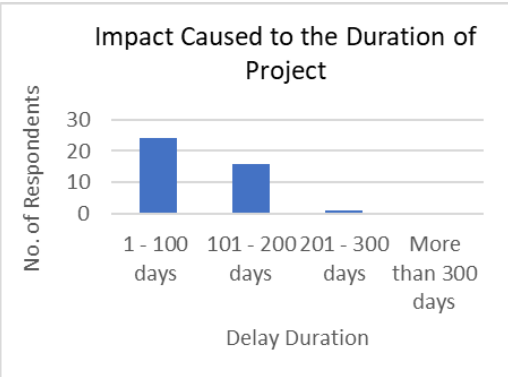


Figure 2: Impact caused to the cost of projects

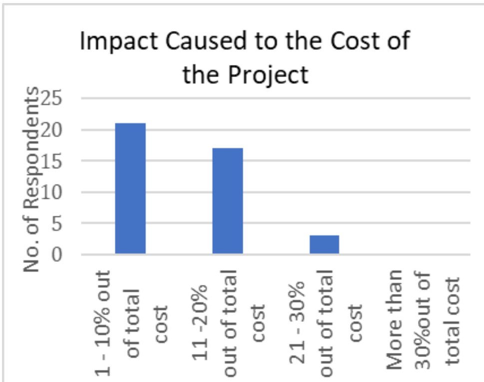


Figure 3: Impact caused to the duration of projects

4.1.4 RII Findings

The RII analysis shows that design changes significantly impact project performance in apartment buildings, with project duration having the highest RII value of 0.84, followed closely by project cost at 0.81. The slight difference indicates a correlation between factors causing time and cost overruns (Olawale & Sun, 2010), as summarised in Table 1.

Table 1: RII data analysis

Ranking							
Factors	Most Significant	Significant	Moderate	In-Significant	Negligible	Weighted Total	
Time	16	19	4	2	0	172	0.839
Cost	13	18	9	1	0	166	0.810

4.1.5 The Commonly used Procurement Type for Apartment Projects

The questionnaire initially focused on gathering data about the contract type and procurement method used in participants' apartment projects. Results revealed that 70% of respondents preferred the design and build procurement method, with others opting for the traditional method. According to Davis et al. (2004) and Hewamulla et al. (2022), the traditional procurement method, despite its flexibility, often results in more client-initiated design changes, leading to time wastage due to design reworks. Understanding these prevalent practices is crucial for contextualising the study's findings and assessing factors that influence project outcomes, particularly the impact of design changes on project feasibility and performance.

4.1.6 Test of Association

Given that time and cost have been identified as the primary factors affected by design changes in apartment buildings, the test of the association focused solely on these two factors to examine their correlation with the following instances.

- Type of the procurement method of the project and the influence of project duration due to design changes
- Type of the procurement method of the project and the influence of cost due to design changes

After conducting the hypothesis testing from a test of association using Chi-Square distribution, below the results were achieved for each instance.

Procurement Method of the Project and the Influence of Project Duration due to Design Changes

Initially, the test of association for the influence of project duration due to design changes was tested. Table 2 presents the summary table of recorded data and Table 3 shows the Chi-Square calculation.

Table 2: Summary of observations

Delay in Project Duration			
Procurement Method	**1-100**	**101-200**	**Sum of rows**
Design and Build	17	11	28
Traditional	5	5	10
Sum of Columns	22	16	38

Table 3: Test of association for the influence of project duration due to design changes

Observations (O)				
O	17	11	5	5
Expected values (E)	16.211	11.789	16.211	4.211
O-E	0.789	-0.789	-11.211	0.789
O-E ı	0.789	0.789	11.211	0.789
O-E I - 0.5	0.289	0.289	10.711	0.289
(O-E)2	0.084	0.084	114.726	0.084
(O-E)2 /E	0.005	0.007	7.077	0.02

Defined hypothesis:

Ho – No association between the type of procurement method of the project and the impacted project duration due to design changes

H1 – There is an association between the type of procurement method of the project and the impacted project duration due to design changes

Since it has been a 2x2 contingency table and has at least one expected value of five, the Chi-Square analysis was conducted with Yate's correction for an unbiased continuity (Camilli & Hopkins, 1978). With a calculated Chi-Square value of 7.109, exceeding the critical Chi-Square value of 3.841 at a 5% significance level, the null hypothesis (Ho) can be rejected. This indicates significant evidence of an association between the type of procurement system and the incidence of project delays in apartment buildings at a 5% significance level.

Procurement Method of the Project and the Influence of Project Cost Due to Design Changes

Table 4 illustrates the summary of the observations and Table 5 shows the table for test association for the influence of cost due to design changes.

Table 4: Summary of observations

Impact on Project Cost			
Procurement Method	**1% - 10%**	**11% - 20%**	**Sum of rows**
Design and Build	16	10	26
Traditional	3	7	10
Sum of Columns	19	17	36

Apart from the set observations, there were another two observations recorded in the impact of project cost of over 20% in the design and build procurement method. Since its outliers with the central tendency of the data distribution, it was excluded from the further data analysis.

Table 5: Test of association for the influence of cost due to design changes

Observations (O)				
O	16	10	3	7
Expected values (E)	13.722	4.722	5.278	4.722
O-E	2.272	5.278	-2.278	2.278
ǀO-Eǀ	2.272	5.278	2.278	2.278
ı O-E I - 0.5	1.778	4.778	1.778	1.778
(O-E)2	3.160	22.827	3.160	3.160
(O-E)2/E	0.230	4.834	0.599	0.670

Defined hypothesis:

Ho – No association between the type of Procurement method of the project and the impacted cost due to design changes

H1 – There is an association between the type of Procurement method of the project and the impacted cost due to design changes

As it follows the Chi-Square distribution, the critical value at 5% on one degree of freedom is 3.84. Since 6.332 is higher than this value Ho can be rejected at a 5% of significance level. Based on this analysis, it became evident that there exists an association between the procurement type employed in the project and the impact on project cost by design changes. Hence, it is apparent that both delays in project completion duration and construction project cost overruns are associated with various procurement systems, primarily attributed to design changes.

4.2 QUALITATIVE DATA ANALYSIS FROM EXPERT INTERVIEWS

The questionnaire survey findings provide concrete evidence of the impact of design changes on project performance in apartment construction. Through expert interviews, the discussion extended to the implications of these performance impacts on project financial feasibility. The data from the expert interviews was analysed across several theme codes: the impact of design changes on selling price, profitability, and the selling volume of apartment projects. Based on that, critiques on financial feasibility arising from project performance were identified and explored in apartment projects.

Table 6: General information of the participants

Code	Profession	Industry experience
R1	Architect	Over 20 years
R2	BIM Manager	Over 9 years
R3	Charted Quantity Surveyor	Over 8 years
R4	Engineer	10-15 years
R5	Senior Quantity Surveyor	Over 7 years
R6	Charted Quantity Surveyor	Over 10 years

4.2.1 Impact of Selling Price of an Apartment Unit

Design changes significantly affect the selling price of apartments, which have been repeated with high frequency in discussing the financial feasibility of apartment construction projects. Unlike other projects, apartment construction involves unique commercial considerations, with the unit price playing a central role in financial viability. This feasibility encompasses both project costs and return on investment. All the interview participants except R2 believe that unit prices are often adjusted to maintain financial feasibility amidst design changes. However, R2 contends that unit prices should remain fixed regardless of project cost fluctuations, only de-escalating if a project is delayed due to design changes and the demand for apartments decreases. All the other believed, that when design changes compromise a project's financial viability, adjusting unit prices becomes essential to restore feasibility. Additionally, R3 stated, "unit costs will only increase if buyers purchase the apartment units after the design changes occur; if purchased beforehand, the unit price remains unchanged". Based on that insight, it is safe to say design changes can impact the unit price of apartments in various ways. Consequently, the apartment construction sector often experiences increased apartment unit prices when financial feasibility is challenged by design changes.

4.2.2 Impact on Profitability of the Apartment

Profitability stands as a crucial determinant of successful completion in apartment projects, as their ultimate goal is to generate profits through unit sales. Interviewees, R2 and R4 concurred that profitability could fluctuate, potentially increasing or decreasing based on project size and circumstances. While one interviewee (R4) suggested profitability could generally be managed despite design changes, R3 highlighted a scenario where their company faced losses due to an inability to adjust selling prices, resulting in reduced profit margins. These perspectives underline the impact of design changes on profitability, which directly influences financial feasibility. Maintaining profitability within acceptable bounds is essential for achieving financial feasibility, as project profitability serves as a key benchmark. Thus, cost overruns resulting from design changes can jeopardise project profitability and, consequently, financial feasibility.

4.2.3 Impact of Selling Volume of the Apartment Project and Reflection on Financial Feasibility

The term "selling volume of the apartment" refers to the quantity of units intended for sale within a given apartment complex or development. Based on the majority of experts' interpretations, it was made clear that the selling volume can be impacted due to design changes in apartment projects. R1, R2 and R3 stated that project delays caused by design changes can threaten the market potentially reducing selling volume. R1 and R4 added that increased unit prices due to design changes can also affect the marketability and reduce the selling volume. However, R5 and R6 argued that design changes have less impact on units sold during construction, yet it can affect the units unsold or units about to be sold. The selling volume and rate of sales will also have an implication on profitability thereby on the financial feasibility, due to the fact that sooner the units are sold the better the chance of achieving payback. Furthermore, the investors generally forecast the Return on Investment (ROI) and demand levels based on the prevailing market condition with reasonable allowances to accommodate for risks. If the apartment units are unsold within the expected time, it may expose the project to greater risks and uncertainties that may jeopardise the financial feasibility. Being delayed for project completion places the property developers at risk of not achieving the intended ROI. Thus, may result in a lack of financial feasibility.

4.2.4 Strategies to Minimise the Impact on Project Performance and Project Feasibility in Apartments

To minimise the impact of design changes on project performance and project feasibility in apartment building ten strategies were scrutinised based on the data gathered by questionnaire survey and expert interviews. The underlying principle was to minimise design changes to lessen the impact on project performances. The given strategies are:

i. Site conditions should be investigated prior to the start of the project,
ii. Proper coordination between parties and the employees,
iii. Identify all client requirements within the design stage (clear project brief),
iv. The design should be in line with the feasibility study,
v. Testing procedures and feasibility should be done properly initially,
vi. Selection of highly recommended employees,
vii. BIM implementation,
viii. Maintain a proper risk management process,
ix. Solid base financial involvement, and

x. Provide provisions for customisation in early stages.

They emphasised the importance of site investigation before project commencement mainly. This is acknowledged in a study done by Wuala and Rarasati (2020) for developing countries. Additionally, improved coordination among stakeholders and employees was crucial to avoid misconceptions. This coordination facilitates timely discussions and implementation of solutions to address design changes thereby minimising their adverse effects. Miscommunication was identified as a significant risk factor. Moayeri et al. (2017) stated that, developing an automated BIM model to visualise and compare original and altered designs, aids in coordinating changes and analysing their ripple effects. Proper risk management practices, financial involvement, and provisions for customisation in the project's early stages were also endorsed in overcoming design changes.

5. CONCLUSIONS

Design changes in construction projects cause delays, cost overruns, and scope alterations (Olawale & Sun, 2015), negatively impacting timelines, expenses, and outcomes (Ekambaram et al., 2014; Hui Yap et al., 2015). Studies show these changes consistently increase project duration and costs, posing global challenges (Hui Yap et al., 2015). The literature review reveals that more focused studies on Sri Lankan apartment construction are needed to address the unique challenges and develop targeted solutions, as these projects frequently face design changes and higher risks. In Sri Lankan apartment construction, the Design and Build procurement method emerged as the prevailing choice as it is widely used offering flexibility to meet clients' preferences yet often leading to many design changes. Design changes are identified as a common occurrence, predominantly influenced by causes such as site conditions, design errors, and scope modifications. These alterations significantly impact project time and cost, with delays ranging from one to 300 days and cost overruns ranging from 1% to 20% of the project's total cost. Notably, the RII underscores the substantial influence of design changes on project time and cost. Expert interviews shed further light on the consequences of design changes on project financial feasibility. A linkage between the selling price, profitability, and selling volume of the apartment units was revealed, indicating that these factors collectively determine the financial feasibility of apartment projects. This emphasises the interconnectedness of pricing strategies, profitability margins, and market demand, all of which play pivotal roles in ensuring the economic viability of such developments. Potential strategies were uncovered through this research that would be helpful in curbing the negative impact of design changes on project performance and its' reflection on project feasibility in apartment projects in the Sri Lankan context. To overcome the design changes impact, the fundamental need is to minimise the design changes during the apartment construction. Through the study, the discussed insights can be utilised to look forward to the betterment of foreign apartment industries as well. More in-depth future research should delve deeper into the impact of design changes towards financial feasibility in apartment construction and reveal the correlated linkages such as causes of design changes and different procurement routes.

6. REFERENCES

Alnuaimi, A. S., Taha, R., Al Mohsin, M., & Al-Harthi, A. S. (2009). Causes, effects, benefits, and remedies of change orders on public construction projects in Oman. *Journal of Construction Engineering and Management*, *136*(5). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000154

Aslam, M., Baffoe-Twum, E., & Saleem, F. (2019). Design changes in construction projects – Causes and impact on the cost. *Civil Engineering Journal, 5*. (7), 1647-1655. http://dx.doi.org/10.28991/cej-2019-03091360

Bassa, M., Reta, A., Alyew, A., & Tora, M. (2019). Causes and effects of design change in building construction projects in three selected southern Ethiopia zones. *International Journal of Engineering Research & Technology (IJERT), 8*(12). https://doi.org/10.17577/IJERTV8IS120213

Camilli, G., & Hopkins, K. D. (1978). Applicability of chi-square to 2 x 2 contingency tables with small expected cell frequencies. *Psychological Bulletin, 85*(1), 163–167. https://doi.org/10.1037/0033-2909.85.1.163

Chang, A. S.-T. (2002). Reasons for cost and schedule increase for engineering design projects. *Journal of Management in Engineering, 18*(1). https://doi.org/10.1061/(ASCE)0742-597X(2002)18:1(29)

Davis, P., Love, P., & Baccari, D. (2004). Building procurement methods. *Eprints.qut.edu.au*. https://eprints.qut.edu.au/26844/

Dosumu, O., & Aigbavboa, C. (2018). An assessment of the causes, cost effects and solutions to design-error-induced variations on selected building projects in Nigeria. *Acta Structilia, 25*(1), 40–70. https://www.ajol.info/index.php/actas/article/view/176848

Ekambaram, P., Love, P. E. D., Kumaraswamy, M., & Ng, S. T. (2014). Causal ascription of rework in building and civil engineering projects. *Engineering, Construction and Architectural Management*, *21*(1), 111–126. https://doi.org/10.1108/ecam-04-2010-0029

Enrica, M., Purba, H. H., & Purba, A. (2021). Risks leading to cost overrun in construction projects: A systematic literature review. *Advance Researches in Civil Engineering, 3*(1), 43–60. https://doi.org/10.30469/arce.2021.130147

Gharaibeh, L. G., Matarneh, S. T., Arafeh, M., & Sweis, G. (2020). Factors leading to design changes in Jordanian construction projects. *International Journal of Productivity and Performance Management, 70*(4), 893–915. https://doi.org/10.1108/ijppm-08-2019-0412

Hau, V., Husein, M., Chung, I.-Y., Won, D.-J., Torre, W., & Nguyen, T. (2018). Analyzing the impact of renewable energy incentives and parameter uncertainties on financial feasibility of a campus microgrid. *Energies, 11*(9), 2446. https://doi.org/10.3390/en11092446

Hewamulla, K., Jayasena, H. S., & Guruge, K. (2022). The impact of procurement method on construction time waste. *Proceedings of 10th World Construction Symposium 2022*. https://doi.org/10.31705/wcs.2022.73

Hui Yap, J. B., Wang, C., & Abdul-Rahman, H. (2015). Impacts of design changes on construction project performance: Insights from a literature review. *14th Management in Construction Research Association (MiCRA 2015)*.

Ibbs, W. (2005). Impact of change's timing on labor productivity. *Journal of Construction Engineering and Management, 131*(11). https://doi.org/10.1061/(ASCE)0733-9364(2005)131:11(1219)

Jaffar, N., Tharim, A. H. A., & Shuib, M. N. (2011). Factors of conflict in the construction industry: A literature review. *Procedia Engineering, 20*, 193–202. https://doi.org/10.1016/j.proeng.2011.11.156

James, O., M., A. L., O., O., P., T.-O., Owoabidele, PeterJoy, & Omuh, Ignatious. (2014). Causes and effects of delay on project construction delivery time. *International Journal of Education and Research, 2*(4).

Lee, J.-S. (2018). Value engineering for defect prevention on building façade. *Journal of Construction Engineering and Management, 144*(8), 04018069. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001500

Mayes, S. (2018, February 9). Sri Lanka real estate market: 2018 predictions. *Daily FT*. https://www.ft.lk/PropertyConstruction/Sri-Lanka-real-estate-market-2018-predictions/10516-649047

Memon, A. H., Rahman, I. A., & Hasan, M. F. A. (2014). Significant causes and effects of variation orders in construction projects. *Research Journal of Applied Sciences, Engineering and Technology, 7*(21).4494-4502. https://www.maxwellsci.com/msproof.php?doi=rjaset.7.826

Moayeri, V., Moselhi, O., & Zhu, Z. (2017). BIM-based model for quantifying the design change time ripple effect. *Canadian Journal of Civil Engineering, 44*(8), 626–642. https://doi.org/10.1139/cjce-2016-0413

Ndihokubwayo, R. (2008). An analysis of the impact of variation orders on project performance [Unpublished master's theses]. *Cape Peninsula University of Technology,* Paper, 33. https://core.ac.uk/download/pdf/148364967.pdf

Olawale, Y. A., & Sun, M. (2010). Cost and time control of construction projects: Inhibiting factors and mitigating measures in practice. *Construction Management and Economics, 28*(5), 509–526. https://doi.org/10.1080/01446191003674519

Olawale, Y., & Sun, M. (2015). Construction project control in the UK: Current practice, existing problems and recommendations for future improvement. *International Journal of Project Management, 33*(3), 623–637. Researchgate. https://doi.org/10.1016/j.ijproman.2014.10.003

Perera, B. A. K. S., Samarakkody, A. L., & Nandasena, S. R. (2020). Managing financial and economic risks associated with high-rise apartment building construction in Sri Lanka. *Journal of Financial Management of Property and Construction, 25*(1), 143–162. https://doi.org/10.1108/jfmpc-04-2019-0038

Sacks, R., & Goldin, M. (2007). Lean management model for construction of high-rise apartment buildings. Journal of construction engineering and Management, 133(5), 374-384. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:5(374)

Sun, M., & Meng, X. (2009). Taxonomy for change causes and effects in construction projects. *International Journal of Project Management, 27*(6), 560–572. https://doi.org/10.1016/j.ijproman.2008.10.005

White, M. D., & Marsh, E. E. (2006). Content analysis: A flexible methodology. *Library Trends, 55*(1), 22–45. https://muse.jhu.edu/pub/1/article/202361/55.1white_tab01.html

Williams, T., Eden, C., Ackermann, F., & Tait, A. (1995). The effects of design changes and delays on project costs. *Journal of the Operational Research Society, 46*(7), 809–818. https://doi.org/10.1057/jors.1995.114

Wuala, H. D., & Rarasati, A. D. (2020). Causes of delays in construction project for developing Southeast Asia countries. IOP Conference Series: *Materials Science and Engineering, 830*(02), 022054. https://doi.org/10.1088/1757-899X/830/2/022054

Yana, A. A. G. A., Rusdhi, H. A., & Wibowo, M. A. (2015). Analysis of factors affecting design changes in construction projects with partial least square (PLS). *Procedia Engineering, 125*, 40–45. https://doi.org/10.1016/j.proeng.2015.11.007

Yap, J. B. H., & Skitmore, M. (2017). Investigating design changes in Malaysian building projects. *Architectural Engineering and Design Management, 14*(3). https://doi.org/10.1080/17452007.2017.1384714

Costa, M.D.D., Costa, M.R.R. and Thayaparan, M., 2024. The impacts of computer vision technology in construction: Investigating applications and challenges. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1024-1037. DOI: https://doi.org/10.31705/WCS.2024.81. Available from: https://ciobwcs.com/papers/

THE IMPACTS OF COMPUTER VISION TECHNOLOGY IN CONSTRUCTION: INVESTIGATING APPLICATIONS AND CHALLENGES

M.D.D. Costa[1], M.R.R. Costa[2], and M. Thayaparan[3]

ABSTRACT

The application of Computer Vision (CV) is transforming many industrial sectors by improving the interactions of technology with the physical environment. According to the research, CV technology heavily impacts construction by offering enhanced solutions to issues such as safety, quality, and progress. This research employed a Systematic Literature Review (SLR) method to find the applications of CV and the related challenges within the construction sector, ensuing the PRISMA 2020 guidelines and PICO framework for the investigation. Out of the 38 studies that were retrieved through Scopus and Web of Science, the review aimed at comparing the application of CV in the following areas: automated progress monitoring, intelligent tracking, real-time quality assessment, improvement of safety, 3D modeling, and object detection. Nevertheless, certain challenges and threats limit the progress of CV such as the high processing times, technologies still in their infancy, and the complexity of integration with other models. Such challenges are grouped and associated with the application they belong to, and it is seen that automated construction progress monitoring faces the most difficulties. Last of all, this research provides construction stakeholders with a framework that links CV applications and challenges as follows with the view of indicating appropriate decisions to make. It is hoped that this framework will assist in avoiding problems and identifying the best practices in the application of CV technologies in construction.

Keywords: *Applications and Challenges; Computer Vision (CV); Construction Industry; Systematic Literature Review.*

1. INTRODUCTION

Computer vision has become a game-changer across industries, transforming our interactions with technology and our understanding of the world (Paneru & Jeelani, 2021). Its applications range from face detection in smartphones, which secures our devices and facilitates transactions, to driving advancements including self-driving cars through techniques such as Simultaneous Localisation and Mapping (SLAM) and object recognition. In healthcare, it aids in early detection and diagnosis, potentially saving lives

[1] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dulshanc@uom.lk
[2] Undergraduate, Department of Computer Science and Engineering, University of Moratuwa, Sri Lanka, rumal.19@cse.mrt.ac.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk

by identifying cancer cells or classifying skin lesions (Martinez et al., 2019). In transportation, computer vision predicts traffic speeds and manages congestion, leading to smarter city planning and smoother commutes. It is crucial in quality inspection, ensuring products meet standards by detecting defects imperceptible to the human eye, thus preserving brand reputation (Fang, Ding, et al., 2020). Its versatility extends to remote inspections in manufacturing, improving safety and efficiency in monitoring and maintenance (Zhang et al., 2021). Moreover, in construction, computer vision enhances safety management by identifying potential hazards, conducting quality checks, and monitoring productivity, ensuring projects stay on track and within budget (Chen et al., 2022).

The construction industry is on the verge of a technological revolution, with automation enhancing efficiency and precision. Computer vision is playing a pivotal role by automating tasks such as safety monitoring and quality inspections and setting new standards for operational excellence (Fang, Love, et al., 2020). It enables real-time tracking of construction progress by comparing actual and planned models, facilitating immediate corrective actions (Moragane et al., 2022). Moreover, computer vision enhances the navigation of construction vehicles, reducing accidents and improving site logistics through precise manoeuvring. The integration of computer vision with automated and robotic processes allows robots to perform tasks such as bricklaying and welding with unmatched consistency and endurance (Ibrahim et al., 2022). Current applications include remote inspections and 3D modelling, offering detailed insights and time savings. Despite these advancements, there is significant untapped potential in computer vision for construction, promising further transformative developments as the technology continues to mature (Liu et al., 2021).

There is a scarcity of literature that presents the current applications and issues of CV in construction. This paper focuses on the analysis of the uses and difficulties of CV technology in the construction industry by employing a SLR that captures contemporary trends. This study offers a thorough analysis of CV in the construction industry, identifying applications and challenges for future research. The research aims to identify the application and challenges of implementing CV technologies in construction projects and offers a framework as a guiding tool for stakeholders in their decision-making stages.

2. RESEARCH METHODOLOGY

2.1 SYSTEMATIC LITERATURE REVIEW

The SLR was employed to identify the applications and challenges of computer vision in the construction industry. As a structured approach, the SLR acts as a foundation to recognise trends and inconsistencies in existing literature material. To ensure the rigorousness of the research methodology “Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020” guidelines were used.

The PICO framework was selected as the most suitable one among the various SLR tools available. The letters: PICO stands for; Population (P), Intervention (I), Comparison (C), and Outcome (O). The structured elements of PICO fit well into the context of identifying the applications and challenges of computer vision in the construction industry. The research question was formulated as, “What are the applications and challenges of computer vision in the construction industry?”.

An initial manual keyword search was initiated to develop the research question. The research findings about applications and challenges related to implementing computer vision in the construction industry were aligned with the PICO elements. The keywords used for PICO elements are presented in Table 1.

Table 1: PICO elements

Population (P)	Intervention (I)	Comparison (C)	Outcome (O)
Construction industry	Computer vision*		Application* Challenge* Barrier* Benefit*

This study utilised three databases. These sources include Scopus and Web of Science which are well-known and credible sources for academic research pertinent to the study's background. A "titles only" approach was used to fine-tune and accurately select studies and a "title-abstract-keyword" approach was utilised to gather detailed results. The Boolean operators (AND, OR) were implemented resulting in more flexibility when seizing the searching outcome. The search filters used were restricted to the last five years starting from the year 2019 to ensure the relevancy and accuracy of the results. The choice was limited only to the articles which were published in English. The search string used to identify relevant records is given below:

> "construction Industry" AND "computer vision*" AND (application* OR challenge* OR barrier* OR benefit*)

2.2 THE SLR PROCESS

The flow diagram for "systematic reviews which included searches of databases and registers only" in the PRISMA (2020) guidelines for systematic reviews was used for this study. The overall summarised process which is followed through the main stages of SLR in this study is presented in Figure 1.

As represented in Figure 1 the identification stage of the SLR began with a total of 112 papers identified through two databases respectively: Scopus (72 records) and Web of Science (40 records). After removing 32 duplicate records, 80 unique records remained for screening. During the screening stage, these 80 records were evaluated for relevance, and 33 were excluded as they were not pertinent to the topic. This left 47 reports, which were sought for full-text retrieval. However, five reports could not be retrieved, resulting in 42 reports for further assessment. These reports were then assessed for eligibility based on specific inclusion and exclusion criteria.

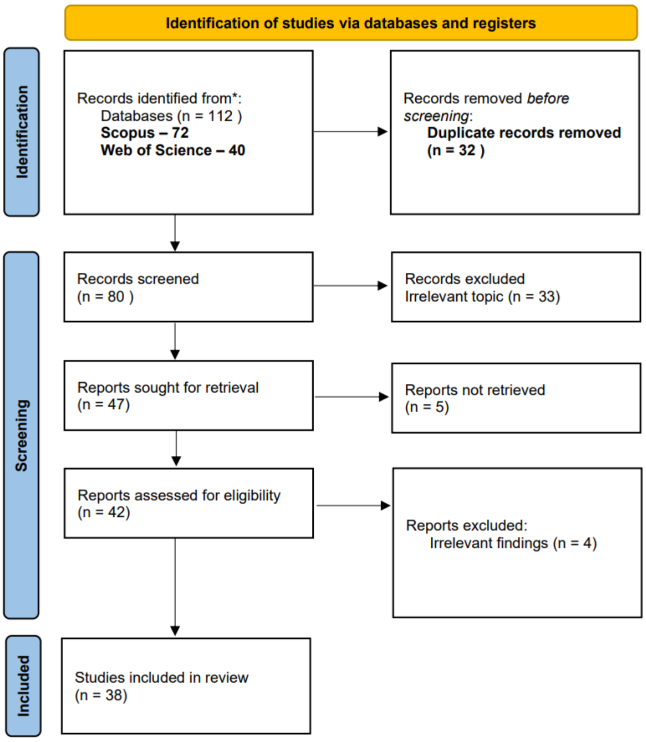


Figure 1: SLR process

Consequently, four reports were excluded due to irrelevant findings. Ultimately, 38 studies were included in the final review as presented in Figure 2 and Figure 3.

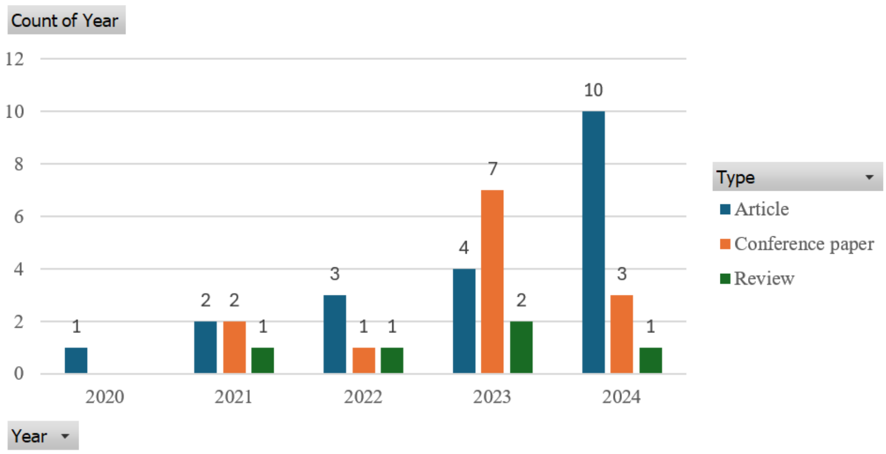


Figure 2: Literature selected

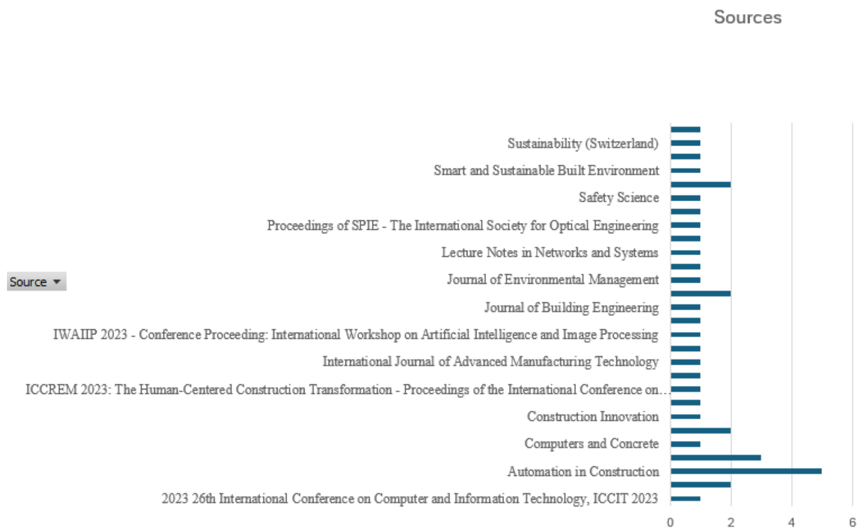


Figure 3: Selected Literature sources

3. RESEARCH FINDINGS AND DISCUSSION

A detailed analysis of the 38 articles selected from the SLR was conducted. The analysis aimed to identify the applications and challenges of computer vision in the construction industry. The next section presents the findings of the analysis.

3.1 APPLICATIONS OF CV TECHNOLOGY IN CONSTRUCTION

According to SLR, the applications of CV technology in construction are analysed and presented in Table 2. All the applications mentioned in Table 2 from SLR have been considered while preparing the framework for this study.

3.2 CHALLENGES FOR CV TECHNOLOGY IN CONSTRUCTION INDUSTRY

The challenges for CV technology in construction are analysed and presented in Table 3. All the challenges for CV in the construction industry which were identified through SLR were included in the framework.

3.3 FRAMEWORK DEVELOPMENT

Framework has been developed to showcase the linkage between applications and challenges for CV in the construction industry. The challenges that arise from each CV application are linked to respective challenges according to the SLR results and it is showcased in Figure 4.

Table 2: Applications of CV in the construction industry

Category	Application	Description	Sources
Automated Monitoring and Progress Tracking	Automated Construction Progress Monitoring	Uses computer vision to track and analyse construction progress automatically, comparing real-time data with plans.	(Feng et al., 2024; Guo et al., 2021; Jiang et al., 2023; Moragane et al., 2024; Pal et al., 2021)
	Intelligent Progress Tracking	Enhances progress monitoring with AI, offering detailed insights into construction stages and potential delays.	(Moragane et al., 2024; Princz et al., 2023)
	Real-Time Activity Intensity Identification	Analyses site activity in real-time to determine intensity levels and workflow efficiency.	(Moohialdin et al., 2023)
	Progress Prediction for Deep Foundation Pit Projects	Predicts construction progress and potential issues for deep foundation pit projects using computer vision techniques.	(Kang et al., 2023)
Quality Control and Assessment	Automated Quality Control	Utilises computer vision to detect and analyse defects or quality issues in construction materials or work.	(Abioye et al., 2021; Martinez et al., 2020; Xie et al., 2024)
	Quality Assessment of Concrete 3D Printing	Evaluates the quality of 3D printed concrete structures, ensuring they meet specified standards.	(Senthilnathan & Raphael, 2022)
	Real-Time Quality Assessment	Provides instant feedback on the quality of construction work during or immediately after execution.	(Martinez et al., 2020)
Safety Monitoring	Safety Monitoring and Enhancement	Monitors construction sites for safety hazards and compliance, enhancing overall safety management.	(Akinsemoyin et al., 2023; Arfan et al., 2023; Hassan et al., 2024; Kim & Yi, 2024)
	PPE Detection and Compliance	Detects whether workers are wearing appropriate PPE and ensure compliance.	(Arfan et al., 2023; Mahmud et al., 2023)
	Fall Prevention and Smart Safety Hook Monitoring	Uses computer vision to prevent falls and monitor the use of safety hooks, enhancing worker safety.	(Khan et al., 2022)
	Automated Risk Assessment for WMSDs	Identifies and assesses risks related to Work-related Musculoskeletal Disorders (WMSDs) using computer vision.	(Sivakumar et al., 2024)
	Hurricane Preparedness and Debris Localization	Assesses hurricane damage and locates debris for efficient cleanup and recovery efforts.	(Kamari & Ham, 2021)
3D Reconstruction and Visualisation	3D Reconstruction and Model Creation	Creates detailed 3D models of construction sites or projects using computer vision technologies.	(Huang et al., 2021; Katsatos et al., 2023; Koulalis et al., 2022)
	Integration with Digital Twins and BIM	Integrates 3D models with digital twins and Building Information Modeling (BIM) for enhanced project visualisation.	(Koulalis et al., 2022; Nguyen et al., 2024)
	Virtual Sensing of Buried Utilities	Uses computer vision to detect and map utilities buried underground, improving planning and safety.	(Oguntoye et al., 2023)
Object Detection and Tracking	Object Detection, Tracking, and Classification	Detects, tracks, and classifies various objects on construction sites to manage inventory and activities.	(Akinsemoyin et al., 2023; Duan et al., 2022; Shrigandhi & Gengaje, 2023)
	Building Automation and Robotics	Employs computer vision for automation and robotics in construction tasks, increasing efficiency and precision.	(Sun et al., 2023)
	Activity Monitoring and Recognition	Monitors and recognises different construction activities to improve workflow and productivity.	(Kikuta & Chun, 2024; Li et al., 2024)
Resource and Waste Management	Waste Identification, Classification, and Forecasting	Identifies, classifies, and forecasts construction waste to optimise waste management and recycling efforts.	(Park et al., 2024; Prasad & Arashpour, 2024; Rodrigo et al., 2024)
	Resource and Waste Optimisation	Utilises computer vision to optimise the use of resources and manage waste more effectively.	(Abioye et al., 2021)

Category	Application	Description	Sources
Data Integration and Analysis	Integration of Various Data Types for Safety and Progress Analysis	Combines data from different sources for comprehensive safety and progress analysis on construction sites.	(J. Liu et al., 2022; Nguyen et al., 2024; Schüle et al., 2024)
	Multi-Modal Data Integration	Integrates multiple types of data (e.g., images, sensor data) for enhanced site analysis and decision-making.	(J. Liu et al., 2022)
	Real-Time Data Retrieval and Interaction	Facilitates real-time access and interaction with data for improved site management and decision-making.	(Nguyen et al., 2024)
Robotic Applications	Automated Rebar Tying	Uses robotics and computer vision for automated rebar tying, improving efficiency and accuracy.	(Feng et al., 2024)
	Robotics for Construction Tasks and Site Monitoring	Implements robotics equipped with computer vision for various construction tasks and site monitoring.	(Kikuta & Chun, 2024; Sun et al., 2023)
Performance Evaluation	Performance Benchmarking of Detection Models	Evaluates and benchmarks the performance of computer vision models used in construction applications.	(Duan et al., 2022)
	Evaluation of Reconstruction Methods	Assesses the effectiveness of different reconstruction methods using computer vision techniques.	(Katsatos et al., 2023)
Others	Underground Construction and Lifecycle Management	Applies computer vision to manage underground construction projects and their lifecycle stages.	(Huang et al., 2021; Mahmud et al., 2023)
	Intelligent Building Management	Uses computer vision for managing and controlling building systems and operations intelligently.	(Ma, 2023)
	Safety Activity Metrics Collection	Collects metrics related to safety activities on construction sites for analysis and improvement.	(Akinsemoyin et al., 2023)
	Data Mining for Safety Management	Applies data mining techniques to safety data to uncover insights and enhance management practices.	(J. Liu et al., 2022)

Table 3: Challenges for CV in the construction industry

Challenge	Description	References
Insufficient Daily Monitoring	Current methods do not effectively capture daily progress due to gaps between as-built 3D point cloud captures, leading to incomplete progress records.	(Patel et al., 2021)
Processing Time	The processing of as-built 3D point clouds requires significant time, which can delay progress monitoring.	(Martinez et al., 2020; Moohialdin et al., 2023; Patel et al., 2021)
Unmodeled Schedule Activities	Some construction activities are not represented in BIM models, making automated progress monitoring of these activities challenging.	(Kang et al., 2023; Patel et al., 2021)
Technological Immaturity	Robotics and computer vision applications in construction are still in the early stages, requiring further development to address specific industry needs.	(Arfan et al., 2023; Xie et al., 2024)
Material Variability	Variability in construction materials, such as lumber misalignments, poses challenges for robotics-based manufacturing, leading to potential reworks and quality control issues.	(Senthilnathan & Raphael, 2022; Xie et al., 2024)
The Complexity of Construction Projects	The intricate nature of construction projects complicates the integration of robotic systems and quality control mechanisms.	(Kang et al., 2023; Patel et al., 2021; Sivakumar et al., 2024; Sun et al., 2023)
Detection and Correction of Misalignments	Ensuring accurate detection of misalignments and transmitting this information for corrective action remains a challenge.	(Oguntoye et al., 2023; Xie et al., 2024)
Complexity in Planning and Control	Planning and controlling production processes, especially in SMEs, is challenging and requires significant expertise.	(Princz et al., 2023; Sun et al., 2023)
Systematic Implementation	There is a need for systematic approaches to implementing intelligent progress-tracking technologies and addressing existing gaps in literature and practical applications.	(Koulalis et al., 2022; Princz et al., 2023)
Limited Applications	Despite advancements, the application of computer vision in the construction industry, particularly in Digital Twins, remains limited.	(Koulalis et al., 2022)
Integration with Existing Models	Combining CV with existing 3D reference models and visual sensor data presents challenges in data compatibility and integration.	(Koulalis et al., 2022)
Variations in Image Capture	Differences in image quality, lighting, and angles can affect the accuracy of PPE detection systems.	(Arfan et al., 2023; Jiang et al., 2023)
Synergy Between CV and CPM	There is a lack of synergy between CV technologies and construction progress monitoring practices, highlighting the need for more research and integration.	(Moragane et al., 2024)
Complex Industry Challenges	The construction industry faces challenges including cost overruns, time delays, health and safety issues, productivity, and labour shortages, complicating computer vision adoption.	(Abioye et al., 2021; Sun et al., 2023)
Integration of Multiple Technologies	Combining CV, AR, GPS, and IMU sensor data to achieve effective real-time verification and management is complex and requires seamless integration.	(Ma, 2023; Nguyen et al., 2024)
High Complexity of High-Rise Buildings	The complexity and scale of high-rise buildings pose significant challenges for automation and robotic systems, requiring advanced solutions for effective implementation.	(Sun et al., 2023)
Labor Productivity and Safety Issues	Addressing issues like low labour productivity, labour shortages, and high worker safety risks through automation and robotics involves overcoming technical and practical challenges.	(Sivakumar et al., 2024)
Accuracy of 3D Models	Ensuring the accuracy and detail of 3D reconstructions is challenging, particularly when dealing with complex construction sites and varying environmental conditions.	(Katsatos et al., 2023)
Data Acquisition and Processing	Acquiring high-quality data from challenging construction environments and processing it effectively for 3D reconstruction can be complex and resource intensive.	(J. Liu et al., 2022; Rodrigo et al., 2024)
Recognition Logic	Establishing effective recognition logic for distinguishing construction workers and their activities is challenging, especially in complex or cluttered environments.	(Jiang et al., 2023; Li et al., 2024)
Complex Environments	Sophisticated computer vision models are needed to accurately detect and classify activities in complex and dynamic construction environments.	(Arfan et al., 2023; Oguntoye et al., 2023)

Challenge	Description	References
Integration of Multiple Models	Combining multiple deep learning algorithms for comprehensive analysis adds complexity and requires careful integration and optimisation.	(Li et al., 2024; J. Liu et al., 2022)
Inadequate Model Performance	Existing models may not perform well in diverse and complex construction environments, requiring further refinement.	(Sivakumar et al., 2024)
Limited Application Scenarios	The practical application of deep learning models in construction safety management scenarios is still limited, with room for improvement in real-world applications.	(J. Liu et al., 2022)
Accuracy Improvement	Improving accuracy in computer vision applications requires addressing challenges related to data quality, processing techniques, and real-world applicability.	(Duan et al., 2022; Senthilnathan & Raphael, 2022)
Integration Complexity	Integrating computer vision systems with existing construction technologies presents challenges in ensuring seamless operation and data compatibility.	(Nguyen et al., 2024)
Training Image Generation	Generating diverse and representative training images is crucial for developing robust computer vision models for construction applications.	(Li et al., 2024)
Model Performance	The performance of CV models can be affected by data quality and environmental factors, requiring continuous improvement.	(Duan et al., 2022; Sivakumar et al., 2024)
Adoption Barriers	Barriers to adopting CV technologies include cost, complexity, and resistance to change within the construction industry.	(Rodrigo et al., 2024)
High Clutter and Diversity	High levels of clutter and diversity in construction environments pose challenges for accurate object detection and classification.	(Arfan et al., 2023)
Accuracy in Detection	Achieving high accuracy in object detection and classification requires addressing challenges related to data quality and system calibration.	(Arfan et al., 2023; Jiang et al., 2023)
Adverse Weather Conditions	Adverse weather conditions can affect the performance of CV systems, requiring robust solutions to handle environmental variability.	(Mahmud et al., 2023)
Complex Site Environments	Complex site environments present challenges for CV systems, requiring advanced methods for accurate analysis and monitoring.	(Kamari & Ham, 2021; Mahmud et al., 2023)
Dataset Complexity	Managing the complexity of datasets for CV applications involves addressing issues related to diversity and volume.	(Duan et al., 2022; J. Liu et al., 2022)
Access to Relevant Datasets	Accessing and utilising relevant datasets is essential for developing and applying effective CV solutions.	(Duan et al., 2022; J. Liu et al., 2022)
Data Collection and Calibration	Collecting and calibrating data for CV systems requires careful attention to ensure accuracy and reliability.	(Akinsemoyin et al., 2023; Hassan et al., 2024)
Accuracy and Stability	Achieving accuracy and stability in CV systems requires addressing challenges related to data variability and processing techniques.	(Ma, 2023; Senthilnathan & Raphael, 2022)
Real-Time Processing	Real-time processing capabilities are essential for effective pose reconstruction and application of CV systems in construction.	(Moohialdin et al., 2023; Schüle et al., 2024)
Dynamic Work Environments	Dynamic work environments in construction present challenges for CV systems, requiring adaptability and robustness in their design.	(Akinsemoyin et al., 2023; Moohialdin et al., 2023)
Defects and Deformities Detection	Detecting defects and deformities in construction materials and structures using CV requires advanced techniques and accurate models.	(Senthilnathan & Raphael, 2022)

.

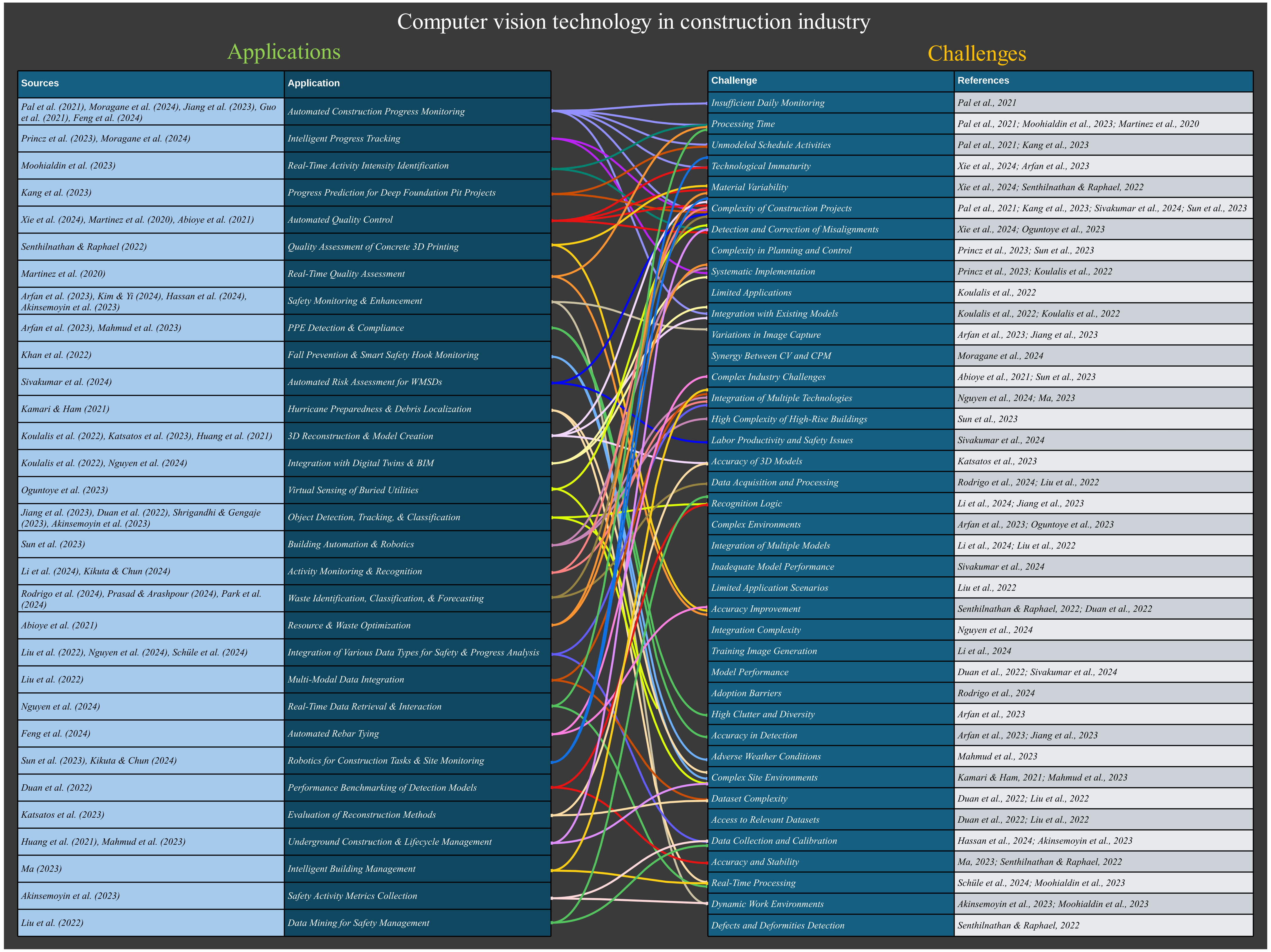


Figure 4: Framework of applications and challenges of computer vision in the construction industry

As per Figure 4, Automated Construction Progress Monitoring has the highest challenges, which are Insufficient Daily Monitoring, Processing Time, Unmodeled Schedule Activities, Technological Immaturity, Complexity in Planning and Control, and Integration with Existing Models. It illustrates Automated Construction Progress Monitoring is the most significant application with many barriers. Then with four challenges, Automated Quality Control takes the second significant application having challenges: Technological Immaturity, Material Variability, Complexity of Construction Projects, and Detection and Correction of Misalignments. Then 3D Reconstruction and Model Creation, Object Detection, Tracking, and Classification, and Building Automation and Robotics take the third place by having three challenges per each, meaning similar significance. On the other hand, all other applications have two challenges each showing their lesser significance compared to others.

This framework will be useful and act as a guiding tool for construction stakeholders in decision-making stages. Since the framework shows the challenges which might arise in applying the selected computer vision technologies in construction projects, it will guide them to take precautionary measures and warnings while selecting CV technologies for their project.

4. CONCLUSIONS

The study brings out the fact that computer vision in construction such as monitoring of projects and their progress, tracking of quality, safety, and 3D reconstruction provides a considerable plus point. These technologies enhance the means of tracking the construction progress in real-time, quality control and assurance, handling safety issues and site visualisation. They have direct benefits in that they increase productivity, decrease rates of mistakes, and raise the effectiveness of projects since they yield insight that can be very hard to come by otherwise. However, the study reveals some of the key issues that are bound to arise when using computer vision in construction projects. The challenges include relatively young technologies and the level of difficulty when incorporating such technologies into the existing systems. Certain challenges that arise include fluctuations in the construction material, time needed to process the items, and precision of the 3D models. The research stresses that these issues must be solved before CV is fully realised in the construction industry.

This study's framework presents the mapping between computer vision applications and their corresponding challenges, which can be helpful for the construction stakeholders. it highlights that Automated Construction Progress Monitoring has the highest challenges compared to other computer vision applications. The assessment of the barriers that are expected to be experienced when implementing each of the contexts will enable the stakeholders to avoid pitfalls that may be detrimental to their cause.

However, this study has the following limitations. The SLR is limited to the published research, which might not reflect all the present and future technologies and uses of computer vision in construction. This exclusion of recent sources might result in missing earlier advancements and basic research performed in the field. Thirdly, the paper only focuses on the literature published in English, which in the authors' contribution could mean that important information from other languages is overlooked. The framework that has been established is founded upon established challenges and applications; these may change as new technology is found or new problems are required to be solved. Therefore, based on the above limitations, several points for future research are suggested to broaden the knowledge of the article. As for the type of studies, the research could follow the developmental changes in CV systems and their effects on construction projects. Including, whether research should encompass both local and international publications, and whether the research should be limited to only English articles or should it encompass international outlooks as well could present a clearer view of the advancements.

5. REFERENCES

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Davila Delgado, J. M., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, *44*. https://doi.org/10.1016/j.jobe.2021.103299

Akinsemoyin, A., Awolusi, I., Chakraborty, D., Al-Bayati, A. J., & Akanmu, A. (2023). Unmanned Aerial Systems and Deep Learning for Safety and Health Activity Monitoring on Construction Sites. *Sensors*, *23*(15). https://doi.org/10.3390/s23156690

Arfan, M., Sumardi, S., & Huboyo, H. (2023). Advancing Workplace Safety: A Deep Learning Approach for Personal Protective Equipment Detection using Single Shot Detector. *IWAIIP 2023 - Conference Proceeding: International Workshop on Artificial Intelligence and Image Processing*, 127–132. https://doi.org/10.1109/IWAIIP58158.2023.10462804

Chen, C., Gu, H., Lian, S., Zhao, Y., & Xiao, B. (2022). Investigation of Edge Computing in Computer Vision-Based Construction Resource Detection. *Buildings*, *12*(12). https://doi.org/10.3390/buildings12122167

Duan, R., Deng, H., Tian, M., Deng, Y., & Lin, J. (2022). SODA: A large-scale open site object detection dataset for deep learning in construction. *Automation in Construction*, *142*. https://doi.org/10.1016/j.autcon.2022.104499

Fang, W., Ding, L., Love, P. E. D., Luo, H., Li, H., Peña-Mora, F., Zhong, B., & Zhou, C. (2020). Computer vision applications in construction safety assurance. In *Automation in Construction* (Vol. 110). https://doi.org/10.1016/j.autcon.2019.103013

Fang, W., Love, P. E. D., Luo, H., & Ding, L. (2020). Computer vision for behaviour-based safety in construction: A review and future directions. In *Advanced Engineering Informatics* (Vol. 43). https://doi.org/10.1016/j.aei.2019.100980

Feng, R., Jia, Y., Wang, T., & Gan, H. (2024). Research on the System Design and Target Recognition Method of the Rebar-Tying Robot. *Buildings*, *14*(3). https://doi.org/10.3390/buildings14030838

Guo, B. H. W., Zou, Y., Fang, Y., Goh, Y. M., & Zou, P. X. W. (2021). Computer vision technologies for safety science and management in construction: A critical review and future research directions. *Safety Science*, *135*. https://doi.org/10.1016/j.ssci.2020.105130

Hassan, S. I., Syed, S. A., Ali, S. W., Zahid, H., Tariq, S., ud, M. M. S., & Alam, M. M. (2024). Systematic literature review on the application of machine learning for the prediction of properties of different types of concrete. *PeerJ Computer Science*, *10*. https://doi.org/10.7717/PEERJ-CS.1853

Huang, M. Q., Ninić, J., & Zhang, Q. B. (2021). BIM, machine learning and computer vision techniques in underground construction: Current status and future perspectives. *Tunnelling and Underground Space Technology*, *108*. https://doi.org/10.1016/j.tust.2020.103677

Ibrahim, A., Golparvar-Fard, M., & El-Rayes, K. (2022). Multiobjective Optimization of Reality Capture Plans for Computer Vision–Driven Construction Monitoring with Camera-Equipped UAVs. *Journal of Computing in Civil Engineering*, *36*(5). https://doi.org/10.1061/(asce)cp.1943-5487.0001032

Jiang, Z., Messner, J. I., & Matts, E. (2023). Computer vision applications in construction and asset management phases: A literature review. *Journal of Information Technology in Construction*, *28*, 176–199. https://doi.org/10.36680/J.ITCON.2023.009

Kamari, M., & Ham, Y. (2021). Semantic Detection of Potential Wind-Borne Debris in Construction Jobsites: Digital Twining for Hurricane Preparedness and Jobsite Safety. *Computing in Civil*

Engineering 2021 - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2021, 902–909. https://doi.org/10.1061/9780784483893.111

Kang, S., Kang, Y., & Kim, S. (2023). Long-term Trends in Construction Engineering and Management Research in Korea. *KSCE Journal of Civil Engineering*, *27*(5), 1883–1897. https://doi.org/10.1007/s12205-023-1249-8

Katsatos, D., Alexiou, D., Kontodina, T., Chatzikonstantinou, I., Kostavelis, I., Giakoumis, D., & Tzovaras, D. (2023). Comparative Study of Surface 3D Reconstruction Methods Applied in Construction Sites. *IST 2023 - IEEE International Conference on Imaging Systems and Techniques, Proceedings*. https://doi.org/10.1109/IST59124.2023.10355721

Khan, M., Khalid, R., Anjum, S., Tran, S. V.-T., & Park, C. (2022). Fall Prevention from Scaffolding Using Computer Vision and IoT-Based Monitoring. *Journal of Construction Engineering and Management*, *148*(7). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002278

Kikuta, T., & Chun, P.-J. (2024). Development of an action classification method for construction sites combining pose assessment and object proximity evaluation. *Journal of Ambient Intelligence and Humanized Computing*, *15*(4), 2255–2267. https://doi.org/10.1007/s12652-024-04753-7

Kim, H., & Yi, J.-S. (2024). Image generation of hazardous situations in construction sites using text-to-image generative model for training deep neural networks. *Automation in Construction*, *166*. https://doi.org/10.1016/j.autcon.2024.105615

Koulalis, I., Dourvas, N., Triantafyllidis, T., Ioannidis, K., Vrochidis, S., & Kompatsiaris, I. (2022). A survey for image based methods in construction: from images to digital twins. *ACM International Conference Proceeding Series*, 103–110. https://doi.org/10.1145/3549555.3549594

Li, J., Zhao, X., Kong, L., Zhang, L., & Zou, Z. (2024). Construction Activity Recognition Method Based on Object Detection, Attention Orientation Estimation, and Person Re-Identification. *Buildings*, *14*(6). https://doi.org/10.3390/buildings14061644

Liu, J., Luo, H., & Liu, H. (2022). Deep learning-based data analytics for safety in construction. *Automation in Construction*, *140*. https://doi.org/10.1016/j.autcon.2022.104302

Liu, W., Meng, Q., Li, Z., & Hu, X. (2021). Applications of computer vision in monitoring the unsafe behavior of construction workers: Current status and challenges. In *Buildings* (Vol. 11, Issue 9). https://doi.org/10.3390/buildings11090409

Ma, W. (2023). Technical framework of energy-saving construction management of intelligent building based on computer vision algorithm. *Soft Computing*. https://doi.org/10.1007/s00500-023-08424-1

Mahmud, S. S., Islam, M. A., Ritu, K. J., Hasan, M., Kobayashi, Y., & Mohibullah, M. (2023). Safety Helmet Detection of Workers in Construction Site using YOLOv8. *2023 26th International Conference on Computer and Information Technology, ICCIT 2023*. https://doi.org/10.1109/ICCIT60459.2023.10441212

Martinez, P., Al-Hussein, M., & Ahmad, R. (2019). A scientometric analysis and critical review of computer vision applications for construction. In *Automation in Construction* (Vol. 107). https://doi.org/10.1016/j.autcon.2019.102947

Martinez, P., Al-Hussein, M., & Ahmad, R. (2020). Intelligent vision-based online inspection system of screw-fastening operations in light-gauge steel frame manufacturing. *International Journal of Advanced Manufacturing Technology*, *109*(3–4), 645–657. https://doi.org/10.1007/s00170-020-05695-y

Moohialdin, A. S. M., Lamari, F., Miska, M., & Trigunarsyah, B. (2023). Proximity Activity Intensity Identification System in Hot and Humid Weather Conditions: Development and Implementation. *Journal of Construction Engineering and Management*, *149*(12). https://doi.org/10.1061/JCEMD4.COENG-13332

Moragane, H. P. M. N. L. B., Perera, B. A. K. S., Palihakkara, A. D., & Ekanayake, B. (2022). Application of computer vision for construction progress monitoring: a qualitative investigation. *Construction Innovation*. https://doi.org/10.1108/CI-05-2022-0130

Moragane, H. P. M. N. L. B., Perera, B. A. K. S., Palihakkara, A. D., & Ekanayake, B. (2024). Application of computer vision for construction progress monitoring: a qualitative investigation. *Construction Innovation*, *24*(2), 446–469. https://doi.org/10.1108/CI-05-2022-0130

Nguyen, L., Htet, H. T., Lee, Y.-J., & Park, M.-W. (2024). Augmented Reality Framework for Retrieving Information of Moving Objects on Construction Sites. *Buildings*, *14*(7). https://doi.org/10.3390/buildings14072089

Oguntoye, K. S., Laflamme, S., Sturgill, R., & Eisenmann, D. J. (2023). Review of Artificial Intelligence Applications for Virtual Sensing of Underground Utilities. *Sensors*, *23*(9). https://doi.org/10.3390/s23094367

Pal, A., Lin, J. J., & Hsieh, S.-H. (2021). A Framework for Automated Daily Construction Progress Monitoring Leveraging Unordered Site Photographs. *Computing in Civil Engineering 2021 - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2021*, 538–545. https://doi.org/10.1061/9780784483893.067

Paneru, S., & Jeelani, I. (2021). Computer vision applications in construction: Current state, opportunities & challenges. In *Automation in Construction* (Vol. 132). https://doi.org/10.1016/j.autcon.2021.103940

Park, M., Kulinan, A. S., Dai, T. Q., Bak, J., & Park, S. (2024). Preventing falls from floor openings using quadrilateral detection and construction worker pose-estimation. *Automation in Construction*, *165*. https://doi.org/10.1016/j.autcon.2024.105536

Patel, A., Kapadia, H., Patel, J., Patidar, S., Richhriya, Y., Trivedi, D., Patel, P., & Mehta, M. (2021). Dry waste segregation using seamless integration of deep learning and industrial machine vision. *Proceedings of CONECCT 2021: 7th IEEE International Conference on Electronics, Computing and Communication Technologies*. https://doi.org/10.1109/CONECCT52877.2021.9622578

Prasad, V., & Arashpour, M. (2024). Optimally leveraging depth features to enhance segmentation of recyclables from cluttered construction and demolition waste streams. *Journal of Environmental Management*, *354*. https://doi.org/10.1016/j.jenvman.2024.120313

Princz, G., Shaloo, M., & Erol, S. (2023). A literature review on the prediction and monitoring of assembly and disassembly processes in discrete make-To-order production in SMEs with machine vision technologies. *ACM International Conference Proceeding Series*, 318–327. https://doi.org/10.1145/3587889.3588217

Rodrigo, N., Omrany, H., Chang, R., & Zuo, J. (2024). Leveraging digital technologies for circular economy in construction industry: a way forward. *Smart and Sustainable Built Environment*, *13*(1), 85–116. https://doi.org/10.1108/SASBE-05-2023-0111

Schüle, J., Burkhardt, M., Gienger, A., & Sawodny, O. (2024). Towards Automated Construction: Visual-based Pose Reconstruction for Tower Crane Operations using Differentiable Rendering and Network-based Image Segmentation. *IEEE International Symposium on Industrial Electronics*. https://doi.org/10.1109/ISIE54533.2024.10595817

Senthilnathan, S., & Raphael, B. (2022). Using Computer Vision for Monitoring the Quality of 3D-Printed Concrete Structures. *Sustainability (Switzerland)*, *14*(23). https://doi.org/10.3390/su142315682

Shrigandhi, M. N., & Gengaje, S. R. (2023). Systematic Literature Review on Object Detection Methods at Construction Sites. *Lecture Notes in Networks and Systems*, *673 LNNS*, 709–724. https://doi.org/10.1007/978-981-99-1745-7_52

Sivakumar, K. S., Bugalia, N., & Raphael, B. (2024). REBAPose -A Computer vision based Musculoskeletal Disorder Risk Assessment Framework. *Proceedings of the International Symposium on Automation and Robotics in Construction*, 607–614. https://doi.org/10.22260/ISARC2024/0079

Sun, K., Liu, J., Yanxin, Z., & Luo, Y. (2023). Automation and Robots Are Developing in the Field of Tall Buildings. *Proceedings of SPIE - The International Society for Optical Engineering*, *12793*. https://doi.org/10.1117/12.3006415

Xie, C., Tehrani, B. M., & Alwisy, A. (2024). A Framework for Automated Quality Control of Wood-Framed Panels in Robotic-Based Manufacturing Using Computer Vision and Deep Learning. *Construction Research Congress 2024, CRC 2024*, *1*, 456–465. https://doi.org/10.1061/9780784485262.047

Zhang, B., Yang, B., Wang, C., Wang, Z., Liu, B., & Fang, T. (2021). Computer vision-based construction process sensing for cyber–physical systems: A review. In *Sensors* (Vol. 21, Issue 16). https://doi.org/10.3390/s21165468

Wanigasinghe, H.S.N., Hadiwattage, C. and Ilangakoon, I.W.M.A.D., 2024. The necessity and opportunity for upgrading quantity surveying practices based on the lessons learned during the COVID-19 pandemic: A literature review. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1038-1049. DOI: https://doi.org/10.31705/WCS.2024.82. Available from: https://ciobwcs.com/papers/

THE NECESSITY AND OPPORTUNITY FOR UPGRADING QUANTITY SURVEYING PRACTICES BASED ON THE LESSONS LEARNED DURING THE COVID-19 PANDEMIC: A LITERATURE REVIEW

H.S.N. Wanigasinghe[1], C. Hadiwattage[2] and I.W.M.A.D. Ilangakoon[3]

ABSTRACT

The COVID-19 pandemic has posed significant challenges to the global construction industry, yet it has presented unprecedented opportunities for adaptation and improvement. This literature review explores the necessity and opportunity of upgrading quantity surveying practices in response to lessons learned during the COVID-19 pandemic. The study delves into the impacts of COVID-19 on the construction sector, highlighting challenges such as project delays, workforce reduction, and supply chain disruptions. Conversely, it identifies opportunities for innovation and resilience, including the adoption of new technologies and flexible working methods. Specifically focusing on quantity surveying practices, the review examines how contractual arrangements, project cost control, and site visits have been affected. Through a meticulous analysis of the literature, the study reveals a pressing need to enhance quantity surveying competencies and embrace digitalisation to navigate future uncertainties effectively. The findings underscore the importance of aligning quantity surveying practices with emerging industry trends and technological advancements to ensure project success and resilience. This study contributes to the knowledge base by shedding light on the necessity and strategies for upgrading quantity surveying practices in response to the lessons learned from the COVID-19 pandemic. Industry practitioners are encouraged to prioritise the evaluation and enhancement of quantity surveying practices to adapt to the evolving demands of the construction landscape. Further, this study is recommended to explore practical approaches for implementing upgraded quantity surveying practices in real-world contexts.

Keywords: *COVID-19 Pandemic; Lessons Learned; Opportunities; Quantity Surveying Practices.*

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, hsnwanigasinghe98@gmail.com

[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, chandanieh@uom.lk

[3] Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, ashinsanai@uom.lk

1. INTRODUCTION

World Health Organisation (2023) in 2019 declared the outbreak of emergence of Corona Virus Disease 2019 (COVID-19) as a pandemic. Hence, the COVID-19 pandemic has created a global health crisis that has disrupted all industries including the construction industry (Hatoum et al., 2021). This had a significant impact on the progress of multiple industries and the global economy including multiple challenges to the construction industry in both developed and developing countries (Iqbal et al., 2021). Due to the extended duration of construction projects, crises are frequently encountered (Mhaske & Khandekar, 2016). Additionally, the high initial capital investments required make construction companies particularly vulnerable to crises (Fadhil & Burhan, 2021).

The construction industry has faced numerous challenges including project termination, labour impact, job loss, time overrun, cost overrun, and financial loss (Gamil & Alhagar, 2020; Likitha et al., 2023), cancellation or delay of contracts and supply chain shortages (Karimi et al., 2022), employee workforce reduction encountered difficulties in completing project deliverables within the schedule (Ghandour, 2020), increase in claims and disputes in contractual formulas and caused low productivity and an inability to workforce mobility (Husien et al., 2021). Whereas challenges persist, Karimi et al. (2022) demonstrated that the COVID-19 pandemic presented a silver lining for construction companies, as it compelled them to adopt new technologies, increase productivity, build more manufacturing facilities and warehouses, create domestic job opportunities, and utilise advanced manufacturing technologies.

From the perspective of a Quantity Surveyor (QS), the COVID-19 pandemic led to several impacts on professional activities including contractual arrangements regarding project time completion and suspension, project cost control, claim arrangement and negotiations, and project tendering (Hansen et al., 2021). Furthermore, site visits for variation work valuation and interim payment valuation are the most affected practices whereas consultative services such as value management and advisory services were the least affected (Tan & Zainon, 2022). Further, Modiba and Harinarain (2024) highlighted those noteworthy impacts for QSs as alterations in work dynamics, modifications in site evaluations, increased instances of cost overruns, shifts in contract interpretation, and changes in the preparation of monthly payment certificates.

As QS has a crucial and definitive function that impacts project success (Eyiah-Botwe et al., 2015), there is a significant requirement to investigate challenges faced by QSs during the COVID-19 pandemic and there is an existing gap in the construction industry to evaluate upgrading quantity surveying practices. Therefore, a significant gap exists between industry requirements and available studies regarding the challenges faced by Quantity Surveyors (QSs) and the changes made to general quantity surveying practices during the COVID-19 pandemic. Furthermore, no research has yet explored the opportunities and necessity of upgrading quantity surveying practices based on lessons learned from the pandemic.

This study aims to review the necessity of upgrading the quantity surveying practices for the future, based on the lessons learned during the COVID-19 pandemic. To achieve this aim, four objectives have been set up i.e., (i) identify challenges and opportunities faced by the construction industry during the COVID-19 pandemic, (ii) identify lessons learned from the COVID-19 pandemic by the construction industry, (iii) review how the COVID-19 pandemic affected the quantity surveying practices, and (iv) identify the necessity and opportunity to upgrade quantity surveying practices based on lessons learned from the COVID-19 pandemic.

2. METHODOLOGY

A substantial body of literature exists detailing the historical evolution on any subject highlighting its significant sources, which deepens the understanding of related key themes (Saunders et al., 2019). Further elucidating this point, Snyder (2019) emphasised that a thorough synthesis of the literature is crucial for establishing a study's theoretical foundations. Hence, this paper builds upon the findings of a comprehensive literature analysis to gain insight into lessons learned from the COVID-19 pandemic by the construction industry.

To summarise the findings, a meticulous assessment of the literature was undertaken. This involved a thorough literature review encompassing various sources such as books, reports, theses, journals, magazines, and conference proceedings. The purpose was to delineate challenges and opportunities faced by the construction industry during the COVID-19 pandemic, identify lessons learned from the COVID-19 pandemic, and identify the necessity and opportunity to upgrade quantity surveying practices. To ensure a comprehensive synthesis of the literature, search terms such as 'COVID-19 pandemic', 'Quantity surveying practices', 'Opportunities from COVID-19 pandemic', 'Lessons learned from COVID-19 pandemic' were meticulously filtered using prominent search engines including 'Scopus,' 'Google Scholar,' 'Emerald,' and 'Science Direct.'

3. RESULTS AND FINDINGS

3.1 CONSTRUCTION INDUSTRY AND COVID–19 PANDEMIC

The COVID-19 pandemic has forced social, cultural, and economic systems to adjust their routines, structures, and procedures (Rokooei et al., 2023). Furthermore, this had a significant impact on the progress of multiple industries and the global economy including multiple challenges to the construction industry in both developed and developing countries (Iqbal et al., 2021). Furthermore, Ogunnusi et al. (2020) mentioned the effects of COVID-19 pandemic in these special circumstances have had a positive and negative impact, especially on the owners, architects, engineers, and other construction professionals.

In addition, construction is subjected to substantial risks and is exposed to internal and external events (Sfakianaki et al., 2015) and crises are frequently encountered in construction projects because of their time-taken nature (Mhaske & Khandekar, 2016; Srinivasan & Nandhini, 2015) and high initial capital investments in construction projects (Fadhil & Burhan, 2021). In addition, Zheng et al. (2021) highlighted construction is one of the typical labour-intensive industries that has been exposed to risk by the COVID-19 pandemic. Moreover, it has brought severe disturbances to the resources and legislation of the construction industry (Husien et al., 2021). According to Pamidimukkala and Kermanshachi (2021), it has affected workforces and workplaces and changed the working atmosphere.

3.2 CHALLENGES FACED BY THE CONSTRUCTION INDUSTRY DURING THE COVID-19 PANDEMIC

According to Iqbal et al. (2021), projects have been delayed, workforce capacity has been reduced, and economic development has fallen significantly because of changes in the work patterns of various organisations. Similarly, Gamil and Alhagar (2020) revealed impacts including suspension of projects, labour impact and job loss, time overrun, cost overrun, and financial implications. Furthermore, Karimi et al. (2022) identified the cancellation or delay of contracts and supply chain shortages as negative impacts of the pandemic. Similarly, Gammanage and Gunarathna (2022) revealed that, delays in project delivery, delays in material delivery, shortage of material, project suspension, reduction in workforce productivity, health and safety concerns, and regular price escalations as the key elements attributed to impact the project progress.

In addition, Ghandour (2020) revealed because of employee workforce reduction difficult to complete project deliverables within schedule. Hence, according to Parameswaran and Ranadewa (2022), impacts are divided into eight categories i.e. (i) resources-related issues, (ii) project management issues, (iii) quality issues, (iv) financial issues, (v) contractual issues, (vi) safety issues, (vii) technology-related issues, and (viii) other issues. Al-Mhdawi et al. (2023) demonstrated impacts including workforce-related issues, supply chain disruptions, and legal and contractual implications. Khalafallah et al. (2022) demonstrated impacts into categories of project finance, construction materials and equipment, labour, contracts, and rental properties. Figure 1 illustrates a summary of literature findings on challenges faced by the construction industry during the COVID-19 pandemic.

3.3 OPPORTUNITIES FROM THE COVID-19 PANDEMIC TO THE CONSTRUCTION INDUSTRY

The word ‘crisis’ in Chinese means both risk and opportunity (Tunji-Olayeni et al., 2019). According to Alsharef et al. (2021), the challenges COVID-19 pandemic provided numerous opportunities for the construction industry.

Similarly, Karimi et al. (2022) demonstrated that COVID-19 pandemic had a silver line for construction companies as forced to adopt new technologies, increase productivity rate, build more manufacturing and warehouses, create domestic job opportunities, and utilise more manufacturing technologies by applying 3D printing, modularisation, and prefabrication, buildings will have more open floor plans, increased ventilation, and active air purification systems. Furthermore, Parameswaran and Ranadewa (2022) demonstrated that the COVID-19 pandemic was both a disaster and an opportunity for Sri Lanka's construction sector. It created a platform for the sector to interact with the digital world, leading to innovative and diverse uses of technology. This technological integration may significantly change the direction of construction even after the pandemic subsides. Considering the above facts, Figure 1 illustrates a summary of literature findings on opportunities from the COVID-19 pandemic to the construction industry.

3.4 LESSONS LEARNED FROM COVID-19 PANDEMIC BY THE CONSTRUCTION INDUSTRY

All construction works are not office-base while the digitalisation of the world, professionals are expected to enhance innovative technology to improve productivity by using virtual working, adapting technology tools, workspace management, additional design considerations, planning with unforeseen circumstances including contingency plans, and the reduction of on-site work with prefabricated elements (Ogunnusi et al., 2020). Furthermore, Likitha et al. (2023) revealed that technology and digital solutions can help to recover firms from challenges including construction project management software used to resolve labour shortage issues through proper scheduling, low productivity rates, and safety issues.

Similarly, Karimi et al. (2022) demonstrated, that the adoption of new technologies helps to increase the productivity rate. In addition, a sense of urgency was imposed on construction professionals by the COVID-19 pandemic which established an effective requirement for the digitalisation and virtual execution of numerous industry processes and operations (Elrefaey et al., 2022). In addition to that, construction companies that used value engineering have effectively navigated the crisis's aftermath by coming up with alternatives to overcome obstacles that have minimally affected the progress of projects (Almuaybid et al., 2022). Furthermore, Bennett and Mayouf (2021) revealed that value management is primarily implemented as a cost-cutting solution, and key stakeholders need to be integrated. Furthermore, Abidi and Irshad (2020) recommended virtual and physical working of a mixed method as the best solution. Furthermore, Ogunnusi et al. (2020) recommended to reevaluating the option of strict office work to the possibility of 'Work From Home' (WFH). Figure 1 illustrates a summary of literature findings on lessons learned from the COVID-19 pandemic by the construction industry.

3.5 SIGNIFICANCE OF QS TO THE CONSTRUCTION INDUSTRY

The QS serves as a financial administrator for construction projects, responsible for estimating costs, material quantities, and project timelines. Coordinating with various teams working on the project is essential to this role and helps ensure that targets are met (Royal Institute of Chartered Surveyors [RICS], 2024). QS is a key stakeholder in construction because of its professional involvement in managing, planning, and delivering projects and because QS plays a crucial, primary, internal, and definitive function that impacts project success (Eyiah-Botwe et al., 2015). Moreover, Agha and Ogbonna (2022) demonstrated that QSs are construction economists who plan cost-effectiveness throughout the pre-construction to post-construction stages. Further, every phase of a construction lifecycle, including feasibility, design, construction, extension, refurbishment, maintenance, and demolition, is essentially performed by QSs (Olanrewaju & Anahve, 2015; Salleh et al., 2020).

In addition to that, quantity surveying is one profession that has seen unprecedented demand recently due to its expanding potential for service diversification and adaptability (Oladotun & Edosa, 2017). Furthermore, Abidin et al. (2014) identified that QSs have traditionally provided cost-estimating services but have recently expanded to offer more diversified services. According to AIQS (2005), QSs are now involved in estimating, cost planning, cost management, procurement management, contract administration, feasibility studies, asset financial management, and all activities related to the financial operations of a project. According to CIQS (2023), those tasks can be completed by QS employed by the contractor or by the client, and they can work from an office or on-site. According to Dada and Jagboro (2012), core competencies that QSs should have been; project management, contract administration, computer literacy, building engineering, information technology, economics, measurement/quantification and knowledge of civil/heavy engineering works and risk management. Furthermore, Chandramohan et al. (2022) highlighted skills including claim management, financial management, Building Information Modelling (BIM) coordination, carbon accounting and data management.

3.6 QUANTITY SURVEYING PRACTICES AND THE COVID-19 PANDEMIC

The practice of architecture, which primarily relies on networking, interaction, coordination, and site visits, was severely impacted by the COVID-19 pandemic (Abidi & Irshad, 2020). For instance, the reduction of direct supervision of project managers adversely affected the junior contractors' productivity and failed to complete the project deliverables because project managers rarely visited the site and worked from home (Ghandour, 2020). Furthermore, that caused changes in the working atmosphere in terms of the lack of a safe environment in the workplace, heavy workloads, home situations, and concerns about job stability often contribute to anxiety, depression, and even suicide (Pamidimukkala & Kermanshachi, 2021).

Similarly, the COVID-19 pandemic had an impact on professional quantity surveying practices including contractual arrangements regarding project time completion and suspension, project cost control, claim arrangement and negotiations, and project tendering (Hansen et al., 2021). Further, site visits for variation work valuation and interim payment valuation are the most affected quantity surveying practices due to the pandemic whereas consultative services such as value management and advisory services were the least affected (Tan & Zainon, 2022). Modiba and Harinarain (2024) highlighted those noteworthy impacts for QSs as alterations in work dynamics, modifications in site evaluations, increased instances of cost overruns, shifts in contract interpretation, and changes in the preparation of monthly payment certificates.

3.7 NECESSITY AND OPPORTUNITY TO UPGRADE QUANTITY SURVEYING PRACTICES

Present changes in projects due to the COVID-19 pandemic in the form of changes in organisation structure, work culture, technological application, and project objectives (Hansen et al., 2021). The quantity surveying profession is significantly changing in the construction industry and with the changes in construction practices, it is required to change the competencies of QS (Hassan et al., 2011). According to Abidi and Irshad (2020), professionals can upgrade by learning novel skills and techniques of working for future benefits, a new method of working will provide optimisation of resources while maintaining quality and recommended virtual and physical working of mixed methods as the best solution. Furthermore, with the digitalisation of the world, professionals are expected to embrace innovative technology to increase productivity while planning for the threats and opportunities provided by risk management is critical (Ogunnusi et al., 2020). Figure 1 illustrates a summary of literature findings on the necessity and opportunity to upgrade quantity surveying practices.

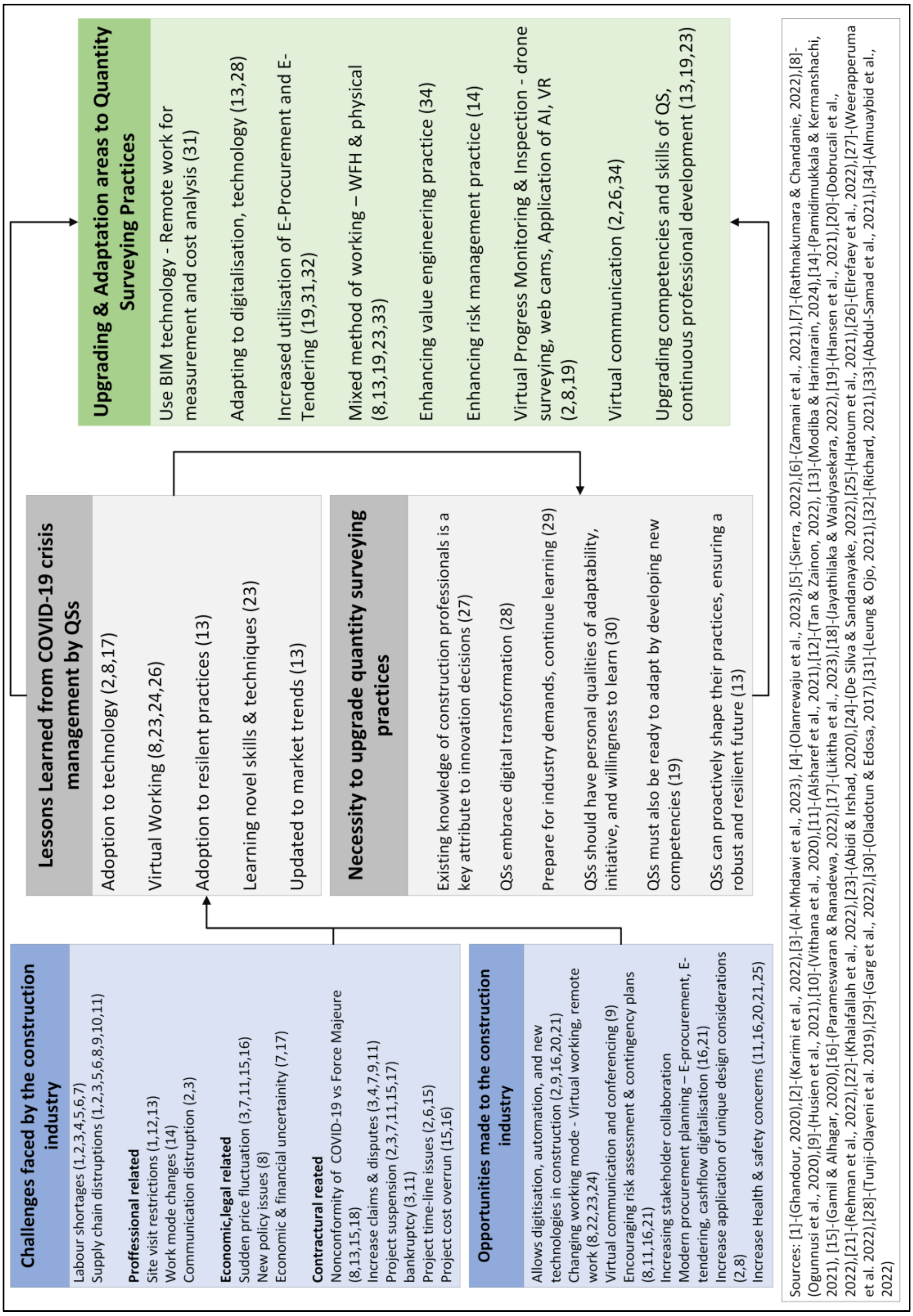


Figure 1: Summary of literature findings

In there, Weerapperuma et al. (2022) revealed that the existing knowledge of construction professionals is a key attribute to innovation decisions and attributes of relative advantage, compatibility, complexity, trialability and observability are affected by those innovative decisions. Hence, according to Tunji-Olayeni et al. (2019), QS needs to adopt Information and Communication Technology (ICT) to remain relevant in this digital age. Following the COVID-19 pandemic, prospective future professionals should be prepared to meet the demands of the construction industry while continuing their independent lifelong learning to achieve worldwide acceptability (Garg et al., 2022).

Furthermore, Adindu et al. (2020) concluded that, due to changes in the construction industry aimed at obtaining a competitive advantage, current and future quantity surveying practitioners must adopt proactive leadership roles. Quantity surveyors around the world must deliver advanced leadership in both traditional and multidisciplinary practices to stay competitive. Hence, QSs should possess personal qualities such as adaptability, initiative, and a willingness to learn. They should have core skills including the ability to present clear information within a group, self-management, critical analysis, and effective listening. Furthermore, QSs must be competent in process skills such as computer literacy, commercial awareness, prioritising, negotiating, acting morally and ethically, and coping with ambiguity and complexity (Oladotun & Edosa, 2017). Furthermore, QS is crucial for key stakeholders' resilience initiatives hence, in between all these unpredictable situations, quantity surveying professionals must also be ready to adapt by developing new competencies (Hansen et al., 2021). Furthermore, the COVID-19 pandemic has already changed the world, not only because of the pandemic itself but because of the long-term effects of the world's reaction to the pandemic (Harper et al., 2020). Hence, Modiba and Harinarain (2024) concluded that by understanding the challenges and adaptations brought about by the pandemic, QSs can proactively shape their practices, ensuring a robust and resilient future for the profession. QSs must stay updated with industry trends, market conditions, and regulatory changes. Adaptability to new circumstances is critical to resilience, and developing strong communication skills, especially when working remotely, is essential.

4. DISCUSSION

The COVID-19 pandemic has affected whole industries negatively worldwide and the construction industry is not exceptional. Consequently, the whole construction industry and its activities were severely affected such as project suspension, supply chain disruption, labour material equipment shortages, productivity declined, project cost and time overruns, and sudden changes in prices (Ogunnusi et al., 2020; Ghandour, 2020; Gamil & Alhagar, 2020; Gammanage & Gunarathna, 2022). Further, professional practices were also severely affected such as restriction on-site access, affected working modes, and traditional practices were not suitable to resist negative impacts. QS as a construction professional whose traditional practices were also severely affected COVID-19 pandemic including site visits, and progress monitoring while affection to those traditional practices, tends to increase practices of value management, risk management and BIM technologies. Additionally, changing their working mode from strict office environments to work-from-home, virtual meetings, and inspections is crucial due to new trends in the construction industry influenced by global technological advancements and opportunities arising from the COVID-19 pandemic. Hence, the COVID-19 pandemic-imposed opportunities on the modern world in addition to challenges.

Such as automation, digitalisation of construction, increased application, and adoption of new technologies of BIM, webcams, drones, modification of health and safety rules and practices, virtual working modes, virtual conferencing, and communication such as Zoom, MS-team platforms, enhancing additional risk management, value management and contingency plans. As a result, those modern practices, tend to change and adopt new professional practices from their traditional practices such as avoiding strict office work while optimising resources and quality of work. With the influence of the COVID-19 pandemic, there is an opportunity to upgrade quantity surveying practices with integration into traditional quantity surveying practices and construction professionals must adopt new trends to increase productivity of construction activities. Hence, the COVID-19 pandemic offered the necessity to upgrade quantity surveying practices for future use and the need to redefine quantity surveying practices significantly.

5. CONCLUSIONS

Accordingly, the literature analysis first discussed challenges and opportunities faced by the construction industry during the COVID-19 pandemic. Then, the discussion pointed to lessons learned from the COVID-19 pandemic by the construction industry. Further, how the COVID-19 pandemic affects quantity surveying practices was discussed. Finally, the necessity and opportunity to upgrade quantity surveying practices were highlighted based on lessons learned from the COVID-19 pandemic. This study contributes to the knowledge in terms of the upgrade quantity surveying practices. Further, the following key contributions to knowledge are made through this research study.

- A detailed literature review on the challenges and opportunities faced by the construction industry during the COVID-19 pandemic was presented by referring to previous research studies in a particular area.
- Since there was no detailed discussion on lessons learned from the COVID-19 pandemic by the construction industry as well as the necessity and opportunity to upgrade quantity surveying practices, the findings of this study contribute to knowledge in that area.

The outcome of the research would be beneficial for industry practitioners to upgrade quantity surveying practices was highlighted based on lessons learned from COVID-19 pandemic. Considering that important outcome, the following recommendations can be made.

- As it was highlighted, prior concern should be given to upgrade quantity surveying practices. Therefore, industry practitioners are encouraged to give more prominence to identify the necessity and opportunity of upgrading their practices.
- This study provides a preliminary analysis of literature focusing on upgrading quantity surveying practices based on lessons learned from COVID-19 pandemic necessity and opportunity globally. The next step in this study would be to conduct a detailed survey on how to practically upgrade quantity surveying practice.

6. REFERENCES

Abidi, M. Z., & Irshad, Q. (2020). Impact of COVID-19 on architecture profession. *An International Bilingual Peer Reviewed Refereed Research Journal*, *10*(39), 214–223. Retrieved from https://www.researchgate.net/publication/347653395

Abidin, N. Z., Adros, A., & Hassan, H. (2014). Competitive strategy and performance of quantity surveying firms in Malaysia. *Journal of Construction in Developing Countries*, *19*(2), 15–32. Retrieved from https://api.semanticscholar.org/CorpusID:167681042.

Adindu, C. C., Obiekwe Ajator, U., Agu, N. N., Okorie, V. N., & Yusuf, S. O. (2020). Enriching quantity surveying curriculum for leadership in the built environment. *Proceedings of the 5th research conference of the NIQS*, 315–331. Retrieved from https://www.researchgate.net/publication/348192924_ENRICHING_QUANTITY_SURVEYING_CURRICULUM_FOR_LEADERSHIP_IN_THE_BUILT_ENVIRONMENT.

Agha, K. A., & Ogbonna, N. J. (2022). Assessment of quantity surveyor's perception on risk management practice in construction projects in Ebonyi state. *World Journal of Advanced Research and Reviews*, *16*(3), 433–445. https://doi.org/10.30574/wjarr.2022.16.3.1324

Al-Mhdawi, M. K. S., Brito, M., Onggo, B. S., Qazi, A., & O'Connor, A. (2023). COVID-19 emerging risk assessment for the construction indus try of developing countries: Evidence from Iraq. *International Journal of Construction Management*. 24(7), 693–706. https://doi.org/10.1080/15623599.2023.2169301.

Almuaybid, A., Abdulghafour, A., Al-Muaybid, A. I., & Mlybari, E. A. (2022). Value engineering role in construction sustainability during covid-19 pandemic in KSA. *Article in Indian Journal of Science and Technology*, *15*(12), 518–526. https://doi.org/10.17485/IJST/v15i12.2293.

Alsharef, A., Banerjee, S., Uddin, S. M. J., Albert, A., & Jaselskis, E. (2021). Early impacts of the covid-19 pandemic on the United States construction industry. *International Journal of Environmental Research and Public Health*, *18*(4), 1–21. https://doi.org/10.3390/ijerph18041559.

Bennett, K., & Mayouf, M. (2021). Value management integration for whole life cycle: Post covid-19 strategy for the UK construction industry. *Sustainability (Switzerland)*, *13*(16). https://doi.org/10.3390/su13169274.

Chandramohan, A., Perera, B. A. K. S., & Dewagoda, K. G. (2022). Diversification of professional quantity surveyors' roles in the construction industry: The skills and competencies required. *International Journal of Construction Management*, *22*(7), 1374–1381. https://doi.org/10.1080/15623599.2020.1720058

Dada, J. O., & Jagboro, G. O. (2012). Core skills requirement and competencies expected of quantity surveyors: Perspectives from quantity surveyors, allied professionals and clients in Nigeria. *Australasian Journal of Construction Economics and Building*, *12*(4). Retrieved from https://www.researchgate.net/publication/287513326_Core_skills_requirement_and_competencies_expected_of_quantity_surveyors_Perspectives_from_quantity_surveyors_allied_professionals_and_clients_in_Nigeria

Elrefaey, O., Ahmed, S., Ahmad, I., & El-sayegh, S. (2022). Impacts of COVID-19 on the use of digital technology in construction projects in the UAE. *Buildings*, *12*(4). https://doi.org/10.3390/buildings12040489

Eyiah-Botwe, E., Aigbavboa, C., & Thwala, W. (2015). Managing construction stakeholders' for effective project delivery: A case of consultant quantity surveyors. In *Journal of Construction Project Management and Innovation*, *5*(2). 1296-1309. https://doi.org/10.36615/jcpmi.v5i2.92.

Fadhil, G. A., & Burhan, A. M. (2021). Investigating the effects of economic crisis on construction projects in Iraq. *E3S web of conferences*, *318*. https://doi.org/10.1051/e3sconf/202131802005.

Gamil, Y., & Alhagar, A. (2020). The impact of pandemic crisis on the survival of construction industry: A case of COVID-19. *Mediterranean Journal of Social Sciences*, *11*(4), 122. https://doi.org/10.36941/mjss-2020-0047.

Gammanage, S. H., & Gunarathna, N. (2022). Delays and disruptions in the construction industry during the global pandemic. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 10th World Construction Symposium* (pp. 326–338). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2022.27.

Garg, R., Sharma, A. K., & Kamal, M. A. (2022). Restructuring architectural education post COVID-19: Professional practice and construction industry expectations. *Architecture and Engineering*, *7*(2), 29–41. https://doi.org/10.23968/2500-0055-2022-7-2-29-41.

Ghandour, A. (2020). The impact of COVID-19 on project delivery: a perspective from the construction sector in the United Arab Emirates. *Humanities & Social Sciences Reviews*, *8*(5), 169–177. https://doi.org/10.18510/hssr.2020.8516.

Hansen, S., Rostiyanti, S. F., Rizaldi, R., & Andjarwati, C. (2021). Quantity surveyors' response to the COVID-19 outbreak: A mixed method approach. *Journal of the Civil Engineering Forum*, *7*(2), 177. https://doi.org/10.22146/jcef.60715.

Harper, L., Kalfa, N., Beckers, G. M. A., Kaefer, M., Nieuwhof-Leppink, A. J., Fossum, M., Herbst, K. W., & Bagli, D. (2020). The impact of COVID-19 on research. *Journal of Pediatric Urology*, *16*(5), 715–716. https://doi.org/10.1016/j.jpurol.2020.07.002

Hassan, F., Ismail, Z., Zaini, A. A., Hassan, S., & Maisham, M. (2011). An evaluation of the competencies, skills and knowledge of quantity surveying graduates in consultant quantity surveying firms in Malaysia. *2011 IEEE Colloquium on Humanities, Science and Engineering Research (CHUSER 2011)*, 228–232. https://doi.org/10.1109/CHUSER.2011.6163722

Hatoum, M. B., Faisal, A., Nassereddine, H., & Sarvari, H. (2021). Analysis of COVID-19 concerns raised by the construction workforce and development of mitigation practices. *Frontiers in Built Environment*, *7*. https://doi.org/10.3389/fbuil.2021.688495.

Husien, I. A., Borisovich, Z., & Naji, A. A. (2021). COVID-19: Key global impacts on the construction industry and proposed coping strategies. *E3S Web Of Conferences*, *263*. https://doi.org/10.1051/e3sconf/202126305056.

Iqbal, M., Ahmad, N., Waqas, M., & Abrar, M. (2021). COVID-19 pandemic and construction industry: Impacts, emerging construction safety practices, and proposed crisis management framework. *Brazilian Journal of Operations and Production Management*, *18*(2). https://doi.org/10.14488/BJOPM.2021.034.

Karimi, B., Yazdanpour, M., & Foley, S. (2022, August). COVID-19 effects on construction industry. 2022 ASEE Annual Conference & Exposition, Minneapolis, MN. 10.18260/1-2—41347.

Khalafallah, A., Soliman, E., & Alrasheed, K. (2022). Impacts of COVID-19 on the middle east construction industry. *Journal of Engineering Research (Kuwait)*, *10*(3), 34–58. https://doi.org/10.36909/jer.14823.

Likitha, K. N., Kundhena, S., Gurudev, S. C., Nischith, G. D., & Rajasekaran, C. (2023). Impact of pandemic crisis of COVID-19 on construction industry in India. *Sustainability, Agri, Food and Environmental Research*, *12*(1). https://doi.org/10.7770/safer-V12N1-art2784.

Mhaske, A., & Khandekar, S. D. (2016). Factors affecting crisis management in construction project. *International Research Journal of Engineering and Technology*, *3*(7). Retrieved from https://www.irjet.net/archives/V3/i7/IRJET-V3I7267.pdf.

Modiba, M., & Harinarain, N. (2024). Building resilience: quantity surveyors in the face of future pandemics. *Journal of Construction Project Management and Innovation*, *14*(1), 1–12. https://doi.org/10.36615/jcpmi.v14i1.2964.

Ogunnusi, M., Hamma-adama, M., Kouider, T., & Salman, H. (2020). COVID-19 pandemic: The effects and prospects in the construction industry. *International Journal of Real Estate Studies*, *14*(2). Retrieved from https://www.researchgate.net/publication/346411838.

Oladotun, A. J., & Edosa, O. M. (2017). The need for professionalism and competencies in the construction industry. *International Journal of Built Environment and Sustainability*, *4*(1). https://doi.org/10.11113/ijbes.v4.n1.154.

Olanrewaju, A., & Anahve, P. J. (2015). Duties and responsibilities of quantity surveyors in the procurement of building services engineering. *Procedia Engineering*, *123*, 352–360. https://doi.org/10.1016/j.proeng.2015.10.046.

Pamidimukkala, A., & Kermanshachi, S. (2021). Impact of COVID-19 on field and office workforce in construction industry. *Project Leadership and Society*, *2*. https://doi.org/10.1016/j.plas.2021.100018.

Parameswaran, A., & Ranadewa, K. A. T. O. (2022). Construction industry on the brink: The COVID-19 impact. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 10th world construction symposium* (pp. 220–235). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2022.19.

Rokooei, S., Alvanchi, A., Shojaei, A., & Ford, G. (2023). Developing an impact model in construction companies during pandemics. *Journal of Engineering, Project, and Production Management*, *13*(2), 159–169. https://doi.org/10.32738/JEPPM-2023-0016.

Royal Institute of charted Surveyors [RICS]. (2024). *Quantity surveying: Your guide to becoming a quantity surveyor*. Royal Institute of Charted Surveyors. https://www.rics.org/surveyor-careers/surveying/what-surveyors-do/what-is-a-quantity-surveyor

Salleh, N. M., Husien, E., Husin, S. N., Muhammad, N. H., & Alang, N. (2020). Quantity surveyors' roles and responsibilities in different job sectors. *International Journal of Academic Research in Business and Social Sciences*, *10*(10). https://doi.org/10.6007/ijarbss/v10-i10/8271.

Saunders, M., Lewis, P., & Thornhill, A. (2019). Research methods for business students (8th ed.). Pearson Education Limited. Retrieved from http://localhost:8080/xmlui/handle/123456789/490.

Sfakianaki, E., Iliadis, T., & Zafeiris, E. (2015). Crisis management under an economic recession in construction: The Greek case. *International Journal Management and Decision Making*, *14*(4), 373–389. doi:10.1504/IJMDM.2015.074015.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Srinivasan, N. P., & Nandhini, N. (2015). A study on crisis management in construction projects. *International Journal of Innovative Research in Science, Engineering and Technology*, *4*(10). Retrieved from https://www.researchgate.net/publication/342097585_A_Study_on_Crisis_Management_in_Construction_Projects.

Tan, S. Y., & Zainon, N. (2022). Impact of COVID-19 pandemic on the quantity surveying practices in Malaysia. *Engineering Construction & Architectural Management*, *30*(4). https://doi.org/10.1108/ECAM-11-2021-0988.

Tunji-Olayeni, P. F., Oyeyipo, O. O., & Nnadi, E. E. (2019). Prospects of quantity surveyors in a dynamic world of climate change, digitalization and economic recession. *IOP conference series: materials science and engineering*, *640*(1). https://doi.org/10.1088/1757-899X/640/1/012130

Weerapperuma, U., Jayasena, S., Rathnasinghe, A., & Thurairajah, N. (2022). The impact of professionals' knowledge on innovation adoption in the construction industry: A critical literature review. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 10th world construction Symposium* (pp. 896–908). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2022.72.

Zheng, L., Chen, K., & Ma, L. (2021). Knowledge, attitudes, and practices toward COVID-19 among construction industry practitioners in China. *Frontiers in Public Health*, *8*(599769). https://doi.org/10.3389/fpubh.2020.599769.

Maddakandage, M.N.U. and Sridarran, P., 2024. The need for a climate database for facilities managers to mitigate the climate change implications on buildings. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1050-1063. DOI: https://doi.org/10.31705/WCS.2024.83. Available from: https://ciobwcs.com/papers/

THE NEED FOR A CLIMATE DATABASE FOR FACILITIES MANAGERS TO MITIGATE THE CLIMATE CHANGE IMPLICATIONS ON BUILDINGS

M.N.U. Maddakandage[1] and P. Sridarran[2]

ABSTRACT

This study focuses on climate change impacts on built-environment categories, including buildings, built infrastructure, and land use. A facility manager is a key person who oversees the built-environment and faces challenges in recognising climate impacts and preparing mitigation strategies to ensure the organisation's operations continue. Climate change directly and significantly affects facilities management. Thus, in climate change mitigation data-driven decision-making in facility management is important. Climate data, such as temperature, precipitation, humidity, wind speed, solar gain, and CO_2 level are already used in the decision-making in facilities management. However, there is less availability and complex accessibility of the existing climate data sources for non-climate expert users such as facility managers. In order to address this gap this paper aims to assess the need for a climate database for facilities managers to mitigate climate change implications on buildings. This study adopts a qualitative expert survey approach to data collection. Eight semi-structured interviews were conducted with industrial experts and their knowledge and experience on climate change were analysed. Facility managers and built-environment experts expressed that there are many available climate data sources that facility managers are not aware of. However, it is difficult to use available climate data for decision-making due to limited knowledge of climate science and the payments and permissions involved. Further, experts highlighted the need for a climate database with freely available recent years' climate data, visualisation tools for using climate data to make informed decisions and a user-friendly interface for non-expert users.

Keywords: *Built Environment; Climate Change; Climate Data; Climate Database; Facilities Management.*

1. INTRODUCTION

The global climate is changing more rapidly and it is expected to be continued in the future due to changes in mean values for temperature, precipitation, humidity, solar radiation, wind, and also by man-made greenhouse gas emissions (Lacasse et al., 2020). Sri Lanka is also facing climate consequences which has an effect on identified key areas including agriculture, water resources, coastal and marine sector, health, human

---

[1]Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, nadeeraumayangani@gmail.com

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

settlement and infrastructure, ecosystem and biodiversity, tourism, energy and transportation (Senevirathna, 2016).

Built Environment sector is also impacted by climate changes in different ways such as increase in cooling loads, premature degradation of building elements and moisture related issues of building elements (Lacasse et al., 2020). In built environment sector Facilities Management (FM) encompasses multiple disciplines including building services, energy management, water conservation, handling building management system and occupational health and safety (Pilanawithana & Sandanayake, 2017). According to Warren (2010) facilities managers must assess climate change risks and develop Business Continuity Management strategies to adapt to climate-driven disasters. Climate data are used for decision making in different FM aspects. In Sri Lanka, the meteorological stations provide climate data. However, there are limitations of using those climate data for different studies such as errors from instruments, measurements, data collectors and incomplete data sets (Chathuranika et al., 2022). Therefore, there is a need of a system for obtaining reliable long-term climate variables (Lacasse et al., 2020). Even though, Integrated Surface Database (ISD) free, it is not enough to create weather files for analysing. Weather files such as Energy Plus have no proper standards (Rao & Rastogi, 2020). Even though, the NASA Earth observations data is a freely available database, the usability is complicate and systematic (Yang et al., 2019) and it highlights the different consequences of accessing existing climate databases for decision making.

Perera and Emmanuel (2018) have identified that lack of data of local climate effects is a key difficulty in applying climate knowledge to decision making of urban planning. To initiate flood risk reduction measures, there is a lack of available historical flood records (Alahacoon et al., 2018). Boverkert climate declaration of Sweden has been introduced an open climate database for the construction phase of buildings (Sadri et al., 2022). Climate change data in Sri Lanka have been used to create a disaster database to draw policy makers' attention towards climate related adaptation (Weerasekara et al., 2021). This study is focused on need of climate database for facilities management applications. The objectives of the paper are: (1) to identify climate change impacts of different facilities management functions, and (2) to identify climate database requirements to mitigate the identified climate change impacts.

2. LITERATURE REVIEW

Different parts of the world are affected by climate change, disasters and challenges posed by climate changes, increasingly (Alam et al., 2023). Climate change has effects on socio-economic factors and other factors such as agriculture, health, rise of sea level and labour scarcity (Thathsarani & Gunaratne, 2018). In addition, climate change creates a variety of risks that affect the built environment, human and social capital (Alam et al., 2023). Sri Lanka is not an exception from the climate change challenges. Cevik et al.(2022) revealed that developing countries including Sri Lanka have significant effects from climate change as they have lesser capacity to adapt to and mitigate climate change. Disasters like floods and earth slips affect people's ability to adapt and their means of livelihood in Sri Lanka (Thathsarani & Gunaratne, 2018). Thus, Sri Lanka is a particularly suitable scenario to be used to evaluate the impacts induced by climate change (Weerasekara et al., 2021). In addition, high rise buildings are introduced to the tropical climate developing nations including Sri Lanka without considering climate sensitivity. This results to unfavourable outcomes to both human and environment (Amarathunga &

Rajapaksha, 2016). The built environment is created to protect, coordinate or change the environment in ways to promote human needs, desires and standards (Wang et al., 2019). Considering different built environment classifications of scholars, this study will continue by adapting to buildings, built infrastructure and land use categories (Joensuu et al., 2020; Lynch & Mosbah, 2017) .

2.1 CLIMATE CHANGE IMPACT ON BUILT ENVIRONMENT

Housing units those lacking proper ventilation are more vulnerable to climate change as they can overheat due to increased temperature (Rañeses et al., 2021). Climate change has an impact on the amount of energy usage in buildings (Jiang et al., 2019). According to United States Agency International Development (USAID) temperature changes in buildings cause health issues, impacting building systems and maintenance. Barrelas et al. (2021) declared that climate events such as landslides will cause to rise in building maintenance costs.

Climate change induced catastrophes have severely damaged infrastructure, including transportation, water, sanitation, and energy systems. Floods cause adverse impacts on land degradation, communication, roads and other infrastructure. Heat waves, hurricanes, and floods can be brought on by climate change can harm or disrupt information systems infrastructure (USAID, 2012a). Bektas and Sakarya (2023) expressed the flood volume in China is significantly impacts the efficiency of urban drainage system as evidenced by urban expansion.

Chathuranika et al. (2022) have studied the impact on hydrological aspects of climate change in consideration of soil and water. Climate change negatively impacts drinking water bodies (Vijayavenkataraman et al., 2012). The alterations of precipitation patterns lead to decrease soil's filtration capacity, porosity and change soil moisture content (Bektaş & Sakarya, 2023). The primary economic activity in Sri Lanka is agriculture and the annually affected croplands by floods is an average of 268 km^2 (Alahacoon et al., 2018). Perera and Emmanuel (2018) highlight the need for climate-sensitive urban planning in Colombo, as the increasing number of mid-rise and high-rise blocks along traffic arteries increases Urban Heat Island.

2.2 CLIMATE CHANGE IMPACT ON FACILITIES MANAGEMENT FUNCTIONS

Facilities managers have challenges in recognising the climate change impacts on the built assets and developing strategies (Jones et al., 2013). Meantime, they have to consider the physical injury and economic losses associated with natural disasters induced by climate changes. Thus, organisations focus on information technology resources to ensure data security in their business continuity plans (Warren, 2010). The following sections discuss the impact of climate change on key FM functions.

2.2.1 Climate Change Implications on Building Maintenance

Climate change may directly affect the deterioration of building equipment and components and affect their maintenance requirements and costs (D'Orazio et al., 2022). In changing climate context, maintenance planning needs to be improved. Lack of maintenance during the service life is also caused to the faults in building façade. Therefore, it is vital to take climate loads into account at every building stage (Barrelas et al., 2021). Bastidas-Arteaga et al.(2022) revealed that the corrosion of reinforced concrete structure will start faster due to the climate change.

2.2.2 Climate Change Impact on Energy Management

Climatic conditions are recognised to have an effect on building's energy efficiency (Najjar et al., 2019). Further, climate-sensitive planning is capable enough to achieve significant energy saving (Aghamolaei et al., 2022). Zhu et al.(2019) stated that energy consumption patterns in commercial buildings are influenced by summertime temperature differences causing a shift in demand. Energy demand for heating is getting decreases and demand for the cooling is getting increased (Fabbri et al., 2020). The best designs should take climate change into account. Ignoring the effects of climate change could result in serious energy disruptions.

2.2.3 Climate Change Impact on Occupational Health and Safety

In Sri Lanka, dengue, disabilities due to landslides and floods, and diseases due to air pollution are identified. Heat-related morbidity and mortality among construction workers are significant among them (Gandhi Marg, 2017). In Ethiopia, the spreading pattern of water and vector-borne diseases are changing due to rising temperatures and shifting rainfall patterns. Recent COVID-19 outbreaks show significant winter seasonality between December and April (Sajadi et al., 2020). Furthermore, USAID (2012b) identified that rising of building interior temperature can lead to heat stress, health problems and reduction of building occupant productivity.

2.2.4 Climate Change Impact on Building Performance

The climate change predications should allow to evaluate the building envelope performance and to design the buildings (Gaur et al., 2019). Building design, envelope, and climate classification all have an impact on performance factors in construction (Najjar et al., 2019). Building performance is influenced by heat transmission, thermal mass, solar heat gain through windows (Fabbri et al., 2020). It is difficult to measure the impact on thermal comfort due to climate conditions as it is subjective from person to person (Soutullo et al., 2020). According to Brown et al. (2022) assets degradation predictions and service life are influenced by climate zones and climate variables.

2.2.5 Climate Change Impact on Disaster Management

Low-income countries are more vulnerable to climate induced disasters than developed countries (Weerasekara et al., 2021). While resilience reduces the cost of government borrowing, climate change vulnerability has a major impact on government bond rates and spreads (Cevik & Jalles, 2022). The metropolitan near of Kelani River, Colombo is prone to regular floods because of the high rainfall and humid climate. Also, with higher positive values of frequency of droughts, households are affected (Thathsarani & Gunaratne, 2018).

2.3 IMPORTANCE OF CLIMATE DATA FOR MITIGATING CLIMATE CHANGE IMPACT ON BUILT ENVIRONMENT

Organisations strive to enhance the quality of climate data for decision making processes and used to derive climate indicators to address issues linked to climate system and humans (Camarillo-Naranjo et al., 2019). Climate data is essential for risk assessment, seasonal prediction, and the design of buildings and accurate sizing of the building systems (Rao & Rastogi, 2020). According to Brown et al. (2022) when selecting assets facility managers need to consider the manufacturers who can provide the best asset performance for the climate zone of assets going to operate. As Sri Lanka is identified as a country with a high degree of climate preparedness vulnerability, it is recommended that national climate monitoring and warning systems be strengthened (Escap, 2016).

2.4 CLIMATE DATA REQUIRED FOR FACILITIES MANAGEMENT FUNCTIONS

By considering the importance of data-driven decision making and the requirement of reliable data, facilities managers are advised to maintain a sufficient data management system (Assaf & Srour, 2021). In data-driven energy load profiling, building automation systems and smart meters are in use to track the exterior temperature and humidity (Zhu et al., 2019). Najjar et al. (2019) claimed that solar radiation, humidity, temperature, heat, precipitation, GHG emissions, are all climate data characteristics that are related to energy consumption. The climate variables including sunlight, humidity and temperature was examined to assist the facility managers in selecting the climate-responsive asset manufacture (Brown et al., 2022). In order to operate and maintenance planning of building systems, NASA time series data such as temperature, humidity, precipitation are utilised (Stackhouse et al., 2023). In addition, climate data including CO_2 concentration, humidity, temperature, cloud cover and aerosol are used to study the effects on building materials (Lacasse et al., 2020). Foreman et al.(2023) listed out safety indicators includes temperature and wind speed average. Further, heat indices such as Humidex are defined using air temperature and vapor pressure. In flood detection systems, sensors are using for measure water level along with water speed, temperature and humidity (Hsu et al., 2020). Amarathunga and Rajapaksha (2016) investigated the micro-climatic behaviour and thermal environment in different levels of a high rise building by measuring air temperature, relative humidity, natural lightning levels and wind velocity data.

2.5 CLIMATE DATABASE AVAILABILITY AND ACCESSIBILITY ISSUES

Despite advancements in Earth Observations and Internet of Things technologies, converting collected data into insights remains challenging due to the complexity of evaluating climate change (Hsu et al., 2020). Weerasekara et al. (2021) attempted to create a specific disaster database using data collected from the Meteorological Department of Sri Lanka. Climate Change Knowledge Portal (CCKP) is a hub created by the World Bank and it provides trends of temperature variations and rainfall variations (Hettiarachchi et al., 2019). Most climate databases are available to the expert users under open-licenses and complex due to technical file formats. Integrated Surface Database (2018) provides online search access and it is composed of location-based surface observational data. Energy analysts use weather files such as IMF (Input Macro Files), DDY (Design Day Files) and EPW (EnergyPlus Weather File) for simulation purposes. These files contain statical values such as thermal comfort index, relative humidity, wind speed, and solar radiation (Rao & Rastogi, 2020). Apart from that, Sea level, seismic, and deep ocean sensor data are evaluated by the Regional Integrated Multi-Hazard Early Warning System (RIMES) for Africa and Asia. A central climate data database with a standard model ensures consistency, reduces costs, and is crucial for analyses, reducing the need for costly web infrastructure (Rao & Rastogi, 2020). However, as climate database management is limited to the expert users, it is vital to release easily accessible tools for non-expert users (Camarillo-Naranjo et al., 2019). Climate databases require for study purposes in various spatial scales such as district, region or country wise (Bastidas-Arteaga et al., 2022).

3. METHODOLOGY

A comprehensive literature review was conducted to identify the climate change impact on the built environment and FM functions, climate data requirement for the FM functions and about climate data availability and accessibility. An expert survey was conducted to gather data from facilities management and built environment related professionals who were having vast knowledge and expertise in built-environment, sustainability, energy management and climate science aspects. Eight experts with over 7 years of experience, including those conducting research and practical work related to climate change impacts, provided their valuable insights to this research. The profiles of the experts are listed in Table 1.

Table 1: Profile of experts

Expert	Designation	Overall experience
E1	Facilities Engineer	09 years
E2	Energy Manager	11 years
E3	Senior Facilities Manager	12 years
E4	Sustainable design engineer	11 years
E5	Assistant Facilities manager	08 years
E6	River and Tsunami Simulation Engineer	07 years
E7	Programme coordinator	15 years
E8	Senior Facilities Manager	13 years

Semi-structured interviews were conducted as primary data collection which is a part of qualitative approach and it allows to explore participant knowledge in flexible manner. In climate researches expert interviews will address the uncertainty and enhance the relevance of climate data in decision making (Dessai et al., 2018). In order to analyse expert survey data, thematic analysis was selected. Pre-established themes, categories and codes are created based on the literature survey.

4. DATA ANALYSIS AND RESEARCH FINDINGS

4.1 IDENTIFY CLIMATE DATABASE REQUIREMENTS TO MITIGATE THE IDENTIFIED CLIMATE CHANGE IMPACTS ON BUILDINGS

The study analysed the awareness of facility managers and building professionals about climate change impacts, finding a medium level of understanding among these professionals about the impacts of climate change on buildings. E2 stated that, "*there is a medium concern, everything was focused or driven by the market itself. they requested the facilities designed to be very sustainable*". Similarly, E5 mentioned that there is definitely have more focused on climate change and all sustainability initiatives. According to E4 "*there's awareness among most of the professionals within the industry at the moment, because it's like hot topic at the moment*". On the other hand, E8 highlighted that "*but it's questionable, how practically they are working towards to mitigate climate change impacts in their day-to-day jobs".* E1 stated the awareness of Sri Lankan FM sector is low because there is no observed season effect in Sri Lanka. However, it was noted that there is a potential for climate change. However, E7 believed that, "*particularly the development planning and construction professionals not adequately consider the factors contribute for climate change and the impacts*."

4.1.1 Experience in Climate Change Impacts on Built Environment

Built environment professionals and FM experts have experienced direct and indirect impacts on their building facilities, built-infrastructures and lands. All experts agreed that there is a high energy consumption in buildings due to climate change impacts. In terms of overheating and high energy usage, E1 stated that "*it's a positive relationship. High heat means its energy consumption is high*". E2 further explained that "*I was involved in some energy audits and noticed that there's a huge impact on HVAC*". Regarding the health issues, E2 explained "*increased extreme heat events over the past few years, there has been several, and caused even deaths in vulnerable persons*". E2 claimed that, there is a huge mould growth impact for wood products in buildings. In addition to that, E3 highlighted that, due to increase of storm water volume there can be floods and maintenance teams have to manage unexpected situations. E8 pointed out about the soil cracks and the foundation damages due to low rains depends upon the region of the country. E1 highlighted that, "*the waterproofing tightness is required, otherwise it will reduce the lifetime of the material*." According to E4, the maintenance frequency of the HVAC systems is increased due to climate changes.

Regarding the built infrastructure, experts mentioned the climate impacts on urban drainage systems, transportation, water supply systems, electricity and information and communication systems. E6 stated that, "*urban planners must be addressed the future expected changes of rainfall intensity when designing drainage systems".* According to E1, "*Sri Lankan electricity generation mainly based on water sources, in March mostly vulnerable for power failures."* In terms of information and communication systems E1 also stated, "*I managed a data centre, in the April, high thundering is very much critical. Once, we had a loss due to electrical surge come through the telephone lines and it affects some servers."* Further, E3 stated there is an increase of the insurance premium and that cause increase the operational costs. In terms of land use, E7 stated that, "*erosion and sedimentation is a huge impact due to high rain flow*. According to E4, overflooding impacts on water wells and creates other sanitary problems. E5 stated that, *"there can be heat islands in adjacent roads and land surfaces, and can be impacted on temperature rises in the buildings*".

4.1.2 Climate Change Impact on Facilities Management Functions

Almost all the professionals mentioned there is a climate impact on energy management. E7 stated that, "*there is huge requirement of selecting appropriate electrical devices which must be energy efficient*." E3 expressed that there is a risk of reducing the life span of the assets and increasing the maintenance frequency. E7 stated that, "*as disasters impacts have increased due to climate change, there is need for more actions on disaster preparedness and climate resilient development*." Additionally, E2 highlighted that "*facility managers would involve in design stage of buildings so that they can request the designing engineers to consider future climate events and climate data*." Further, E7 mentioned there is an impact on development projects and fails due to climate changes.

4.1.3 Climate Data Requirement in Facilities Management Functions

Almost all the experts mentioned the use of climate data for decision making process in their relevant fields. According to E2 "*we develop protocols for extreme heat and cold events considering climate data".* E3 stated that facilities managers have to use climate data for risk mitigation. E6 mentioned that, "*I used climate data for flood modelling in Kelani River basin for disaster management*. "Further, E4 mentioned, "*we're using* *climate data to energy modelling and analyse the building performance*". According to E5, climate data would require to identify monsoon seasons and have to clean their gullies and roofs before it starts. E2 further explained that, short term weather data are used to train the building automation system. In construction stage, they have to adjust the working schedule if it is expected to have high rains. Majority of experts definitely agreed on climate data usage is an essential requirement to mitigate climate change implications on buildings. According to E4 "*we can use climate data to model certain scenarios and see how these changes or measures are going to reduce the climate change impact*." However, according to E5 opinion, even though the climate data are required, climate data monitoring is not a function of FM.

When considering the climate data types used in decision making, experts are using temperature as measure to design HVAC systems and use in maintaining thermal comfort. E1 stated that humidity is a measure that they almost checking due to water condensation of HVAC systems. Regarding precipitation data, E4 stated that, "*we are doing rainwater harvesting system sizing or calculations using the precipitation data*". E2 pointed out that wind speed data require to passive cooling of buildings and structural considerations. According to E8, "*solar radiation is used in specially for the installation of tilt mounted of roof surfaces, which facing to north-east directions*". E1 stated that solar gain data was used to tinted glass applications. In terms of CO_2 constraints E3 expressed that there is a standard to maintain CO_2 level below 800 ppm. Few of the experts are using cloud cover, land use and water level data. Table 2 presents the need of climate data in FM.

Table 2: Need of climate data in facilities management

Experts		E1	E2	E3	E4	E5	E6	E7	E8
Climate data usage									
Use of decision making in FM /built-environment sectors		✓	✓	✓	✓	✓	✓	✓	✓
Essentially use of mitigating climate change impacts on built environment		✓	✓	✓	✓	✓	✓	✓	✓
Types of climate data in use									
i.	Temperature	✓	✓	✓	✓	✓	✓	✓	✓
ii.	Precipitation	✓	✓	-	✓	✓	✓	✓	-
iii.	Humidity	✓	✓	✓	-	✓	✓	✓	✓
iv.	Wind speed	-	✓	-	✓	-	✓	✓	✓
v.	Solar radiation	✓	✓	-	✓	-	-	-	✓
vi.	Co2 emissions	✓	✓	✓	-	-	-	-	✓
vii.	Vapor pressure	-	-	-	-	-	-	-	-
viii.	Water level	-	✓	-	-	-	✓	✓	-
ix.	Cloud Cover	-	✓	-	✓	-	-	-	-
x.	Land use	-	-	-	-	-	✓	✓	✓

4.1.4 Assess Climate Data Sources

The climate data sources were assessed based on easy accessibility, high availability, convenience for non-expert usage, and difficulties faced. Majority of the experts are using climate data issued by Department of Meteorology, Sri Lanka. Further, few of them are relied on commercial data bases like AccuWeather and Weather Underground. Only few of the experts are using Climate change knowledge portal and Energy Plus weather data. Rather than the mentioned climate data sources, experts have used different other sources specifically for their usage. E2 explained that, "*in Sri Lanka, we've used Typical Meteorological Year data and I've used a software called eQuest to model energy and, we used a software called Red Screen, it takes climate data from NASA directly*". E4 have used National Oceanic and Atmospheric Administration database to obtain wind data. E6 has used Global Circulation and Regional Climate Model for retrieve climate data for the disaster management. Majority of experts have used in-situ climate data measures and E3 explained that, "*we have use sensors in to maintain temperature, Indoor Air Quality measurements and take spot measurements of Relative Humidity."*

Majority of experts mentioned that there is a high availability or moderate availability of existing climate databases and these climate databases are not convenient to use for non-expert users such as facilities mangers. Further, experts have suggested to use climate data for the areas including water proofing, chiller upgrades, risk mitigation and capital projects. E4 stated that *"if we can use climate data to digital twin and simulate the energy models with actual data before implement."* E2 suggested to improve accessibility of climate data for facilities managers, it is a good initiative to create a visualisation tool and then facilities managers can convince the management on budget requirements. According to E8 "*it will be good to have a tool, that can use to connect the actual weather data and see some quick information rather than very detail analysis*". Table 3 summarises the use of existing climate data sources in built environment sector.

Table 3: Use of climate data sources

	Experts	E1	E2	E3	E4	E5	E6	E7	E8
Use of existing climate data	Easy Accessibility	✓						✓	
	High Availability	✓	✓	✓		✓	Mod*	Mod*	Mod*
	Convenience to use non climate experts	✓				n/a	Mod*		
	Any Difficulties occurred			✓	✓	n/a	✓		✓

[Mod*- Moderately agreed; n/a *- not answered]

5. DISSCUSSION

Literature findings and expert interview findings both confirmed that there is a huge climate change impact on built environment sector in both global and Sri Lankan context. It is notable that the awareness and the experience of experts towards climate change impacts on buildings is considerably high. When comparing the global built-environment sectors, Sri Lankan industry experts give less attention to mitigate the climate change impacts on built-environment. Organisations are typically taken into account for climate change initiatives because of market forces, sustainability, or green building considerations. Considering the mitigation of climate impacts on built environment scholars highlighted the importance of using climate data. Experts validated the literature by stating that climate data usage an essential requirement for mitigate the climate change impacts on built environment. All most all the experts have used climate data in decision-making in their fields of expert. Apart from the identified FM areas in literature, experts have mentioned that climate data are using in developing protocols for extreme weather events, flood modelling, energy modelling, identifying monsoon periods for pre-maintenance, water proofing, storm water runoff designs and HVAC upgrading. Considering the climate data types in use, Sri Lankan FM industry is mostly using temperature, humidity, precipitation, wind speed, CO_2 level and solar radiation. Scholars suggested the need of central climate database and it is vital to release freely available climate data for non-expert users (Rao & Rastogi, 2020). Even though literature have identified some other freely available climate data sources very few experts have mentioned the use of them. Experts are using some commercial climate databases such as Weather Underground, AccuWeather as NOAA climate data, eQuest, TMY data and Red Screen. Considering the climate data sources, scholars identified that even though there is limitless data, converting data into knowledge or insights was an issue. Similarly, majority of experts agreed that even though the availability of the climate data sources is high, converting them to actionable insights and informed decision making is an issue. Further, both literature and expert interview analysis found that using climate data from existing sources is complex for non-expert users, especially facilities managers do not have climate science knowledge and less engineering knowledge. Scholars suggested the need of central climate database and it is vital to release freely available climate data for non-expert users as well. FM and built-environment experts suggested to have freely available recent years' climate data records including visualisation tools to make informed decisions quickly rather than detailed analysis. Furthermore, experts stated that the climate database for facilities managers will be a good initiative. Experts also stated that it is a challenging task due to unpredictability of climate changes and not having proper base sources. Table 4 summarises the key points from the discussion on literature and expert interview findings.

Table 4: Literature and expert interview findings

	Literature Findings	**Expert Interview findings**
Availability	Highly available	Highly available
Accessibility issues of existing climate databases	Complex due to technical file formats Climate database management is limited to the expert users Converting collected data into insights is challenging Complexity of evaluating climate change involving geophysical, biological, and social systems	Complexity of accessing climate data Not user friendly for non-climate experts for effective decision making. Unawareness of user-friendly tools. Associated licensing agreements and payments. Require specific permissions. Response delays. Lack of expertise of FMs in climate science is a barrier to interpret and use climate data.
Needs of climate databases for FM	Need of central climate database Need freely available climate data for non-expert users	Need to use in building services designing, risk mitigation, maintenance. Need visualisation tools for climate databases. Easily understandable tool for non- expert users. Need of quick information without detailed analysis. Need of centralised database for all, and separate tool for FMs to visualise the data.

6. CONCLUSIONS

The comprehensive literature review identified that there are different climate change impacts on different sectors in global and Sri Lankan contexts and specifically on built-environment sector. Built environment categories including buildings, built-infrastructure and land-use areas have largely affected by the climate changes. In built environment sector, facility managers have responsibilities on mitigating climate change impacts on their facilities. The FM functions were further investigated across energy management, building maintenance, building performance, OSH and disaster management and found that each FM function has a direct and significant impact through climate changes. Experts validated the literature findings during the expert interview rounds. Climate data has been used for the decision-making purposes of built-environment fields and that it is an essential requirement to mitigate the climate change implications on built-environment. Further, different types of climate data are used in facilities management functions and different climate data sources were identified However, there were different availability and accessibility issues associated with these sources. And also, there is a less awareness of climate change impacts and use of climate data sources in Sri Lanka when comparing to the global. It was identified that there is an actual need of freely available and easily accessible user-friendly climate database for non-expert users such as facilities managers with simplified decision-making tools and visualisation tools.

7. REFERENCES

Aghamolaei, R., Azizi, M. M., Aminzadeh, B., & O'Donnell, J. (2022). A comprehensive review of outdoor thermal comfort in urban areas: Effective parameters and approaches. *Energy and Environment*, *34*(6), 2204–2227. https://doi.org/10.1177/0958305X221116176

Alahacoon, N., Matheswaran, K., Pani, P., & Amarnath, G. (2018). A decadal historical satellite data and rainfall trend analysis (2001-2016) for flood hazard mapping in Sri Lanka. *Remote Sensing*, *10*(3), 448. https://doi.org/10.3390/rs10030448

Alam, E., Juthi, R. Z., Samuel, C., & Kaluarachchi, Y. (2023). Enhancing effectiveness of occupational health and safety of garments and textile industry workers in Chittagong, Bangladesh. In I. Pal, R. Shaw, T. Ichinose, Yonariza, & T. Oda (Eds.), *Proceedings of the 2nd international symposium on disaster resilience and sustainable development. Lecture notes in civil engineering (Vol*. 283, pp. 209–224). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-981-19-4715-5_13

Amarathunga, & Rajapaksha. (2016). A critical review on high rise buildings in the context of bio climatic design- A case of vertical diversity in tropical Colombo. In Rajapaksha.U & et al (Eds.), *Building the Future - Sustainable and Resilient Environments* (pp. 425–441).

Assaf, S., & Srour, I. (2021). Using a data driven neural network approach to forecast building occupant complaints. *Building and Environment*, *200*, *107972*. https://doi.org/10.1016/j.buildenv.2021.107972

Barrelas, J., Ren, Q., & Pereira, C. (2021). Implications of climate change in the implementation of maintenance planning and use of building inspection systems. *Journal of Building Engineering*, *40*, 102777. https://doi.org/10.1016/j.jobe.2021.102777

Bastidas-Arteaga, E., Rianna, G., Gervasio, H., & Nogal, M. (2022). Multi-region lifetime assessment of reinforced concrete structures subjected to carbonation and climate change. *Structures*, *45*, 886–899. https://doi.org/10.1016/j.istruc.2022.09.061

Bektaş, Y., & Sakarya, A. (2023). The Relationship between the Built Environment and Climate Change: The Case of Turkish Provinces. *Sustainability*, *15*(2), 1659. https://doi.org/10.3390/su15021659

Brown, S. L., Schuldt, S. J., Grussing, M. N., Johnson, M. A., & Delorit, J. D. (2022). Evaluating climatic influences on the technical performance of built infrastructure assets. *Journal of Performance of Constructed Facilities*, *36*(2). https://doi.org/10.1061/(asce)cf.1943-5509.0001707

Camarillo-Naranjo, J. M., Álvarez-Francoso, J. I., Limones-Rodríguez, N., Pita-López, M. F., & Aguilar-Alba, M. (2019). The global climate monitor system: from climate data-handling to knowledge dissemination. *International Journal of Digital Earth*, *12*(4), 394–414. https://doi.org/10.1080/17538947.2018.1429502

Cevik, S., & Jalles, J. T. (2022). This changes everything: Climate shocks and sovereign bonds. *Energy Economics*, *107*, 105856. https://doi.org/10.1016/j.eneco.2022.105856

Chathuranika, I. M., Gunathilake, M. B., Azamathulla, H. M., & Rathnayake, U. (2022). Evaluation of Future Streamflow in the Upper Part of the Nilwala River Basin (Sri Lanka) under Climate Change. *Hydrology*, *9*(3), 48. https://doi.org/10.3390/hydrology9030048

Dessai, S., Bhave, A., Birch, C., Conway, D., Garcia-Carreras, L., Gosling, J. P., Mittal, N., & Stainforth, D. (2018). Building narratives to characterise uncertainty in regional climate change through expert elicitation. *Environmental Research Letters*, *13*(7), 074005. https://doi.org/10.1088/1748-9326/aabcdd

D'Orazio, M., Di Giuseppe, E., & Bernardini, G. (2022). Occupant density impact on building maintenance: Data-driven approach for university buildings. *Automation in Construction*, *141*, 104451. https://doi.org/10.1016/j.autcon.2022.104451

Escap. (2016). Annual Report 2016-2017 - ESCAP Multi-Donor Trust Fund for Tsunami, Disaster and Climate Preparedness. www.unescap.org

Fabbri, K., Gaspari, J., & Felicioni, L. (2020). Climate change effect on building performance: A case study in New York. *Energies*, *13*(12), 3160. https://doi.org/10.3390/en13123160

Foreman, A. M., Friedel, J. E., Ludwig, T. D., Ezerins, M. E., Açikgöz, Y., Bergman, S. M., & Wirth, O. (2023). Establishment-level occupational safety analytics: Challenges and opportunities. *International Journal of Industrial Ergonomics*, *94*, 103428. https://doi.org/10.1016/j.ergon.2023.103428

Gandhi Marg, M. (2017). Framework for action in building health systems resilience to climate change in South-East Asia Region, World Health Organization. www.searo.who.int

Gaur, A., Lacasse, M., & Armstrong, M. (2019). Climate data to undertake hygrothermal and whole building simulations under projected climate change influences for 11 Canadian cities. *Data*, *4*(2), 72. https://doi.org/10.17605/OSF.IO/UPFXJ

Hettiarachchi, P., & Madhavie, M. K. J. (2019, October). Climate Change in Sri Lanka - What do the Data Actually Reflect. *In Proceedings of the 7th International Symposium on Advances in Civil and Environmental Engineering Practices for Sustainable Development*, Faculty of Engineering, University of Ruhuna, Galle, Sri Lanka (Vol. 17). https://www.researchgate.net/publication/337007884

Hsu, A., Khoo, W., Goyal, N., & Wainstein, M. (2020). Next-generation digital ecosystem for climate data mining and knowledge discovery: A review of digital data collection technologies. *Frontiers in Big Data*, *3*, 29. https://doi.org/10.3389/fdata.2020.00029

Jiang, A., Liu, X., Czarnecki, E., & Zhang, C. (2019). Hourly weather data projection due to climate change for impact assessment on building and infrastructure. *Sustainable Cities and Society*, *50*, 101688. https://doi.org/10.1016/j.scs.2019.101688

Joensuu, T., Edelman, H., & Saari, A. (2020). Circular economy practices in the built environment. *Journal of Cleaner Production*, *276*, 124215. https://doi.org/10.1016/j.jclepro.2020.124215

Jones, K., Mulville, M., & Brookes, A. (2013). FM, risk and climate change adaptation. FM for a Sustainable Future. *FM for a Sustainable Future, 12th EuroFM Research Symposium*, 22–24 May 2013. https://doi.org/10.21427/ang9-5g16

Lacasse, M. A., Gaur, A., & Moore, T. V. (2020). Durability and climate change-implications for service life prediction and the maintainability of buildings. *Buildings*, *10*(3), 53. https://doi.org/10.3390/buildings10030053

Lynch, & Mosbah. (2017). Improving local measures of sustainability: A study of built-environment indicators in the United States. *Cities*, *60*, 301–313. https://doi.org/10.1016/j.cities.2016.09.011

Najjar, M. K., Tam, V. W. Y., Di Gregorio, L. T., Evangelista, A. C. J., Hammad, A. W. A., & Haddad, A. (2019). Integrating parametric analysis with building information modeling to improve energy performance of construction projects. *Energies*, *12*(8), 1515. https://doi.org/10.3390/en12081515

Perera, N. G. R., & Emmanuel, R. (2018). A "Local Climate Zone" based approach to urban planning in Colombo, Sri Lanka. *Urban Climate*, *23*, 188–203. https://doi.org/10.1016/j.uclim.2016.11.006

Pilanawithana, N. M., & Sandanayake, Y. G. (2017). Positioning the facilities manager's role throughout the building lifecycle. *Journal of Facilities Management*, *15*(4), 376–392. https://doi.org/10.1108/JFM-06-2016-0024

Rañeses, M. K., Chang-Richards, A., Wang, K. I. K., & Dirks, K. N. (2021). Housing for now and the future: A systematic review of climate-adaptive measures. *Sustainability (Switzerland)*, *13*(12), 6744. https://doi.org/10.3390/su13126744

Rao, S., & Rastogi, P. (2020). Towards a standard climate data model for building design and analysis. *In ASHRAE Topical Conference Proceedings* (pp. 285-292). American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

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

Sajadi, M. M., Sajadi, M. M., Habibzadeh, P., Vintzileos, A., Shokouhi, S., Miralles-Wilhelm, F., Miralles-Wilhelm, F., Amoroso, A., & Amoroso, A. (2020). Temperature, humidity, and latitude analysis to estimate potential spread and seasonality of coronavirus disease 2019 (COVID-19). *JAMA Network Open*, *3*(6), e2011834. https://doi.org/10.1001/jamanetworkopen.2020.11834

Senevirathna (Ed.). (2016). *National Adaptation Plan for Climate Change Impacts in Sri Lanka Climate Change Secretariat Ministry of Mahaweli Development and Environment 2016*. Climate Change Secretariat, Ministry of Mahaweli Development and Environment.

Soutullo, S., Giancola, E., Jiménez, M. J., Ferrer, J. A., & Sánchez, M. N. (2020). How climate trends impact on the thermal performance of a typical residential building in Madrid. *Energies*, *13*(1), 237. https://doi.org/10.3390/en13010237

Stackhouse, P. W., Macpherson, B., Hegyi, B. M., Mikovitz, J. C., Zhang, T., Broddle, M. P., Barnett, A. J., & Patadia, F. (2023, June 24). *Using Time Series Data Products to Support ASHRAE's Historic and Future Climate Data Needs through NASA's POWER Web Services*. NASA Technical Reports Server (NTRS). https://ntrs.nasa.gov/citations/20230008796

Thathsarani, U. S., & Gunaratne, L. H. P. (2018). Constructing and index to measure the adaptive capacity to climate change in Sri Lanka. *Procedia Engineering*, *212*, 278–285. https://doi.org/10.1016/j.proeng.2018.01.036

USAID. (2012a, November). *Addressing climate change impacts on infrastructure: Preparing for change ICT 1*. United States Agency International Development (USAID). http://www.defra.gov.uk/publications/files/climate-resilient-infrastructure-full.pdf

USAID. (2012b). *Addressing climate change impacts on infrastructure: preparing for change buildings*. United States Agency International Development (USAID). https://www.climatelinks.org/resources/addressing-climate-change-impacts-infrastructure-preparing-change-buildings

Vijayavenkataraman, S., Iniyan, S., & Goic, R. (2012). A review of climate change, mitigation and adaptation. *Renewable and Sustainable Energy Reviews*, *16*(1), 878–897. https://doi.org/10.1016/j.rser.2011.09.009

Wang, L., Xue, X., Yang, R. J., Luo, X., & Zhao, H. (2019). Built environment and management: exploring grand challenges and management issues in built environment. *Frontiers of Engineering Management/Frontiers of Engineering Management*, *6*(3), 313–326. https://doi.org/10.1007/s42524-019-0049-9

Warren, C. M. j. (2010). The facilities manager preparing for climate change related disaster. *Facilities*, *28*(11–12), 502–513. https://doi.org/10.1108/02632771011066567

Weerasekara, S., Wilson, C., Lee, B., Hoang, V.-N., Managi, S., & Rajapaksa, D. (2021). The impacts of climate induced disasters on the economy: winners and losers in Sri Lanka Central Bank of Sri Lanka, Sri Lanka. *Ecological Economics*, *185*, 107043. https://doi.org/https://doi.org/10.1016/j.ecolecon.2021.107043.

Yang, C., Yu, M., Li, Y., Hu, F., Jiang, Y., Liu, Q., Sha, D., Xu, M., & Gu, J. (2019). Big Earth data analytics: a survey. *Big Earth Data*, *3*(2), 83–107. https://doi.org/10.1080/20964471.2019.1611175

Zhu, J., Shen, Y., Song, Z., Zhou, D., Zhang, Z., & Kusiak, A. (2019). Data-driven building load profiling and energy management. *Sustainable Cities and Society*, *49,* 101587. https://doi.org/10.1016/j.scs.2019.101587

Wijayawardena, D.S.I., Sandanayake, Y.G. and Bandaranayake, D.M.L.N., 2024. The role of stakeholders in business model innovation in construction organisations in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1064-1076. DOI: https://doi.org/10.31705/WCS.2024.84. Available from: https://ciobwcs.com/papers/

THE ROLE OF STAKEHOLDERS IN BUSINESS MODEL INNOVATION IN CONSTRUCTION ORGANISATIONS IN SRI LANKA

D.S.I. Wijayawardena[1], Y.G. Sandanayake[2] and D.M.L.N. Bandaranayake[3]

ABSTRACT

The Business Model (BM) has become a distinctive feature that guides enterprises in fighting against challenges and navigating toward success. Construction organisations also face challenges due to expanding project scopes, increasing project participants, external factors and tight budgets. Hence, innovating BMs to keep up with the changing market and retain the competitive edge is essential. In this context, the stakeholders play a vital role in Business Model Innovation (BMI). There is therefore a need to investigate the role of stakeholder in BMI. Hence, this paper investigates the role of stakeholders in BMI in Sri Lankan construction organisations. This research gap was addressed using a literature review followed by in-depth semi-structured interviews with 20 experts using the qualitative research approach. Collected data were analysed through content analysis. Findings revealed that stakeholder engagement in BMI is led by the mutual benefits gained by all parties while creating a win-win situation. Semi-structured interview findings revealed that government, shareholders, clients, Board of Directors (BoDs) and management significantly influence BMI, while stakeholders such as employees, sub-contractors, competitors, financial providers and material suppliers possess a moderate influence. As per the interview findings, shareholders provide capital and foster innovation, BoDs/top management make final decisions after evaluating all suggestions, middle and low-level managers execute BMIs and guide subordinates, clients shape BMs to fit project needs, and the government influences BMIs through regulations. In conclusion, the stakeholders in construction industry can use the research findings in developing BMIs and implementing them successfully.

Keywords: *Business Model (BM); Business Model Innovation (BMI); Construction Organisations; Sri Lanka; Stakeholder Role.*

1. INTRODUCTION

Construction organisations frequently deal with challenges caused by the external environment due to economic uncertainty, the highly competitive global construction market, technological changes, and the impact of regulatory bodies and laws (Liu et al., 2017; Martins et al., 2015). Further, these organisations also face challenges that arise

[1] Research Student, Department of Building Economics, University of Moratuwa, Sri Lanka, suthira0303@gmail.com

[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ysandanayake@uom.lk

[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, lakshithab@uom.lk

within the businesses due to expanding project scopes, increasing project participants, and tight budgets (Antunes & Gonzalez, 2015). Accordingly, firms in the construction industry must develop Business Models (BMs) to adopt the best modifications to survive and prosper in dynamic business settings packed with internal changes and external influences (Martins et al., 2015). BMs have received considerable attention in recent years (Abeynayake et al., 2022a), and BM is defined as a plan that creates value for an organisation (Pekuri et al., 2013;). BMs significantly influence how (a) well international construction organisation’s function and (b) these firms make decisions about their BMs in the hope that they will provide better results (Jang et al., 2019). However, with the economic, social, and environmental challenges, the need for profound and comprehensive BMs has become essential for organisations (Shakeel et al., 2020), indicating the need for Business Model Innovation (BMI). Yunus et al. (2010) conceptualised BMI as a way of generating new sources of profit by finding novel value propositions. Further, the BMI process necessitates changes made holistically to an organisation's value-creation, value-delivery, and value-capture activities (Bouncken & Fredrich, 2016). While proposing a roadmap for BM adaptation in the construction industry, Abeynayake et al. (2022a) mentioned that BM is a novel concept in Sri Lanka, probably because BM adaptation in the industry has not been sufficiently studied.

On the other hand, the stakeholders of a firm have the capabilities in influencing the goals of a business while their engagement in business creates sustainable value, which empowers changes within a business environment (Marcon Nora et al., 2023; Stocker et al., 2020). This implies that the stakeholders could influence BMI (Han et al., 2022). When considering the construction industry, engagement of direct stakeholders such as clients, consultants, and contractors, and indirect stakeholders such as suppliers, government, regulatory bodies, financial institutions and competitors is crucial as they influence the decisions, operations and other activities of construction organisations (Pekuri et al., 2013; Han et al., 2022; Abuzeinab & Arif, 2014). Furthermore, Han et al. (2022) highlighted that due to the rapid evolution of the new knowledge and technology areas and resource scarcity in the construction industry, the need for stakeholders with the relevant knowledge and resources for BMI development has become vital. Although stakeholder engagement is vital for BMI in the construction industry, it is less discussed and researched in the field (Pekuri et al., 2013). There is, therefore, a need to examine the stakeholders’ involvement in BMI. Hence, this paper aims to investigate the role of stakeholders in BMI in Sri Lankan construction organisations.

This paper begins with an introduction followed by a literature review. Then, the research methodology, the research findings, and the discussion are presented, respectively, before concluding the findings with recommendations.

2. LITERATURE REVIEW

A literature synthesis on BMI and stakeholder engagement in BMI in the construction industry are presented in the following sub-sections.

2.1 BUSINESS MODEL INNOVATION IN CONSTRUCTION INDUSTRY

BMs fundamentally explain how organisations generate value while considering society and the environment (Dembek & York, 2022). BMI is an extension of the BM concept (Hossain, 2017). According to Jang et al. (2019), BMI supports an organisation's continuous value improvement. Further, BMI can be referred to as the search for a new logic of the firm and new ways to create and capture value for its stakeholders (Casadesus-Masanell & Zhu, 2013). According to Kraus et al. (2020), innovation is always a driver for value creation, and a successful BMI is the path to value creation. Ever-increasing complexity and competition in the construction industry necessitate that construction organisations consider BMI to be a vital element in maintaining a competitive edge in the market. Abeynayake et al. (2022b) defined construction BM as a condensed conceptual illustration of a construction company that uses critical resources to create value by client requirements, taking into account the proper level of engagement from all relevant stakeholders in the fundamental processes leading to revenue and profit generation, and expressing the company's strategic decisions while being conscious of the opportunities and changes that must be made.

Construction professionals learned from the manufacturing sector (Das et al., 2023) and understood BMs as essential to creating value. Rottke et al. (2011) added a new angle to the study of BMs in the construction industry by examining how construction companies expand vertically into the real estate value chain through mergers and acquisitions to strengthen their position in the market. Furthermore, prefabrication was considered a case to be examined by Liu et al. (2017) during their study of BMI in Chinese construction companies. Further, the authors claimed that BMI can transform emerging technologies like prefabrication into valuable products and is likely to generate four times more revenue growth than innovations in products or services. Moreover, Pekuri et al. (2013) emphasised that managers in the construction industry had significant difficulties in explaining the BMs and value-creation logic of their organisation, indicating a lack of comprehension of client values and needs in the project delivery process. Further, the study revealed client satisfaction as a focal point of BMI in the construction industry. Hence, stakeholder involvement is pivotal in BMI.

2.2 STAKEHOLDER ENGAGEMENT IN BMI

Construction is an impactful sector in terms of resource use and has a complex network of stakeholders (Senaratne et al., 2023). Integration and partnerships of stakeholders in the construction industry have been identified as crucial factors that influence the performance of construction projects. Nguyen and Mohamed (2021) stated that efficient stakeholder management is a vital success factor for construction projects. Hence, any organisation needs to understand its stakeholders properly (Guerra & Leite, 2021). According to Pekuri et al. (2013), the general impression is that success in the construction industry depends more on the individual qualities of personnel, particularly managers. Further to the authors, managers in many other industries feel the effects of globalisation on their companies' competitive position on differentiation and the strength of their organisational systems in response to changing environmental conditions.

Businesses that want to change and adapt in response to environmental factors must work more closely with stakeholders inside and outside the company (Abuzeinab et al., 2016). According to Han et al. (2022), construction companies to develop a BMI that could attract more clients since the engagement of clients is essential to increase the financial resources needed for BMI. Further to the authors, in the construction industry, knowledge and skills rapidly iterate, resources are increasingly difficult to obtain, and environmental dynamism positively moderates the relationship between BMI and corporate performance (Han et al., 2022). This indicates the need for stakeholders with the necessary knowledge, skills and resources for BMI.

According to Han et al. (2022), middle and low-level management engagement is crucial for construction companies to make wise strategic decisions in a changing environment because, in the face of intense industry competition, construction companies need to develop sound strategic thinking, spot possibilities in a changing environment, and innovate BMs to gain long-term competitive advantages. Further to the authors, when choosing the middle and low-level management, it is essential to consider how well team members cooperate internally and avoid any confusion due to unbalanced information in decision-making to assist businesses in developing strategies and BMI. Collaborative, informed decision-making among teams is imperative for construction BMI to respond to dynamic environmental changes and maintain a competitive advantage (Abuzeinab et al., 2016). Hence, stakeholder engagement, especially with clients and senior management, fuels BMIs (Han et al., 2022).

2.3 FACTORS THAT AFFECT STAKEHOLDER ENGAGEMENT IN BMI

Yu and Leng (2018) stated that different stakeholder interests and levels of influence might impact the outcomes of construction development projects by either directly influencing the results or indirectly influencing them. Hence, increasing stakeholder interest in the business would increase the attention received for a BMI (Han et al., 2022). The following sub-sections present factors that enhance and hinder stakeholder engagement in BMI.

2.3.1 Factors that Enhance Stakeholder Engagement in BMI

One key factor contributing to enhanced stakeholder engagement is market orientation, where organisations align strategies with market needs and preferences (Han et al., 2022). Further to the authors, this approach attracts new clients and increases profitability by responding effectively to market dynamics. Meanwhile, training is crucial in keeping employees motivated and aligned with organisational goals (Abuzeinab & Arif, 2014). Further to the authors, by offering incentives and empowering staff, organisations ensure that stakeholders understand the significance of BMI and their role in its implementation. Moreover, effective internal and external communication channels are vital for stakeholder engagement (Zarewa, 2019). Abuzeinab and Arif (2014) stated that clear messaging helps attract clients, collaborate with the supply chain, and educate end-users about sustainable practices. According to Abuzeinab et al. (2016), providing all employees with roles and explaining their roles properly would drive the organisation towards common objectives and goals, fostering a sense of ownership and commitment at their optimum level of involvement in BMI initiatives. Additionally, tailoring strategies to meet stakeholders' interests, such as providing economically viable solutions and flexible working patterns, enhance engagement and fosters a collaborative environment (Eyiah-Botwe et al., 2016).

2.3.2 Factors that Hinder Stakeholder Engagement in BMI

Stakeholders face challenges when involved in BMI in the construction industry due to its unique nature (Pekuri et al., 2013). According to Zarewa (2019), the factors that hinder stakeholder engagement can be personal, such as insufficient knowledge, conflict of interests, and attitudes that depend on the qualities of the individuals or could be organisational, such as lack of leadership, insufficient time allocation for work, and limited information available. Insufficient knowledge and training among stakeholders on the principles and benefits of BMI hinders their engagement in the construction industry. Without a solid understanding and proper training, it is challenging for employees to contribute their best to the company, and they may view BMI as unnecessary or disruptive, which diminishes their willingness to participate (Abuzeinab & Arif, 2014). Wilson and Rezgui (2013) identified a lack of technical capacity, limited access to information, and insufficient support among stakeholders as factors that hinder their ability to engage in BMI activities meaningfully. Moreover, maintaining robust relationships with stakeholders is crucial for a successful business, and failure to nurture these relationships can leave stakeholders feeling undervalued or marginalised, reducing their willingness to engage in BMI initiatives (Agyekum et al., 2023).

2.4 STAKEHOLDERS ENGAGE IN BMI IN SRI LANKAN CONSTRUCTION INDUSTRY

Weerakkody and Thoradeniya (2012) described how the Sri Lankan construction industry is securing the involvement of all relevant stakeholders at the design stage and preserving coordination among them in resolving crucial issues related to accomplishing the main goals of building projects. According to Jayathissa et al. (2016), the most common stakeholders in road construction projects are the government, the general public, insurance companies, the media, environmental pressure groups, and funding bodies. In contrast, Kulathunga (2018) has identified clients, end users, consultants, and contractors as the primary stakeholders of building construction projects in Sri Lanka. Haigh and Sutton (2012) suggested that strategic planning should prioritise early stakeholder participation in Sri Lankan post-disaster reconstruction programmes. Hence, it is evident that the engagement of stakeholders is vital to the BMI in the construction industry. Identifying the roles of different stakeholders in BMI would encourage its development in construction organisations. Furthermore, as per the literature review, some factors enhance and hinder stakeholder engagement in BMI. Proper identification of these factors in BMI would be vital to maintain a competitive edge in a dynamic environment for construction organisations.

3. RESEARCH METHODOLOGY

A research design serves as a roadmap for research and in this study, it includes a background inquiry, a survey of the literature, data collection, and data analysis. Since this research aimed to investigate the role of stakeholders in BMI in Sri Lankan construction organisations, a qualitative approach was selected. Interviews with industry experts was applied as the suitable research strategy. Accordingly, semi-structured interviews were used as the data collection method as it is one of the most important sources to collect qualitative data. As Dawadi et al. (2021) stated, semi-structured interview technique was used in this study due to its: (a) flexibility, (b) less chance of missing any data and identifying aspects the researcher may have missed, (c) ability to collect in-depth and detailed information, and (d) integration of human touch that allows the researcher to identify the actual feelings and emotions of the participants. BM is a rarely explored subject in the context of construction literature, so the above characteristics of qualitative research would immensely help to have a comprehensive understanding without missing any data while extracting practical information from industry professionals.

Accordingly, 20 semi-structured interviews were conducted with industry experts having more than 10 years of experience to identify the role of stakeholders in BMI in Sri Lankan construction organisations. However, the data collection was limited to the owners and the top-level managers of the construction organisations as the top-level management is involved in strategic decision making and BMI. Furthermore, snowball sampling was used to make the selection of respondents more effective. The profile of respondents is given in Table 1.

Table 1: Profile of the respondents

Respondents	Designation	Experience	Type of the firm
R1	Director	17 years	Consultant
R2	Contract Manager	13 years	Contractor
R3	Owner/Director	20 years	Consultant
R4	Deputy General Manager	26 years	Contractor
R5	Owner	21 years	Consultant
R6	Co-Owner	25 years	Consultant
R7	Co-Owner	25 years	Consultant
R8	Senior Manager	11 years	Consultant
R9	Deputy General Manager	13 years	Contractor
R10	Co-Owner/Director	21 years	Contractor
R11	Owner	32 years	Consultant
R12	Director	16 years	Contractor
R13	Deputy General Manager	20 years	Contractor
R14	Chief Executive Officer	20 years	Consultant
R15	Director	13 years	Consultant
R16	Director	49 years	Consultant
R17	Owner/ Director	26 years	Consultant
R18	Contract Manager	13 years	Contractor
R19	Owner	12 years	Consultant
R20	Deputy General Manager	12 Years	Contractor

Since the organisation's top management is mainly involved in BMI, interviews were limited to the organisation's owners, directors, and senior managers. This selection made the information collected more reliable and realistic as the respondents work closely with the BMs than the other stakeholders of the construction organisations. Out of 20 respondents, 55% of respondents have more than 20 years of experience while others (45%) have experience between 10 to 20 years. Further, 60% of respondents represent consultancy organisations while the others (40%) attach to contractor organisations. Furthermore, the data collection was carried out until data saturation was reached and no new themes or insights emerged. This indicates the consistency in the responses given by the respondents representing both consultancy and contractor organisations.

The collected data were analysed by using code-based content analysis techniques. QSR NVivo.12 software was used in data analysis as it manages all data very easily. The key findings derived through data analysis are presented below.

4. RESEARCH FINDINGS AND DISCUSSION

The interview guideline was structured under four sections. Section 1 focussed on gathering information about the respondents' profile. The next section explored the respondents' opinions on the factors that should be focused on BMI in a construction organisation. Section three collected insights on stakeholder influence on BMI in the construction industry. The final section explored the role and contribution of various stakeholders in BMI in the construction industry. The key findings are presented below.

4.1 FACTORS TO BE FOCUSED IN BMI IN A CONSTRUCTION ORGANISATION

All 20 respondents agreed and emphasised that BMIs of all organisations in the construction industry, whether a consultancy firm or a contractor firm, should focus on making profits for the owners or their shareholders. However, R10 highlighted that sometimes the BMI may have to consider their survival or long-term benefits over making profits. Nevertheless, almost all the respondents highlighted that BMIs in the construction industry should focus on client satisfaction. Similarly, Pekuri et al. (2013) and Jang et al. (2019) also highlighted the importance of considering client satisfaction in BMI.

In addition, R1 emphasised the importance of the value proposition of a BM, highlighting the need to add value to the work that clients undertake. The respondent further mentioned that adding value to the work would help a business to create a proper relationship with the clients. Accordingly, Rydehell (2019) and Yunus et al. (2010) also acknowledged the BM's ability to find new value prepositions for a business. Despite this, R3 introduced the BM as a *"way of conducting the business ethically while considering shareholder profit"*. This was asserted by R11 and R15, mentioning that integrity and ethical practice are something their organisations focus on, and even BMI also align with that.

4.2 STAKEHOLDER INFLUENCE ON BMI IN THE CONSTRUCTION INDUSTRY

Section three in the interview guideline aimed to collect insights of respondents on the influence of stakeholders on BMI in the construction industry based on their roles, decision-making power, ability to influence the factors in business environment and ability to allocate resources. The level of significance of the influence was categorised as significant, moderate and minor impacts based on the opinions of the respondents. The research findings on the stakeholders who influence BMI in construction industry were analysed using NVivo and shown in Figure 1.

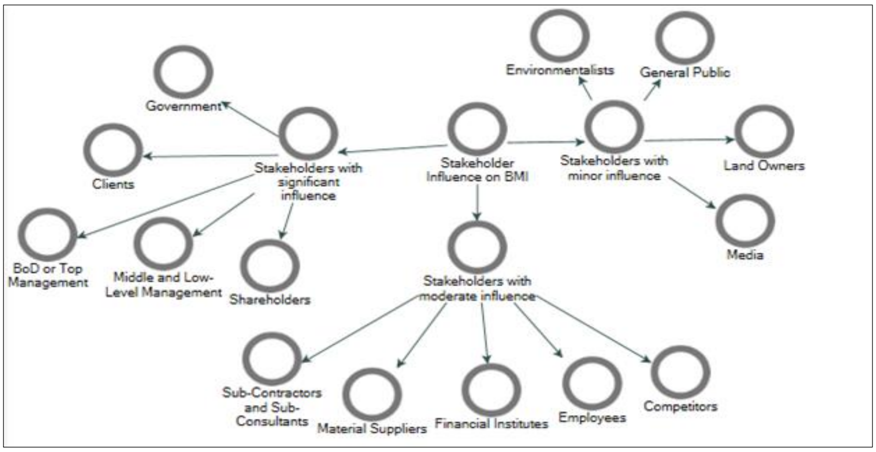


Figure 1: Stakeholder categorisation based on their influence over BMI in construction organisations

As shown in Figure 1, the respondents identified the stakeholders who have a significant influence on BMI, and this group includes shareholders, the Board of Directors (BoD)/top management, middle and low-level managers, clients, and government entities. This finding is in line with the research findings of Han et al. (2022), and Abeynayake et al. (2022b). Further, there are stakeholders with moderate influence on BMI, encompassing suppliers, employees, sub-contractors and sub-consultants, and financial institutes. The respondents identified stakeholders such as environmentalist, media, land owners and general public as the group with a minor impact on BMI in construction industry.

R14 described the decision-making power of stakeholders as having significant influence by highlighting *"their decision-making power, which directly shapes the direction and execution of BMIs"*. This underscores the pivotal role they play in driving the organisation towards BMI. R1 further elaborates on the influence of these stakeholders, emphasising *"governments and clients' impact over BMI by changing market demands, regulations, and policies within which the organisation operates"*. This projects how the actions and directives of these stakeholders shape the organisation's path to BMI. Nevertheless, respondents also commented on the stakeholders with moderate influence over BMI. According to R14, *"their contributions are valuable for day-to-day operations but may not directly impact the formulation or implementation of BMIs"*. While they may offer input or feedback on innovations, they generally lack the authority to drive substantial changes in BMs.

4.3 ROLE OF STAKEHOLDERS IN BMI IN CONSTRUCTION INDUSTRY

The influence of stakeholders varies based on their roles and contributions to BMI in the construction industry. Respondents were asked to describe the specific roles of these stakeholders in BMI in construction organisations, and the findings are presented below.

4.3.1 Role of Stakeholders with Significant Influence over BMI in the Construction Industry in Sri Lanka

The respondents were requested to identify the role of shareholders, BoD/top management, middle and low-level managers, clients, and the government. The role of stakeholders with significant influence over BMI is discussed below.

Shareholders: As emphasised by R3, shareholders play a pivotal role in providing capital, resources, and investment for implementing new BMIs, significantly influencing the organisation's direction and pace of innovation. Additionally, R18 and R10 mentioned that the shareholders should be flexible in innovations and willing to take risks when successfully conducting BMI in a construction organisation.

BoD/Top Management: According to the respondents, top management is involving in and responsible for strategic decision making and BM development. R1 stated that BoD serves as a crucial guiding force in BMI endeavours. Their influence on the organisation's strategy ensures alignment with its mission and values in pursuing innovation. R16 noted that *"…BoD takes the final decision"*, highlighting that the board's diverse expertise and experience contribute to strategic decision-making in BMI, enabling them to identify emerging opportunities and navigate potential risks effectively. Furthermore, R14 emphasised that as a director, they should communicate with all the other stakeholders, and R7 emphasised that they should consider outsourcing or recruiting professionals, including specialists or advisors who are essential for BMI, before finally taking the decision. Hence, the decision taken would be much more balanced and informed. In addition, many respondents mentioned that the environment or the culture that the directors build decides the engagement of other stakeholders in BMI.

Middle and Low-Level Management: Further to the respondents, middle and low-level management should be involved in the BMI process and share their ideas with top management. However, their primary role will be to implement the innovated BM in the organisation. R2 appreciated their current culture, where the middle and low-level managers get a chance to voice their thoughts as they actually experience the pros and cons of the BM in projects. Furthermore, R4 highlighted the importance of utilising managers' recruiting powers and other abilities in the best interest of the BMI.

Clients: According to the responses, many construction organisations innovate or completely change their BM to meet their client's requirements, which aligns with the highlights of Pekuri et al. (2013). Due to this, clients have become one of the main stakeholders influencing an organisation's BMI, as their feedback, preferences, and evolving needs serve as valuable inputs for the organisation to get more projects from the client. Furthermore, some clients take the risk of experimenting with innovations with construction organisations through projects.

Government: As emphasised by R2, the government has a significant influence over BMI through its regulatory frameworks and policies. On the other hand, the government is the biggest client in the construction industry. The government can facilitate or impede BMI within organisations in the changing regulatory environment. Accordingly, R11 mentioned that by offering incentives such as grants, tax breaks, or funding opportunities for construction organisations, governments can encourage businesses to invest in BMI initiatives, as the industry still has not recovered from the recent adverse economic conditions in Sri Lanka.

4.3.2 Role of Stakeholders with Moderate Influence over BMI in Construction Industry in Sri Lanka

The respondents were requested to identify the role of material suppliers, sub-contractors, sub-consultants, employees, financial institutes and competitors. The role of stakeholders with moderate influence over BMI is discussed below.

Material Suppliers, Sub-Contractors, Sub-Consultants: According to insights from R8, material suppliers are crucial for providing essential resources and components for construction projects. R9 and R13 said that similar to material suppliers, sub-contractors and sub-consultants provide specialised services or expertise to support specific aspects of construction projects. These stakeholders provide feedback and suggest new ideas while being dependable sources to the organisation, which would be the main contributions expected in BMI.

Employees: The term 'employees' represents all the organisation's employees, excluding directors and middle and low-level managers. R5 mentioned that *"employees deal with customers and other stakeholders frequently and have an updated knowledge about company environment; hence, I consider their opinion in BMI-related decision making"*. Similar to R5, others also demonstrated that employees' primary role is to share their BMI experience while supporting its implementation.

Financial Institutes: As the respondents emphasised, the involvement of financial institutes, including banks, investors, and insurance organisations, is crucial in financial activities or investment decisions in BMI. They support in funding BMI initiatives. R1 and R13 stated that financial institutes play a role as financial advisers in BMI.

Competitors: According to the respondents, competition is one force that drives organisations to innovate. Furthermore, R3, R7, R9, and R17 mentioned that the primary role of competitors is to maintain healthy competition and ensure that there is a difference among organisations, which increases the quality of the service provided. In addition, respondents mentioned that they analyse the concepts and techniques that have worked and failed for their competitors and try to adapt successful concepts and techniques in developing their BMIs, indicating the role of competitors in sparking innovations.

However, it was also identified that the above-mentioned roles and contributions could slightly vary according to the nature of the organisation. The summary of overall findings on the stakeholder’s role in BMI is shown in Figure 2.

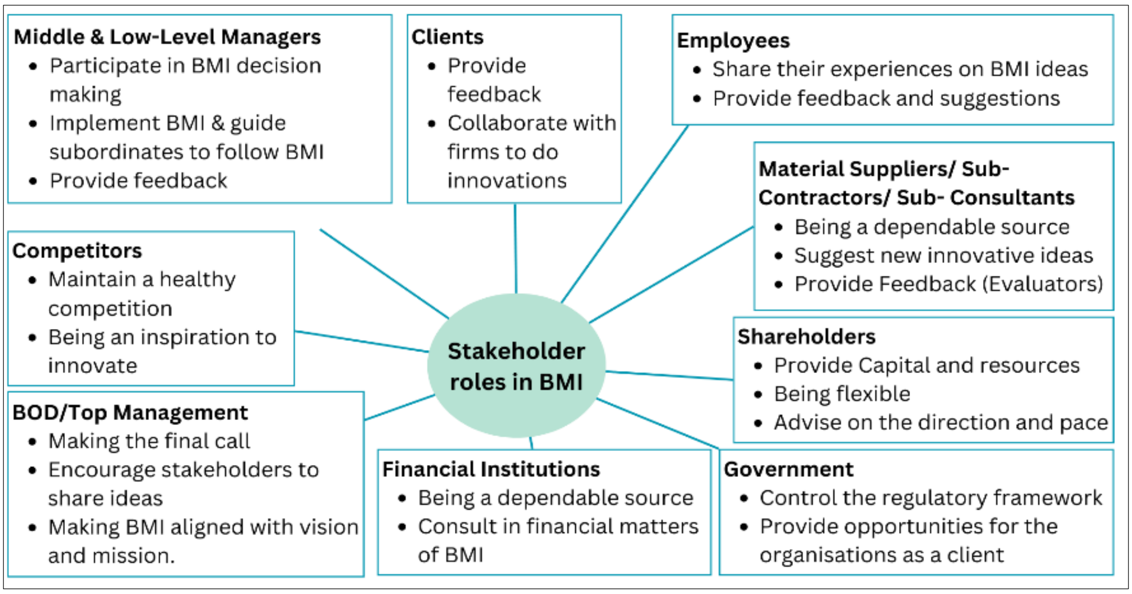


Figure 2: Stakeholder roles in BMI

As depicted in Figure 2, each stakeholder's role is different, indicating its uniqueness. For example, the government cannot make the final decision, while it can control the regulatory framework. Moreover, although employees, clients, and middle and low-level managers provide feedback on BMI, these roles also become unique due to their different perspectives. Accordingly, each stakeholder has some key roles to play in BMI. The quality of these roles being played determines the success of BMI. Hence, encouraging stakeholder engagement in BMI is vital for construction organisations.

5. CONCLUSIONS AND RECOMMENDATIONS

As one of the industries prone to many dynamic changes, construction organisations' BMs must be updated and innovative. Accordingly, BMI has been one of the main concepts adopted in the global construction industry to keep up with the dynamic changes. This study explored the roles of stakeholders in BMI, gathering insights from 20 respondents across roles. It was revealed that profitability, balanced with long-term viability, is one of the critical aspects of BMI. Moreover, client satisfaction and value prepositions emerged as crucial in BMI. As per the study's findings, stakeholders such as shareholders, BoD/top management, middle and low-level management, clients and government were recognised as stakeholders who can significantly influence the BMI, while employees, materials suppliers, sub-contractors, sub-consultants, and finance providers are stakeholders with moderate influence over BMI. The findings elaborated on the roles of stakeholders in BMI. For example, shareholders provide capital and foster innovation, BoD/top management makes the final call after evaluating all suggestions, middle and low-level managers execute BMs and guide subordinates, clients shape BMs to fit project needs, and governmental entities influence BMIs through regulations. Material suppliers, sub-contractors, sub-consultants, employees, and financial institutes contributed variably to projects and BMIs. It was noted that stakeholder engagement in BMI is led by the mutual benefits both parties earn, creating a win-win situation. Accordingly, the study highlights the importance of stakeholder engagement and collaboration as essential for BMI's success in construction, offering insights for industry decision-making. The findings of this research will be beneficial to the construction organisations in Sri Lanka as well as developing countries who share socio-economic, demographic or cultural traits similar to Sri Lankan construction industry. As the next step, this research will investigate the strategies to enhance stakeholder engagement in BMI in construction industry.

6. REFERENCES

Abeynayake, D.N., Perera, B.A.K.S., & Hadiwattege, C. (2022a). A roadmap for business model adaptation in the construction industry: A structured review of business model research. *Construction Innovation*, *22*(4), 1122-1137. https://doi.org/10.1108/ci-05-2020-0077

Abeynayake, D.N., Perera, B.A.K.S., & Hadiwattege, C. (2022b). Defining a 'business model' in the construction context. *Intelligent Buildings International*, *14*(4), 473-486. https://doi.org/10.1080/17508975.2021.1927660

Abuzeinab, A., & Arif, M. (2014). Stakeholder engagement: A green business model indicator. *Procedia Economics and Finance*, *18*, 505-512. https://doi.org/10.1016/s2212-5671(14)00969-1

Abuzeinab, A., Arif, M., Kulonda, D.J., & Awuzie, B.O. (2016). Green business models transformation: Evidence from the UK construction sector. *Built Environment Project and Asset Management*, *6*(5), 478-490. https://doi.org/10.1108/bepam-10-2015-0060

Agyekum, A.K., Fugar, F.D.K., Agyekum, K., Akomea-Frimpong, I., & Pittri, H. (2023). Barriers to stakeholder engagement in sustainable procurement of public works. *Engineering, Construction and Architectural Management*, *30*(9), 3840-3857. https://doi.org/10.1108/ECAM-08-2021-0746

Antunes, R., & Gonzalez, V. (2015). A production model for construction: A theoretical framework. *Buildings*, *5*(1), 209-228. https://doi.org/10.3390/buildings5010209

Bouncken, R.B., & Fredrich, V. (2016). Business model innovation in alliances: Successful configurations. *Journal of Business Research*, *69*(9), 3584-3590. https://doi.org/10.1016/j.jbusres.2016.01.004

Casadesus-Masanell, R., & Zhu, F. (2013). Business model innovation and competitive imitation: The case of sponsor-based business models. *Strategic Management Journal*, *34*(4), 464-482. https://doi.org/10.1002/smj.2022

Das, P., Hijazi, A.A., Maxwell, D.W., & Moehler, R.C. (2023). Can business models facilitate strategic transformation in construction firms? A systematic review and research agenda. *Sustainability*, *15*(17), 1-20. https://doi.org/10.3390/su151713022

Dawadi, S., Shrestha, S., & Giri, R.A. (2021). Mixed-methods research: A discussion on its types, challenges, and criticisms. *Journal of Practical Studies in Education*, *2*(2), 25-36. https://doi.org/10.46809/jpse.v2i2.20

Dembek, K., & York, J. (2022). Applying a sustainable business model lens to mutual value creation with base of the pyramid suppliers. *Business & Society*, *61*(8), 2156-2191. https://doi.org/10.1177/0007650320973450

Eyiah-Botwe, E., Aigbavboa, C., & Thwala, W.D. (2016). Mega construction projects: Using stakeholder management for enhanced sustainable construction. *American Journal of Engineering Research*, *5*(5), 80-86. https://www.academia.edu/download/47615519/L0505080086.pdf

Guerra, B.C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resources, Conservation and Recycling*, *170*, 105617. https://doi.org/10.1016/j.resconrec.2021.105617

Haigh, R., & Sutton, R. (2012). Strategies for the effective engagement of multi-national construction enterprises in post-disaster building and infrastructure projects. *International Journal of Disaster Resilience in the Built Environment*, *3*(3), 270–282. https://doi.org/10.1108/17595901211263657

Han, W., Zhou, Y., & Lu, R. (2022). Strategic orientation, business model innovation and corporate performance - Evidence from construction industry. *Frontiers in Psychology*, *13*, 971654. https://doi.org/10.3389/fpsyg.2022.971654

Hossain, M. (2017). Business model innovation: past research, current debates, and future directions. *Journal of Strategy and Management*, *10*(3), 342-359. https://doi.org/10.1108/jsma-01-2016-0002

Jang, Y., Ahn, Y., Park, M., Lee, H.S., & Kwon, N. (2019). Business models and performance of international construction companies. *Sustainability*, *11*(9), 2575. https://doi.org/10.3390/su11092575

Jayathissa, K.H.N.P., Samaraweera, A., & Ranadewa, K.A.T.O. (2016). Stakeholder management in road construction projects in Sri Lanka: A contractor perspective. In. Y.G. Sandanayake, G. Karunasena, & T. Ramachandra, (Eds.), *The 5th world construction symposium 2016: Greening environment, eco innovations and entrepreneurship*. (pp. 448-457). Ceylon Institute of Builders. http://dl.lib.uom.lk/handle/123/17244

Kraus, S., Filser, M., Puumalainen, K., Kailer, N., & Thurner, S. (2020). Business model innovation: A systematic literature review. *International Journal of Innovation and Technology Management*, *17*(6), 1-20. https://doi.org/10.1142/S0219877020500431

Kulathunga, W. R. (2018). *Stakeholder management issues in construction projects: A case study* [Master's theses, University of Moratuwa]. Digital Library, University of Moratuwa http://dl.lib.mrt.ac.lk/handle/123/14120.

Liu, G., Li, K., Zhao, D., & Mao, C. (2017). Business model innovation and its drivers in the Chinese construction industry during the shift to modular prefabrication. *Journal of Management in Engineering*, *33*(3), 04016051. https://doi.org/10.1061/(asce)me.1943-5479.0000501

Marcon Nora, G.A., Alberton, A., & Ayala, D.H.F. (2023). Stakeholder theory and actor-network theory: The stakeholder engagement in energy transitions. *Business Strategy and the Environment*, *32*(1), 673-685. https://doi.org/10.1002/bse.3168

Martins, L.L., Rindova, V.P., & Greenbaum, B.E. (2015). Unlocking the hidden value of concepts: A cognitive approach to business model innovation. *Strategic Entrepreneurship Journal*, *9*(1), 99-117. https://doi.org/10.1002/sej.1191

Nguyen, T.S., Mohamed, S., & Mostafa, S. (2021). Project stakeholder's engagement and performance: A comparison between complex and non-complex projects using SEM. *Built Environment Project and Asset Management*, *11*(5), 804-818. https://doi.org/10.1108/bepam-11-2020-0181

Pekuri, A., Pekuri, L., & Haapasalo, H. (2013). The role of business models in Finnish construction companies. *Construction Economics and Building*, *13*(3), 13–23. https://doi.org/10.5130/ajceb.v13i3.3402

Rottke, N., Schiereck, D., & Pauser, S. (2011). M&A in the construction industry-wealth effects of diversification into real estate life cycle related services. *International Real Estate Review*, *14*(3), 283-310. https://shorturl.at/1cTzL

Senaratne, S., Rodrigo, N., Almeida, L.M.M.C.E., Perera, S., & Jin, X. (2023). Systematic review on stakeholder collaboration for a circular built environment: Current research trends, gaps and future directions. *Resources, Conservation & Recycling Advances*, *19*, 200169. https://doi.org/10.1016/j.rcradv.2023.200169

Shakeel, J., Mardani, A., Chofreh, A.G., Goni, F.A., & Klemeš, J.J. (2020). Anatomy of sustainable business model innovation. *Journal of Cleaner Production*, *261*, 121201. https://doi.org/10.1016/j.jclepro.2020.121201

Stocker, F., de Arruda, M.P., de Mascena, K.M., & Boaventura, J.M. (2020). Stakeholder engagement in sustainability reporting: A classification model. *Corporate Social Responsibility and Environmental Management*, *27*(5), 2071-2080. https://doi.org/10.1002/csr.1947

Weerakkody, Y.D.C., & Thoradeniya, W.B.M. (2012). Importance of design phase stakeholder management for successfully achieving objectives of building projects: A Sri Lankan perspective. In. S. Senaratne, & Y.G. Sandanayake (Eds.), *World Construction Symposium 2012* (pp. 386-395). Ceylon Institute of Builders. http://dl.lib.uom.lk/handle/123/17011

Wilson, I.E., & Rezgui, Y. (2013). Barriers to construction industry stakeholders' engagement with sustainability: Toward a shared knowledge experience. *Technological and Economic Development of Economy*, *19*(2), 289-309. https://doi.org/10.3846/20294913.2013.799105

Yu, J., & Leung, M. (2018). Structural stakeholder model in public engagement for construction development projects. *Journal of Construction Engineering and Management*, *144*(6), 04018046. https://doi.org/10.1061/(asce)co.1943-7862.0001462

Yunus, M., Moingeon, B., & Lehmann-Ortega, L. (2010). Building social business models: Lessons from the Grameen experience. *Long Range Planning*, *43*(2-3), 308-325. https://doi.org/10.1016/j.lrp.2009.12.005

Zarewa, G.A. (2019). Barriers to effective stakeholder management in the delivery of multifarious infrastructure projects (MIPs). *Journal of Engineering, Project, and Production Management*, *9*(2), 85-96. https://doi.org/10.2478/jeppm-2019-0010

Pradeep, W., Thayaparan, M. and Nanayakkara, N.B., 2024. Training and development strategies to enhance the use of modern software in Quantity Surveying practice in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1077-1087. DOI: https://doi.org/10.31705/WCS.2024.85. Available from: https://ciobwcs.com/papers/

TRAINING AND DEVELOPMENT STRATEGIES TO ENHANCE THE USE OF MODERN SOFTWARE IN QUANTITY SURVEYING PRACTICE IN SRI LANKA

W. Pradeep[1], M. Thayaparan[2], and N.B. Nanayakkara[3]

ABSTRACT

Information technology (IT) has been developing day by day making a great impact on the construction industry including the Quantity Surveying (QS) profession. To perform the duties of the quantity surveyor in an innovative manner, software packages such as WinQS, Vector, Cost X, QSCAD, QSPlus, Masterbill, CATA, Planswift, Cubi cost, Revit, Excel and Autodesk Quantity take off, are introduced. The software is compatible with the task specialisation, speed up the performance and enhance the accuracy. Training programmes, seminars, workshops, software tutorials, higher education about software and Continuing Professional Development (CPD) are identified as approaches to integrate IT usage among the QS practices. This research aimed explore the gap between the awareness and practice of modern software in QS practices in Sri Lanka to propose suitable training and development strategies to achieve technological advancement. A mixed method approach was adopted to carry out this research using a survey as the main research strategy. Questionnaires were collected from 65 practising quantity surveyors in Sri Lanka to explore the gap between the level of awareness and practice of modern software. Five expert interviews were conducted with senior Quantity Surveyors who have been extensively using modern software in their practice. Gap analysis and manual content analysis were used to analyse primary data collected through questionnaires and interviews respectively. Development of the national construction guideline, professional training programmes, government concessionaries, professional degree programmes addressing modern software knowledge, and implementation of a marketing approach were the strategies recommended to address the training needs to achieve technological advancement in the QS practice in Sri Lanka.

Keywords: *Modern Software; Quantity Surveying Practice; Sri Lanka; Training and Development.*

1. INTRODUCTION

The world today is dynamic and characterised by constant technological advancement (Jaiswal et al., 2021). In this developing world, competitive advantages are being achieved with the aid of rapid technological improvement and innovative practices

[1]Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, pradeepqs77@gmail.com
[2]Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk
[3]Lecturer Department of Building Economics, University of Moratuwa, Sri Lanka, nishadhibn@gmail.com

(Kulasekara et al., 2013). All the business and industries are transforming their methods of practices with fundamental changes according to the advancement of IT system (Li et al., 2000). Global recognition and widespread adoption of Information Communication Technology (ICT) have encouraged competition not only among organisations yet among various professions worldwide (Oyediran & Odusami, 2005).

Quantity surveyors provide important and essential services to their clients which are unique from other consultants and contractors (Agyekum et al., 2015). Due to factors such as client's requirements, development and application of information and communication technology, research and developments of the profession, graduate capabilities and the size of practice, the role of the surveyors is expected to be developed in future (Thayaparan et al., 2011). Therefore, the construction industry certainly needs to improve its information flow and project delivery mechanism (Ibironke et al., 2011).

The lack of knowledge and skills concerning the practice of sophisticated software and techniques can usually be overcome through solutions such as training programmes, seminars, workshops and tutorials on the use of software (Raphael & Priyanka, 2014). As per the authors, staff will need training not only regarding the use of new software yet about changes in accountabilities and changes within the company itself. However, the limited usage of modern software in practice can affect badly to the productivity, efficiency, standards and development in Sri Lankan construction industry (Hewage et al., 2024). Even though measures have been taken to integrate ICT usage among QS practitioners, research exploring the efficiency of such modern software in QS practices in the Sri Lanka is limited. There is a dearth of research on effective training and development strategies to enhance the use of modern technology in QS practices. In addressing this research gap the aim of this study was to propose suitable training and development strategies to improve the use of modern software in QS practices in Sri Lanka. The research first explored the gap between awareness and practice of modern software used by QS in Sri Lanka, then the factors contributing to such gap were investigated to develop suitable training and development strategies to reduce the gap between awareness and practice.

2. LITERATURE REVIEW

The QS profession has experienced developmental changes from a measurement-oriented background to the current position where a quantity surveyor is accepted as a financial specialist and adviser in the construction industry of the countries where his expertise is recognised (Seidu et al., 2020). Salleh et al. (2020) stated important roles and responsibilities of a quantity surveyor such as providing approximate cost estimates, advice on procurement, cost planning, measuring items on-site, preparing bills of quantities, preparing schedules of works, preparing financial statements, controlling costs throughout project, and assessing and negotiating tender. The constant demands for greater precision of costs from the QS profession is a considerable challenge because of the increasing complexity of construction projects (Agyekum et al., 2015). During the pre-1960s, the roles of QS were limited to a scope including approximate estimating, bills of quantities, and final accounts, whereas they were widened during the last two decades to include e-procurement, Building Information Modelling (BIM), low-Carbon building technologies, private finance, public-private partnership and modern procurement, risk management, suitability etc. (Ashworth & Perera, 2015; Cartlidge, 2018).

Built environment professionals embraced IT into their practice with the prime intention of levelling up with other industries (Ibim, 2024). According to Smith (2011), IT shall be introduced into the QS practice in three main phases i.e. (i) Automation: to automate technical and specialist tasks using IT, (ii) Value addition: to improve the information management systems of QS firms by linking electronically with other partners of the construction supply chain, and (iii) Business process re-engineering: to operate the firms with the use of IT in order to transform the core business. In general, modern IT applications improve the quality of QS services in terms of shortened time, reduced cost, enhanced efficiency and effectiveness (Newman et al., 2020), less repetitive work, and improved communication modes (Haupt & Naidoo, 2016).

Although there have been potential benefits through ICT in the construction industry, the level of application used in the construction industry is limited (Gambo, 2017) due to challenges such as inadequate training and education in the use of IT tools, higher cost of investing and learning new technology, inadequate IT content in construction education, resistance to organisational change, lack of industry standards, additional cost of engaging computer staff, lack of management desire and appreciation of IT, breakdown problems, and fear of IT making professionals redundant (Agyekum et al., 2015). The less usage of IT in QS practices causes operational inhibitors, educational problems, poor return on investments, and high costs of software among others (Oyediran & Odusami, 2005). The lack of knowledge and skills related to the use of sophisticated software, resistance to organisational changes, and software becoming outdated and requiring frequent upgrading are the key reasons why IT is less used in QS practices (Raphael & Priyanka, 2014). However, limited usage of IT can badly affect the productivity, efficiency, standards and development of the Sri Lankan construction industry (Kulasekara et al., 2013).

When selecting software packages there are several factors considered by the QS organisations such as user-friendliness, flexibility, compatibility, initial cost, running cost, experience, security, and training (Jacky et al., 2007). As per the manufacture details, QS Plus, CATO, QSCAD, Quikest and Cost X software shall be used for the taking-off purpose, Win QS, QS Plus, CATO, QSCAD and Vector are used in BOQ preparation, and software such as CostX, Vector, Wessex, QSCAD, Estimate, QS Plus, Win QS and Master Bill are used as the tendering and estimating tools. Further, Quantity Surveyors are the one of most potential characters who utilise modern ICT applications during the project life cycle (Newman et al., 2020). When considering one main function done by QS professionals, quantity take-off, IT provides automated quantity take-offs that shall enable reduced errors and allow quicker take-offs (Adesi et al., 2018). This indicates that the QS profession does have the potential to improve its practice with the use of modern technology. By considering the demand for training on software usage for QS professionals, training shall be implemented by the current practitioners in the QS industry via Senior practitioners' advice and guidance, structured Continuous Professional Development (CPD), regular help from assigned tutors on the subject, in house seminars from the organisations, time allocation for self-training and self-studying, and update on the latest developments (Ying & Kamal, 2021). However, before deciding on the most suitable training and development programme, the existing level of knowledge and awareness that the quantity surveyors have of modern software and the level of actual practice using such software needs to be explored. The next section explains the research methodology adopted for this research.

3. METHODOLOGY

A mixed-method approach was selected to carry out the research integrating quantitative and qualitative approaches (Hands, 2022). A quantitative approach was used explore the gap between awareness and the practices of modern software and a qualitative approach to investigate the factors contributing to the gap, and to develop training and development strategies to reduce such gaps. The research problem “what is the gap between awareness and practice of modern software in the quantity surveying practice?” has placed the research in a fact-finding approach with the question starting with “what”, hence a quantitative approach was more appropriate to establish the gap. Besides, the research intends to cover a larger sample to explore the level of awareness and usage of different technologies used in QS practices. Hence, a survey was considered as the most suitable research strategy. Proposing training and development strategies to achieve technological advancement in QS practices would become a function of the researcher’s insights and impressions along with an assessment concerned with attitudes, opinions and behaviour of different industry professionals. This was achieved through a qualitative approach (Sutton & Austin, 2015).

Data collection was carried out using a questionnaire survey among Sri Lankan Quantity Surveyors to explore the gap between awareness and practice of modern software used in QS practice. Random sampling coupled with snowball technique was used to recruit the respondents for the questionnaire. Several databases maintained at the professional institutes of quantity surveyors and alumni associations were used to gather the contact details of quantity surveyors working in Sri Lanka, and email invitations were sent to all. In addition, the researchers asked the quantity surveyors to forward the survey invitation to other quantity surveyors, who are not included in the database. Hence the total population of Sri Lankan Quantity Surveyors who received the invitation was not known. 65 completed questionnaires were received which were used for the gap analysis. When analysing the features of this study, it shall be emphasised that 65 is an appropriate sample size for this study (Lakens, 2022). Additionally, expert interviews with five QS professionals who had at least ten years of experience and extensive knowledge and practical experience in using modern software were carried out to identify the reasons behind the gap between awareness and practice, and to propose suitable training and development strategies to achieve technological advancement in QS practices. Table 1 demonstrates the demographic factors of the experts interviewed.

Table 1: Demographic factors of the expert interviewees

	E1	**E2**	**E3**	**E4**	**E5**
Profession	Director/ Lecturer	General Manager	Senior quantity surveyor	Deputy general manager contracts	Senior Lecturer
Type of organisation	Consulting	Contracting	Contracting	Contracting	Academic institutes
Knowledge and experience with modern software	Yes	Yes	Yes	Yes	Yes
Industry experience	15 years	13 years	12 years	14 years	20+ years

The collected data from the questionnaire were analysed using gap analysis with the aid of a radar chart (Zhang & Chu, 2010), and the data gathered from the expert interviews were analysed using manual content analysis (Hsieh & Shannon, 2005).

4. RESEARCH FINDINGS

4.1 GAP ANALYSIS BETWEEN AWARENESS AND PRACTICE OF MODERN SOFTWARE

The questionnaire survey was conducted to explore the awareness (knowledge) and the actual usage (practice) of modern software in QS practices. The results of the questionnaire helped to establish the gap between the awareness and practice of the software. The study considered the software that is popularly used by QS professionals, such as MS Excel, MS Word, CostX, Planshift, Blue beam, Cubi cost, QSCAD, Win QS, QS PLUS, CATO, Vector, Estimate and Master Bill. Awareness of the QS professionals on the modern software was ranked based on the response rate obtained through the questionnaire survey. Accordingly, MS Excel had a response rate of 0.95 where it marked the highest awareness rate. MS Excel was used for BOQ preparation. MS Word, Cost X, PlanSwift, Blue Beam, QSCAD, and Cubi Cost reported considerably high rates of awareness which marked the response rates as 0.83, 0.74, 0.58, 0.65, 0.37, and 0.40 respectively. The lowest rate of awareness was reported for Win QS and Master Bill where the response rates were respectively 0.23 and 0.14. Cost X, Planswift, Bluebeam, QS CAD, and Cubi cost are mostly used for taking-off quantities and Win QS and Master Bill software are used for estimation. Further, MS Word is solely used for the purpose of report writing and documentation. Moreover, it was reported that none of the respondents were aware of software such as QS PLUS, CATO, Vector, and Estimate and they claimed that have never used such software in practice.

When it comes to practice, the survey revealed that MS Excel was highly used, showing a rate of 0.95, followed by MS Word with a 0.80 response rate. Apart from that, software such as Planswift, Blue Beam, Cost X, QS CAD, and Cubi cost had very low actual usage whereas Win QS had the least actual usage among the quantity surveyors.

Based on the questionnaire survey, even though the industry representatives are aware of the existence of most of the software the actual usage of such software in practice is lower than the awareness. Figure 1 illustrates the gap analysis done between awareness and practice against nine software that was used by Sri Lankan quantity surveyors.

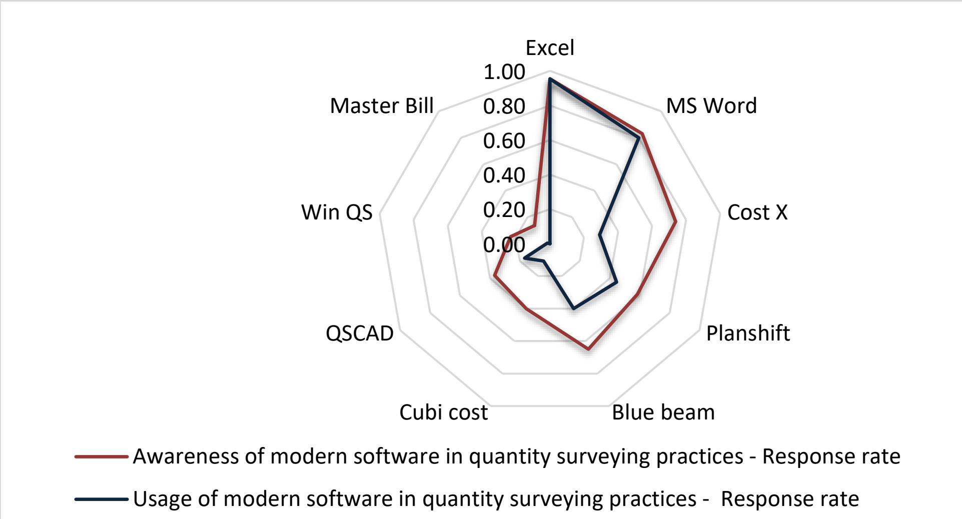


Figure 1: Gap identification of awareness and usage of modern software

As per Figure 1, it is visible that there is a considerable gap between the awareness and actual usage of most software except for MS Excel and MS Word, which had the highest level of awareness and usage. MS Excel is used for several QS tasks including, taking-off measurements, BOQ production, feasibility, estimation, cost planning, cost modelling, tender analysis, valuation, cost control, financial account reviewing, and report writing. It was evident that the respondents were aware of the use of Excel to perform the aforementioned tasks.

Cost X software has the highest gap between awareness and actual usage demanding critical attention for its improvement. This software enables to perform taking-off measurements and BOQ production more efficiently, however, the respondents seem comfortable with using MS Excel to perform such tasks.

The next highest gap is seen with Cubi Cost, which is used for quantity take-offs and estimations. Both the level of awareness and actual usage of Cubi Cost is comparatively lower than that than that of Cost X. Another considerable gap could be seen in Blue Beam, QSCAD and Planswift. The application of this software extends to several tasks such as quantity take-off, BOQ production, estimation, cost planning, tender analysis, and valuation. However, the respondents' awareness of the task performed by this software was limited to quantity take-off. The least awareness was on Master Bill and Win QS, where respondents have never practised. Hence it might consume more time and cost to implement strategies to introduce such software for QS practices.

The gap analysis helps to establish the customised training needs to minimise the gap between awareness and practice.

4.2 ANALYSIS OF THE FACTORS CONTRIBUTING TO THE GAP BETWEEN KNOWLEDGE AND PRACTICE

The gap analysis presented in Section 4.1 reveals the gap between the level of awareness and knowledge of several modern software and the level of actual usage of such software in QS practices. The factors that contributed to the gap between knowledge and practice were investigated through expert interviews.

E1 and E2 highlighted that the lack of practice is affected by the ***unavailability of software irrespective of its benefits and usage***. Further, most of the respondents confirmed the lack of usage shall also be due to the ***higher licensing cost and the maintenance cost of the software*** and is creating a gap between the knowledge and practice of the software. Moreover, ***personal computers which do not support high-functioning graphic software*** are a practical concern confronted by QS professionals in the office environment when practising modern software. However, E4 rejected the argument stating, "*software licenses are approaching as cloud license and it can share the licenses for view purposes*". Furthermore, as per E1 ***security issues, cyber-attacks, and risk of data redundancy*** are contributing to the gap between the knowledge and practice in the Sri Lankan context. E2 commented ***lack of time available for industry professionals due to tight schedules*** is demotivating the knowledge improvement of the professionals on modern software. As per E5, even though the professionals engage in developing the knowledge, the respective ***companies shall depict a lack of motivation towards the practice of the modern software,*** which shall waste the knowledge obtained by the professionals regarding the modern software. Demotivation towards modern software may arise due to several ambiguities such as the effect made on the traditional processes of the entity, working methods of employees, poor return on investment, less compatibility for the working environment, high initial cost or periodical payments for updates, and lack of experience on operating the software.

Furthermore, E1, E4, and E5 highlighted ***insufficient marketing on the software*** as another concern for the lack of awareness of modern software in Sri Lankan QS practice. Even though, higher education provides a structured education on MS Excel and MS Word, ***less concern was given to the modern software in university education***. This creates a knowledge gap in the QS industry. E3 pinpointed employees who know the software such as Cubi Cost cannot practically apply them to their daily tasks since it requires practice and structural guidance on the software irrespective of the knowledge. Furthermore, E5 highlighted that the ***lack of user-friendliness*** of advanced software such as 'Cubi Cost' and 'CostX' is demotivating the practice of the software. Nevertheless, E4 commented that it is not a reason for the increase of knowledge and practice of modern software since they are updating frequently.

4.3 STRATEGIES TO REDUCE THE GAP

The gap between awareness and the practice of modern software shall be addressed through implementing various strategies. Table 2 illustrates the strategies proposed by experts in reduce the identified gap.

Table 2: Strategies to reduce the gap between knowledge and practice in modern software

Strategies	E1	E2	E3	E4	E5
Introducing software in higher education	✓		✓		
Promoting the usage	✓	✓			
Reducing licensing fees	✓	✓	✓	✓	✓
Conducting practical workshops	✓	✓		✓	✓
Encourage employees to familiarise modern software		✓			
Reduce the fee for the software-related courses			✓	✓	
Increase the use of modern software in government organisations		✓	✓	✓	

Strategies	E1	E2	E3	E4	E5
Create standards and policies	✓		✓	✓	
Organising CPD sessions	✓		✓		✓

According to Table 2, "*reducing licence fees*" and "*organising practical workshops*" are the most accepted strategies to minimise the gap between knowledge and practice. Respondents emphasised on "*increasing promotional activities on the modern software to increase awareness*" and "*introducing practical and theoretical learning packages at higher education*". However, "*organising CPD sessions*", "*creating national standards and policies*", "*increase the use of modern software*", and "*encourage the use of modern software at professional practice*" are several other strategies proposed. However, E4 disagreed with conducting CPDs stating that "*CPD sessions on modern software practices will not provide the expected outcome since a technical skill is impossible to obtain within a few hours of training*".

The experts further added the following factors as the barriers to effective implementation of the strategies proposed by them. According to the respondents, ***lack of financial capabilities*** of the companies, as well as the ***high consumption of time*** is affecting the acquisition of the knowledge and practice of the modern software. It was further highlighted that ***privacy issues, malfunctions, and vulnerability of hackers*** as the challenging factors for the adaptation of modern software for QS aspects. Furthermore, ***lack of interest of the students and the professionals to familiarise modern technology*** is a challenge arising from personal perspectives. Along with the lack of interest, ***higher resistance to change*** appear as a demotivating factor. In the academic perspective, there prevails a ***shortage of lecturers in the academic institutions***, and in the industry perspective, there is a ***lack of trainers***, which challenges the implementation of strategies. The experts emphasised that ***unavailability of marketing approaches for familiarity with modern software*** has become a challenge in the modern industry to increase awareness. Further, ***unavailability of a common platform and resources for the project stakeholders to proceed*** has become a challenge that affects the increase of the gap of knowledge and practice in the QS profession. Additionally, ***complexity of the modern software*** when compared to traditional software such as MS Excel and MS Word, irrespective of the user's capabilities, is a key challenge that degrades the implantation of strategies to reduce the gap between knowledge and practice.

4.4 TRAINING AND DEVELOPMENT FRAMEWORK TO IMPROVE THE USE OF MODERN SOFTWARE IN QUANTITY SURVEYING PRACTICE

Technological advancement for QS practices shall be attained via several modes, especially through training and development. Training and development of software are achievable through the building up both knowledge and the practice of the modern software used to perform QS related tasks. Figure 2 illustrates the training and development strategies proposed by the experts to achieve technological advancement in QS practices. The specific initiatives discussed by the experts under each strategy are presented in Figure 2. If the initiatives can be undertaken by the identified stakeholders, such as the government, professional bodies, and the professionals, that would help to implement the strategies, which in turn will help to reduce the gap between the awareness and practice of modern software in QS practice. However, the effective implementation of such strategies can be hindered by the barriers identified by the experts that are discussed in Section 4.4.

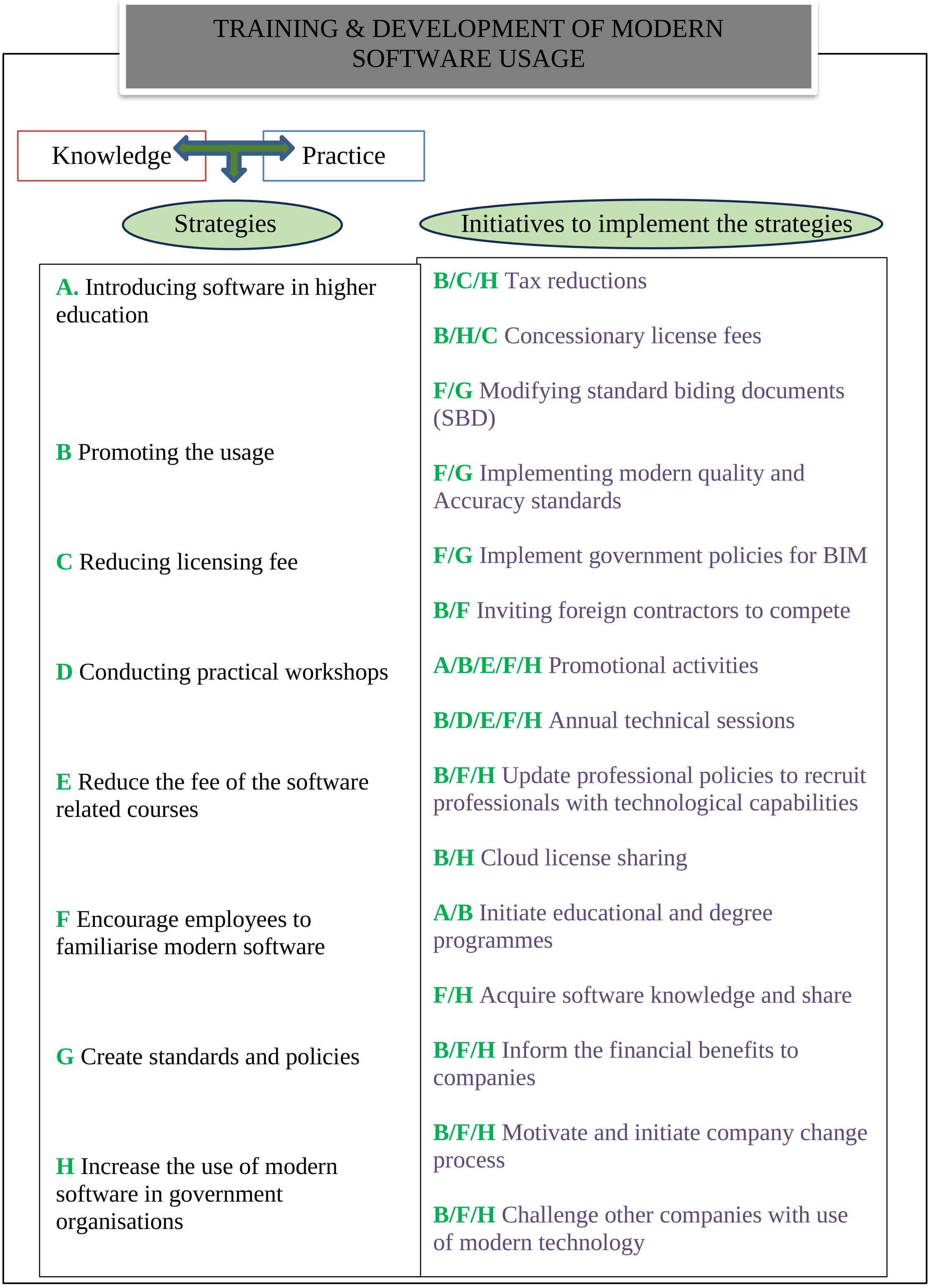


Figure 2: Training and development approaches in achieving modern technological advancements in the QS practice

5. CONCLUSIONS

This study has explored the gap between awareness (knowledge) and practice (actual usage) of modern software in QS practice. The factors, contributing to such a gap were identified to propose suitable training and development strategies to address the existing gap. Additionally, specific initiatives along with the responsible stakeholders were identified under the strategies. The research further discussed the barriers to the effective implementation of the strategies.

The evolutionary nature of the roles played by the quantity surveyors shall be made more efficient and effective with the use of modern software. Much software is available, and each software shall be used to perform general and specific tasks of quantity surveyors. This research proposed the training and development strategies for quantity surveyors to reduce the gap between awareness and practice of modern software. To efficiently utilise such training and development strategies, support is necessary from the government and professional bodies. Accordingly, the framework developed has identified the necessary strategies, along with the initiatives to be undertaken by the government, professional bodies, higher education institutes and QS professionals to improve the application of modern software in QS practice in Sri Lanka. The findings of this study shall be used by higher education institutions and industry professionals in leveraging the software usage to streamline the QS-related job roles. The findings shall be utilised to implement strategies in providing training and development for QS professionals on modern software usage.

6. REFERENCES

Adesi, M., Murphy, R., & Kehily, D. (2018). Information Technology (IT) for strategy formulation in Irish quantity surveying firms: A literature review. *RICS COBRA 2018 conference, RICS HQ, London*. https://doi.org/10.21427/fv6p-rv91

Agyekum, K., Ayarkwa, J., & Acheanpong, A. (2015). Incorporating information technology in quantity surveying practice in Ghana: Challenges and benefits. *International Journal of Engineering, 13*(4), *4*9-56.

Ashworth, A., & Perera, S. (2015). *Cost studies of buildings* (6th ed.). Routledge.

Cartlidge, D. (2018). *New aspects of quantity surveying practice* (4th ed.). Routledge.

Gambo, M. D. (2017). Impact of information communication technology on building construction project delivery in Nigeria. *International Journal of Sciences, Engineering & Environmental Technology (IJOSEET), 2*(2), 10-16. https://www.repcomseet.org/journal/Gambo-Impact_of_ICT_on_Building-160117.pdf

Hands, A. S. (2022). Integrating quantitative and qualitative data in mixed methods research: An illustration. *The Canadian Journal of Information and Library Science*, *45*(1), https://doi.org/10.5206/cjilsrcsib.v45i1.10645

Haupt, T., & Naidoo, S. (2016). The threat of technology to the way quantity surveying is practiced in Kwazulu-Natal. ASOCSA: *10th Built environment conference* (pp. 25-36). Port Elizabeth, South Africa.

Hewage, I. S., Manorathna, G.L., & Halwatura, R.U. (2024). Effectiveness of software applications in construction project management; *PM World Journal*, *13*(4), https://pmworldlibrary.net/wp-content/uploads/2024/04/pmwj140-Apr2024-Hewage-Effectiveness-of-Software-Applications-in-Construction- PM.pdf.

Hsieh, H. F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research*, *15*(9), 1277–1288. https://doi.org/10.1177/1049732305276687

Ibim, A. A. (2023). Awareness Level and Barriers to the Use of Quantity Surveying Software in the Nigerian Built Environment. *Nolegein Journal of Information Technology & Management*, *6*(2), https://mbajournals.in/index.php/JoITM/article/view/1239

Ibironke, O. T., Ekundayo, D., & Awodele, O. A. (2011). A survey on the use and impact of information technology in quantity surveying service delivery in Nigeria. *ARCOM 2011 - proceedings of the 27th Annual Conference*. Bristol, UK: Association of Researchers in Construction Management. https://core.ac.uk/reader/5901260

Jacky, C., Shen, Q., & Zhen, C. (2007). The use of information technology by the quantity surveying profession in Hong Kong. *International Journal of Project Management*, *25*, 134-142.

Jaiswal, A., Arun, C. J., & Varma, A. (2021). Rebooting employees: Upskilling for artificial intelligence in multinational corporations. *The International Journal of Human Resource Management*, *33*(6), 1179–1208. https://doi.org/10.1080/09585192.2021.1891114

Kulasekara, G., Jayasena, H. S., & Ranadewa, K. (2013). Comparative effectiveness of quantity surveying in a building information modelling implementation. *The second world construction symposium 2013: Socio-economic sustainability in construction*.

Lakens, D. (2022). Sample size justification. *Collabra: Psychology*, *8*(1), https://doi.org/10.1525/collabra.33267

Li, H., Irani, Z., & Love, P.E.D. (2000). The IT performance evaluation in the construction industry. *Proceedings of the 33rd Hawaii international conference on system sciences*. http://dx.doi.org/10.1109/HICSS.2000.926927

Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W. D., & Rillie, I. (2020). Industry 4.0 deployment in the construction industry: A bibliometric literature review and UK-based Case Study. *Smart and Sustainable Built Environment*, *10*(4), 557–580. https://doi.org/10.1108/sasbe-02-2020-0016

Oyediran, O. S., & Odusami, K. T. (2005). A study of computer usage by Nigerian quantity surveyors. *ITcon*, *10,* 291-303. https://www.itcon.org/2005/20

Raphael, V., & Priyanka, J. (2014). Role of Building Information Modelling (BIM) in quantity surveying practice. *International Journal of Civil Engineering and Technology (IJCIET), 5*(12), 194-200. https://iaeme.com/MasterAdmin/Journal_uploads/IJCIET/VOLUME_5_ISSUE_12/IJCIET_05_12_021.pdf

Salleh, N. M., Husien, E., Husin, S. N., Muhammad, N. H., & Alang, N. (2020). Quantity surveyors' roles and responsibilities in different job sectors. *International Journal of Academic Research in Business and Social Sciences*, *10*(10), 1090-1101. https://doi.org/10.6007/ijarbss/v10-i10/8271

Seidu, R. D., Young, B. E., Clack, J., Adamu, Z., & Robinson, H. (2020). Innovative changes in quantity surveying practice through BIM, big data, artificial intelligence and machine learning. *The Journal of Applied Science University, 4*(2), 37–47. https://doi.org/10.18576/jasu/040201

Smith, P. (2011). Information technology and the QS practice. *Construction Economics and Buildings, 1*(1), 1-21. https://doi.org/10.5130/AJCEB.v1i1.2276

Sutton, J., & Austin, Z. (2015). Qualitative research: Data collection, analysis, and management. *The Canadian Journal of Hospital Pharmacy*, *68*(3), 226–231. https://doi.org/10.4212/cjhp.v68i3.1456

Thayaparan, M., Siriwardena, M., Amaratunga, R., Malalgoda, C., & Keraminiyage, K. (2011). Lifelong learning and the changing role of quantity surveying profession. *15th Pacific Association of Quantity Surveyors Congress* (p. 355). https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=9ad69ca126d62c0db46bc1948eaac39b9092e2e0

Ying, T. Y., & Kamal, E. M. (2021). The revolution of quantity surveying profession in Building Information Modelling (BIM) era: The Malaysian perspective. *International Journal of Sustainable Construction Engineering and Technology*, *12*(1), https://doi.org/10.30880/ijscet.2021.12.01.019

Zhang, Z., & Chu, X. (2010). A new approach for conceptual design of product and maintenance. *International Journal of Computer Integrated Manufacturing*, *23*(7), 603–618. https://doi.org/10.1080/09511921003736766

Wijerathna, M.R.D.P., Waidyasekara, K.G.A.S. and Atapattu, A.M.D.S., 2024. Unveiling the benefits of radio frequency identification (RFID) technology for enhancing technological applications in Sri Lankan construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1088-1100. DOI: https://doi.org/10.31705/WCS.2024.86. Available from: https://ciobwcs.com/papers/

UNVEILING THE BENEFITS OF RADIO FREQUENCY IDENTIFICATION (RFID) TECHNOLOGY FOR ENHANCING TECHNOLOGICAL APPLICATIONS IN SRI LANKAN CONSTRUCTION INDUSTRY

M.R.D.P. Wijerathna[1], K.G.A.S. Waidyasekara[2], and A.M.D.S. Atapattu[3]

ABSTRACT

The research delves into the underexplored realm of Radio Frequency Identification (RFID) technology within the Sri Lankan construction industry. Although it is relatively new to the construction industry, sectors such as healthcare and agriculture have effectively adopted RFID. For Sri Lanka's construction industry, a developing sector, integrating RFID could substantially advance its technological applications. Despite its potential, RFID implementation has not commenced in Sri Lanka's construction sector. Therefore, this study aims to investigate the benefits of RFID technology for enhancing technological applications in the Sri Lankan construction industry. An exploratory mixed research approach was used. Eleven semi-structured interviews were conducted during the preliminary survey with RFID technology experts. Subsequently, a questionnaire was distributed among 110 professionals in the Sri Lankan construction industry who are familiar with RFID technology. A total of 96 responses were collected resulting 80% response rate. The research findings revealed that the implementation of RFID technology has a higher potential to enhance the product quality and safety of the Sri Lankan construction industry. Theoretically, this study demonstrates the potential of RFID technology to enhance technological applications within the Sri Lankan construction industry. The findings of this study offer practical insights that can aid Sri Lankan construction industry practitioners in the successful implementation of RFID technology.

Keywords: *Benefits; Construction Industry; Radio Frequency Identification (RFID); Sri Lanka; Technology.*

1. INTRODUCTION

The construction industry is a vital contributor to economic growth, providing infrastructure and employment opportunities while increasing Gross Domestic Product (GDP) in developing countries (Alaloul et al., 2020). However, the industry encounters criticism for its lack of safety, productivity, output quality, and system performance (Bansal et al., 2019). It is reasonable to anticipate that the construction sector's success

[1] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dewminir@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dilmia@uom.lk

will be stimulated by Information Technology (IT) investments (Gaith, 2012). Effective management of the construction process is vital, and new technologies present one of the greatest chances to enhance the process via increased efficiency and greater integration (Holt et al., 2015). More importantly, advancements in technology offer the potential to address issues in the construction industry, particularly through the adoption of intelligent systems that utilise the Internet of Things, artificial intelligence, and Big Data (Kozlovska et al., 2021).

Among the studies on new technologies, Lanko et al. (2018) describe RFID as a technique that automatically identifies objects which use RFID scanners to read or write data stored in RFID tags using radio signals. RFID, a next-generation technology for tracking and data collection, has been successfully adopted across various industries, including manufacturing, retail, and logistics (Haddara & Staaby, 2018). RFID technology is a significant advancement in IT that presents new opportunities for the construction industry to enhance teamwork, communication, and information management (Tan & Sidhu, 2022). RFID can be used for sensing, detecting, identifying, tracking, and monitoring various items, making it particularly useful in construction projects (Kereri & Adamtey, 2019). Valero and Adán, (2016) mentioned that during the life cycle of a building, many different operations have been made simpler and even automated using RFID. Further, the adoption of RFID technology has the potential to improve efficiency, quality, safety, and economy in construction while reducing labour and material costs and optimising project timelines (Valero et al., 2015).

Over the past ten years, it seems that a reasonable amount of technology transfer was accomplished with a rather well-equipped technical and managerial basis, however, there is still much more to be accomplished (Santoso & Gallage, 2020). Although the IT sector is expanding rapidly, the use of IT in the Sri Lankan construction industry is still in its adolescent period (Atapattu et al., 2023; Manoharan et al., 2023). Furthermore, Sri Lanka's construction industry seldom ever uses automation and digital transformation, despite being a developing nation (Munmulla et al., 2023). At the same time, even if RFID technology has plenty of proven benefits, Sri Lanka has yet to implement RFID technology for the construction industry (Ruchiranga & Samarasekara, 2018). Therefore, in addressing this gap, this study aims to investigate the benefits of RFID technology for enhancing technological applications in the Sri Lankan construction industry. The main objective of the study is to investigate the significant benefits of RFID in Sri Lankan construction industry. This paper consists of an introduction, a literature review of the research area, a research method, data analysis and finally, the conclusions and recommendations.

2. LITERATURE REVIEW

2.1 INTRODUCTION TO RFID TECHNOLOGY

According to Costa et al. (2021), RFID has become popular since it is a viable alternative to conventional barcode technology, offering more benefits compared to other alternatives. Due to its minimal expense, passive wireless power transfer capability, adaptability, and non-line-of-sight communication, RFID technology is viewed as a new sensing prototype (Dobkin, 2012; Suresh & Chakaravarthi, 2022). The components of an RFID system are designed to fulfil the purpose of identifying people and objects (Kereri & Adamtey, 2019).

RFID uses radio waves for tracking or identifying objects with attached tags (Gao et al., 2022). In RFID systems, there are tags or transponders, a reader or transceiver and an antenna where the reader and transponder communicate data (Kereri & Adamtey, 2019). The tags or transponders are responsible for identifying the location of an object or person (Dobkin, 2012). Readers or transceivers are used to read the information encoded on these tags (Patil & Shelake, 2021). The computer database stores and analyses the data received from the tags, enabling effective data management and utilisation (Borda et al., 2019). The antenna plays a critical role by providing an electromagnetic field that activates the tags, facilitating communication between the tags and the readers (Roh et al., 2009).

2.2 APPLICATIONS OF RFID TECHNOLOGY IN THE CONSTRUCTION INDUSTRY

RFID has been successfully utilised for many applications in the construction industry (Domdouzis et al., 2007). There are several countries including Turkey (Hamadneh et al., 2021), the United States of America (USA) (Kereri & Adamtey, 2019), Malaysia (Huang et al., 2019) and the United Kingdom (UK) (Valero et al., 2015) that have initiated the implementation of RFID technology in their construction industries. Li and Becerik-Gerber (2011) have identified twelve countries where RFID is currently used in the construction industry to manage equipment, tools, inventories and workforce and to improve the safety of construction sites. Moreover, to track machinery and tools and minimise loss, misplacement, or theft, RFID tags can preserve a record of borrowing and returning them (Kereri & Adamtey, 2019). Locating equipment and tools can be performed using RFID technology. With its wavelength and contactless advantages, RFID technology can aid in resolving issues with machine and tool tracking (Huang et al., 2019). Patil and Shelake (2021) mentioned that the employment of RFID is done to support current practices of materials management on the construction site and is considered to improve the effective management of construction materials on site. An efficient access control system can help effective labour management by securing the site, staff, and assets (Lake & Jaselskis 2000). RFID systems can be used in conjunction with an attendance checking system, which can provide time and attendance records that can be used as a foundation for other purposes, such as allocating tasks and determining pay (Huang et al., 2019).

Multiple subcontractors and employees are using an RFID card that can be combined with an existing card to store their IDs, and photographs, and provide access information to government agencies and businesses (Valero & Adán, 2016). The information is retrieved, compared, and either granted or denied access is determined by a reader at the construction site's entrance and exit (Ergen et al., 2017).

2.3 BENEFITS OF RFID TECHNOLOGY IN THE CONSTRUCTION INDUSTRY

Valero and Adán, (2016) mentioned that during the life cycle of a building, many different operations have been made simpler and even automated using RFID. However, RFID technology is not entirely new to the construction sector (Lu et al., 2011). RFID has been successfully utilised for many applications in the construction industry (Valero et al., 2015). The potential applications of RFID technology have offered the most significant benefits and values for the construction industry (Roh et al., 2009). Hamadneh et al. (2021) mentioned that first, construction industry practitioners must be convinced about the benefits before justifying the need to implement new technology.

RFID tag implementation comes with both fixed and recurring expenses, however, over time, these costs are reduced overall due to lower inventory stock levels and inventory handling costs (Li & Becerik-Gerber, 2011). Additionally, the techniques boost sales by lowering shrinkage and out-of-stock, increasing order fulfilment rates, increasing inventory turns, and generally providing better customer service (Piramuthu, 2008). Workflow is significantly accelerated as the first result of the use of RFID tag technologies (Kasim et al., 2013). Time can be greatly saved by automatically recording information such as the time of production, access to the customer's site, and departure from the concrete plant's territory (Sudarshan et al., 2022). Along with reducing time, accompanying document completion that is automatic or semi-automatic will help cut down on the number of workers needed for processing and control (Suresh & Chakaravarthi, 2022).

The key advantages of RFID are increased component traceability and visibility, process speed and accuracy, and a decrease in material losses (Lu et al., 2011). Material managers can control their inventories efficiently with the use of RFID systems (Valero & Adán, 2016). Productivity has been a problem in the building construction industry, and it has an impact on project costs and schedules (Lu et al., 2011). Performance and productivity are indirectly increased by RFID readings because they increase the accuracy of information communication and speed (Wang, 2008). Further, RFID technology increases efficiency by automating certain superfluous activities and reducing their number (Kereri & Adamtey, 2019).

2.4 NEED FOR RFID TECHNOLOGY IN THE SRI LANKAN CONSTRUCTION INDUSTRY

According to Rajakaruna et al. (2008), due to the fast rise in large-scale projects such as irrigation, electricity, and industrials, construction activity was undertaken, necessitating a vast technological input.

It did, however, show that the local building sector was not entirely equipped to fulfil this increasing technical demand (Jayasena & Weddikkara, 2012). Most of the large building projects were awarded to foreign contractors due to a lack of technological improvements in local construction organisations (Gunawardena et al., 2016). According to a study by Rajakaruna et al. (2008), approximately 90% of the Sri Lankan public sector projects encounter cost and time overruns due to the lack of technologies used for the construction mechanisms. The authors further state that this problem impairs the nation's construction projects' general efficacy and efficiency.

Research suggests that there are advanced technologies used in the Sri Lankan construction sector (Gamlath et al., 2020; Jayasena & Weddikkara, 2012; Rosayuru et al., 2022; Waidyasekara et al., 2020). Drone technology and Building Information Modelling (BIM) are two examples of technologies that are becoming more popular in the Sri Lankan construction sector (Perera et al., 2020). However, it is important to understand that, when considering the global context, these technologies can be regarded as antiquated. Furthermore, there are numerous resource management issues in the Sri Lankan sector due to the minor involvement of advanced technologies (Manoharan et al., 2023), which can be overcome by the implementation of novel technologies such as RFID technology (Zhu et al., 2012).

RFID technology is one of the main factors influencing the construction industry's ability to operate effectively (Patil & Shelake, 2021). Past research has been conducted on applying RFID technology to different countries' construction industries around the world (Lu et al., 2011; Roh et al., 2009; Valero et al., 2015). At the same time, the Sri Lankan construction industry is in dire need of adhering to new technologies for the improvement of the construction industry (Rajakaruna et al., 2008). According to Zhu et al. (2012), RFID technology improves efficient equipment use, labour tracking, and inventory management, yet there is no available literature on applying RFID to the Sri Lankan construction industry. Given this research gap and the need in the industry, it is crucial to investigate the applicability of RFID technology in enhancing technological applications in Sri Lankan construction industry since the advancement of the construction industry in developing economies such as Sri Lanka will have a remarkable impact on the growth of the particular local economy and indirectly to the global economy as well (World bank, 2021).

3. METHODOLOGY

This study aims to investigate the benefits of RFID technology for enhancing technological applications in the Sri Lankan construction industry. Considering the limitations to achieve this aim, the study adopted an exploratory mixed-method approach, which allowed to collection of both qualitative and quantitative data. The study included a review of the literature, semi-structured interviews and a questionnaire survey. Toit (2012) justified this method by asking respondents to apply results from the literature to their own experiences, therefore, providing a platform for an exploratory and thorough assessment of their real-life experiences. The study used purposive sampling to select professionals involved in the construction industry during Phase 1. In the preliminary survey, eleven semi-structured interviews were conducted with a group of experts in RFID technology. Table 1 provides a summary of the details of the experts who participated in the preliminary survey.

Table 1: Details of the interviewees

Interviewee ID	Discipline	Designation	Experience	Country
E1	Civil Engineering	Senior professor	15 years	USA
E2	Civil Engineering	Senior Civil Engineer	18 years	Nigeria
E3	Civil Engineering	Senior Civil Engineer	10 years	Sri Lanka
E4	Civil Engineering	Senior professor and Consultant	16 years	Malaysia
E5	Quantity Surveying	Senior quantity surveyor	23 years	USA
E6	Quantity Surveying	Project quantity surveyor	10 years	UAE
E7	Quantity Surveying	Project quantity surveyor	09 years	Nigeria
E8	Quantity Surveying	Senior professor	16 years	China
E9	Quantity Surveying	Project Manager	23 years	USA
E10	Quantity Surveying	Senior professor	10 years	Australia
E11	Quantity Surveying	Consultant Quantity Surveyor	13 years	UK

During Phase 2 of data collection, a questionnaire survey was designed to collect quantitative data. The questionnaire was based on a Likert scale and consisted of closed-ended questions. It was distributed as an online survey among Sri Lankan construction industry professionals who had an awareness of RFID technology. The questionnaire was completed with a response rate of 80%, since out of 120, 96 professionals had responded. Figures 1 and 2 illustrate the industry experience of the respondents and their level of awareness of RFID respectively.

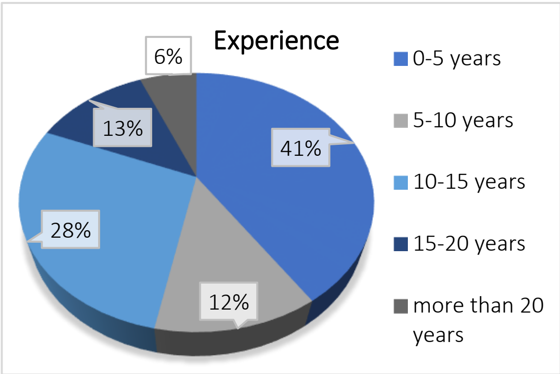


Figure 1: Experience of respondents

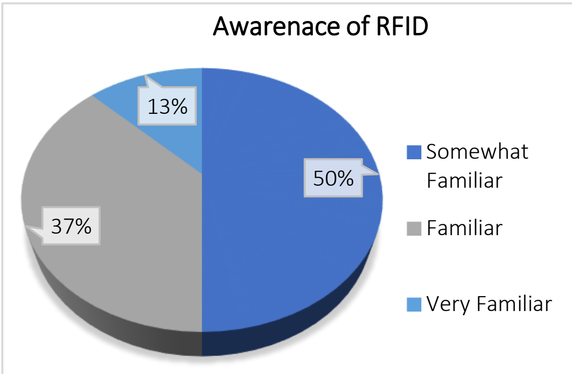


Figure 2: Level of awareness

The qualitative data collected from the preliminary survey were analysed using content analysis to identify themes and patterns related to the adoption of RFID technology in the Sri Lankan construction industry. The quantitative data collected from the questionnaire survey were analysed using the Relative Importance Index (RII) technique to identify the most important benefits that influence the adoption of RFID technology in the Sri Lankan construction industry. Factors with RII values of 0.800 or more than 0.800 are considered highly significant factors in this study (Akadiri et al., 2013). Whereas RII values between $0.6 \leq \text{RII} < 0.8$ and less than 0.600 are considered significant and not significant respectively.

4. DATA ANALYSIS AND FINDINGS

4.1 IMPLEMENTATION OF RFID TECHNOLOGY IN SRI LANKAN CONSTRUCTION INDUSTRY

During the preliminary expert survey, it was revealed that the USA, European countries, Middle Eastern countries, China, Malaysia, Singapore, and Australia have successfully implemented RFID technology in the construction industry. Experts highlighted their opinions regarding why Sri Lanka has not implemented RFID technology in the construction industry and most of them highlighted, as a developing country, Sri Lanka has financial and technical limitations when adopting new technologies. E3 elaborated "*construction companies in Sri Lanka do not have resources such as finances, technical staff, equipment related to this technology*". Additionally, E4 added "*developing countries most of the time prefer to stick to traditional methods rather than adopting innovative technologies. The construction industry is no different. People are reluctant to move from their comfort zones*". Further, E2 highlighted that the younger generation prefers innovative technologies to senior professionals in the construction industry and they will be a greater influence when implementing RFID technology. According to E4, "*more benefits are available if we could implement the RFID technology. Therefore, it is beneficial to implement it in the construction industry*". Eventually, all the experts commented positively on introducing RFID technology to the Sri Lankan construction industry. In this sense, it is worth noting E1's explanation where it was claimed that "*RFID improves the quality of the operation. RFID is a better technology available with many benefits which are essential for the development of the Sri Lankan construction sector*".

4.2 APPLICATIONS OF RFID TECHNOLOGY IN THE CONSTRUCTION INDUSTRY

According to the responses of experts, they all agreed that RFID technology can be applied to **Machinery Management**. E5 mentioned, "*RFID is one of the most effective automated technologies used for machinery management*". However, experts did not agree with the guiding, operation as one of the RFID applications. E1 explained, "*guiding and operation is the same process done in tracking*". E2 and E4 had similar thoughts to E1. Additionally, E3 mentioned that the phrase guiding, the operation does not explain the exact application of RFID and he supported his view with an example that "*as an example machine used in a construction site can be tracked and operated using RFID technology. There is no need to repeat it".*

Five experts accepted that RFID can be used in **Material management**. E2 did not agree with the Logistic and Supply Chain Management (LSCM) application since he did not have any idea about it. E4 mentioned, "*applying RFID to ensure the quality assurance application is not that effective. There are other applications to which RFID technology can be applied*". Further E4, suggested that lifecycle information tracking using RFID technology is an additional application.

All the experts have agreed with **Labour management** as an application of RFID technology. **"***When it comes time to process payroll, this means that there will be more work for the person who needs to find these wayward employees and make the necessary repairs. Each employee's hard hat or employee ID card has an RFID tag attached to it. A portable reader or a gateway at the job site's entrance can be used to scan the tags".* E3 elaborated stating, "*there is an RFID solution to suit your demands, whether you want to increase efficiency, increase safety, or better manage your assets, personnel, and equipment".* Further, E5 mentioned that RFID technology can be applied to onsite inspections.

4.3 BENEFITS OF RFID TECHNOLOGY IN THE CONSTRUCTION INDUSTRY

The experts were requested to express their opinions regarding the benefits of RFID technology in the construction industry. All the experts agreed that **cost reduction** is a major benefit of RFID technology if implemented in the construction industry. E1 explained, "the *main purpose of applying a modern technology rather than forwarding through the traditional methods is to reduce the cost*". According to the opinion of experts, RFID technology **enhances product quality and safety**. It was acknowledged that RFID technology improves the services in the construction site in return which helps the outcome of the project to be an enhanced quality product.

All experts agreed that **inventory discrepancy reduction** is a benefit of RFID technology in the construction industry. Further experts mentioned that anything that is lost can be found using the RFID system which in return ensures security. Moreover, E3 agreed on the benefit mentioning *"definitely RFID improves inventory management*". All eleven experts accepted that **productivity improvement** is a benefit of RFID technology in construction. E7 elaborated "*implementing RFID in a construction site would assist efficient work management and time management with its numerous applications. Therefore, the productivity of the construction would improve".* Every expert believes that the **availability of real-time data** is a benefit of RFID technology. E3 pointed out that using RFID staff, machine and material localisation can be done. Whenever someone needs to know the information, they are already available on the computer since tags are sending radio signals about their current location. Additionally, E4 stated, "*with one mouse click one can locate the person, material or machine without wasting time*".

Though **tracking** is identified as a benefit of RFID technology in the construction industry by many researchers, four experts disagreed mentioning that it is an application of RFID rather than a benefit. However, E3 had a different opinion than the other four experts stating that tracking could be taken as a benefit of RFID. The common view of experts was that inventory discrepancy reduction is equal to an **error rate reduction.** E2 explained, "*as per my knowledge error reduction and discrepancy reduction are the same thing".* Therefore, it was removed from the benefits list since there is no need to repeat the same benefit twice.

As per the experts' opinion, **system automation** is a benefit of implementing RFID in the construction industry. E1, E3, and E4 highlighted the importance of implementing RFID technology in construction sites, as RFID tags help to identify objects, transmit information, and store the information automatically. Moreover, E5 explained, "*RFID technology acts as a base in the data acquisition, the automatic identification and analysis systems worldwide".* Further E2 mentioned that this is conservative with resources in the construction industry. All experts believe that the RFID technology in the construction industry offers **data backup** as a benefit. E6 explained, "*information gathered through RFID tags is stored in a database*". Further E5 added, "*daily backups are available in the database. Necessary information can be obtained easily*". Furthermore, the preliminary survey identified several benefits not mentioned in the literature survey, including better asset management and handling of returnable assets, improved efficiency of store operations, enhanced connections with suppliers, and improved time management.

4.4 SIGNIFICANT BENEFITS OF RFID TECHNOLOGY IN SRI LANKAN CONSTRUCTION INDUSTRY

The questionnaire was intended to collect information regarding respondents' opinions on the benefits which the Sri Lankan construction industry would gain from the implementation of RFID technology. Figure 1 and Table 3 illustrate the results of the respondents regarding the benefits that the Sri Lankan construction industry could gain if RFID technology is implemented.

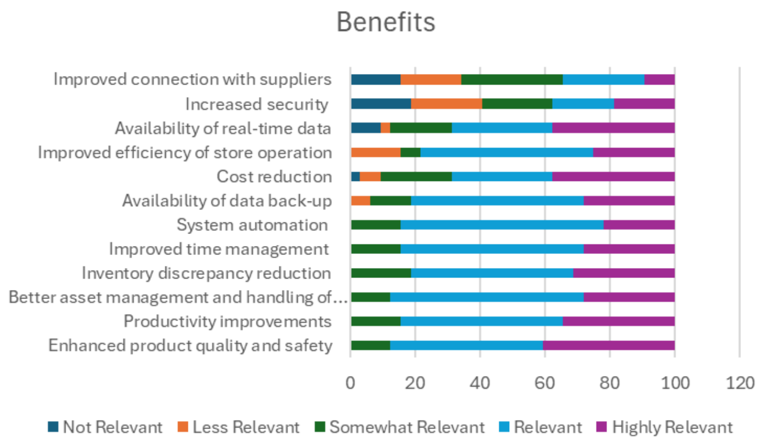


Figure 3: Relevancy of benefits of RFID

Table 2: Benefits of RFID

Benefits	RII value	Significance level	Rank
Enhanced product quality and safety	0.856	Highly Significant	1
Productivity improvements	0.838	Highly Significant	2
Better asset management and handling of returnable assets	0.831	Highly Significant	3
Inventory discrepancy reduction	0.825	Highly Significant	4
Improved time management	0.825	Highly Significant	4
System automation	0.813	Highly Significant	6
Availability of data back-up	0.806	Highly Significant	7
Cost reduction	0.788	Significant	8
Improved efficiency of store operation	0.775	Significant	9
Availability of real-time data	0.769	Significant	10
Increased security	0.594	Not Significant	11
Improved connection with suppliers	0.588	Not Significant	12

According to Table 3, respondents have identified “enhanced product quality and safety” as the most significant benefit. This benefit had an RII of 0.856 which was the highest RII value. “Productivity improvement” was ranked number two among other benefits with a 0.838 RII value. Better asset management and handling of returnable assets, inventory discrepancy reduction, improved time management, system automation, and availability of data back-up are selected as highly significant benefits other than the above-mentioned benefits. Significant benefits of RFID were ranked after highly significant benefits. They had scored a range of 0.6-0.8 RII value. Respondents have identified cost reduction, availability of real-time data, and availability of real-time data as significant benefits to the Sri Lankan construction industry. However, increased security and improved connection with suppliers were identified as non-significant benefits of RFID technology to the Sri Lankan industry during the analysis of the questionnaire. Two benefits have scored RII of 0.594 and 0.588 respectively which were identified as a non-significant benefit to the Sri Lankan construction industry since it had less than 0.6 RII value.

5. DISCUSSION

Findings of the expert interviews and the questionnaire findings have elaborated similar concerns about benefits. Enhanced product quality and safety, productivity improvements, better asset management and handling of returnable assets, inventory discrepancy reduction, improved time management, system automation and availability of data back-up were identified as the significant benefits to the Sri Lankan construction industry through the questionnaire. More importantly, this study produced results which corroborate the findings of studies conducted in the global context (Valero & Adán, 2016; Wang, 2008). However, 'increased security' and 'improved connection with suppliers' were identified as non-significant benefits of RFID technology to the Sri Lankan industry during the analysis of the questionnaire. These benefits were suggested by the experts during the preliminary survey. However, most respondents believe RFID tags can be easily manipulated, and the database of the RFID can be hacked. Therefore, the respondents may not perceive RFID as a technology capable of enhancing construction site security.

According to the findings, it was revealed that enhanced product quality and safety are the most significant benefits of RFID in the Sri Lankan construction industry. Subsequently, material, labour and machinery tracking applications were identified as the most significant applications of RFID in construction. When RFID technology is applied to tracking resources, it would provide effective resource management in the construction site which would derive a product with high quality and safety. Moreover, this would result in better asset management and handling of returnable assets in construction sites and reduce the error rate. Lastly, this would enhance time management and productivity improvements of the construction projects. However, it is important to acknowledge that RFID technology faces challenges in indoor construction environments, such as signal interference and limited range, which can hinder its effectiveness. Addressing these limitations requires further research and development to optimise RFID performance in such conditions.

6. CONCLUSIONS AND RECOMMENDATIONS

The study revealed that RFID technology has several advantages over traditional methods, including cost reduction, improved productivity, automation, and real-time data availability. Among them, enhanced product quality, safety, and productivity improvements are identified as the most significant benefits of implementing RFID technology in the Sri Lankan construction industry. The other highly significant benefits revealed from this study include better asset management and handling of returnable assets, inventory discrepancy reduction, improved time management, system automation and availability of data backup. Eventually, the study recommends that Sri Lankan construction firms should consider implementing RFID technology to improve the efficiency and productivity of their construction processes.

Moreover, this study contributes to the theory by identifying the potential of implementing RFID technology in the Sri Lankan construction sector which can be used as a benchmark in a similar context. The research findings revealed that the implementation of RFID technology has a higher potential to enhance the product quality and safety of the Sri Lankan construction industry. Theoretically, this study serves by manifesting the potential of RFID technology in improving technological applications in the Sri Lankan construction industry. However, the findings of this study are limited to the Sri Lankan context yet can be used as a benchmark study for similar construction contexts. Further studies are aimed at conducting comprehensive discussions on the application of RFID technology within the Sri Lankan construction industry, focusing on strategies to enhance its utilisation in the country.

7. REFERENCE

Akadiri, P. O., Olomolaiye, P. O., & Chinyio, E. A. (2013). Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Automation in Construction*, *30*, 113–125. Retrieved from https://doi.org/10.1016/j.autcon.2012.10.004

Alaloul, W. S., Liew, M. S., Zawawi, N. A. W., Mohammed, B. S., Adamu, M., & Musharat, M. A. (2020). Structural equation modelling of construction project performance based on coordination factors. *Cogent Engineering*, *7*(1), 1726069. Retrieved from https://doi.org/10.1080/23311916.2020.1726069

Atapattu, A.M.D.S., Wattuhewa, R.M., Waidyasekara, K.G.A.S. and Dilakshan, R., (2023). Big data analytics in the Sri Lankan construction industry: An assessment of the challenges and strategies. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ramachandra, T. and Ranadewa, K.A.T.O. (eds). *Proceedings of the 11th world construction symposium*, *Sri Lanka.*, 21-22 July 2023. (pp. 281-292). doi:10.31705/WCS.2023.24.

Bansal, A., Sharma, S., & Khanna, R. (2019). Compact meandered RFID tag antenna with high read range for UHF band applications. *International Journal of RF and Microwave Computer-Aided Engineering*, *29*(11). e21695. Retrieved from https://doi.org/10.1002/mmce.21695

Borda, N., Pitroda, Dr. J., & Rathod, J. (2019). A framework for RFID enabled material management for construction industry, *International Journal of Technical Innovation in Modern Engineering & Science. 5*(5), 152–159.

Costa, F., Genovesi, S., Borgese, M., Michel, A., Dicandia, F. A., & Manara, G. (2021). A review of RFID sensors, the new frontier of Internet of Things. *Sensors*, *21*(9), 3138. Retrieved from https://doi.org/10.3390/s21093138

Dobkin, D. M. (2012). History and practice of RFID. In D.M. Dobkin (Eds.), *The RF in RFID* (pp. 7–49). Elsevier. https://doi.org/10.1016/B978-075068209-1.50002-4

Domdouzis, K., Kumar, B., & Anumba, C. (2007). Radio-frequency identification (RFID) applications: A brief introduction. *Advanced Engineering Informatics*, *21*(4), 350–355. Retrieved from https://doi.org/https://doi.org/10.1016/j.aei.2006.09.001

Ergen, E., Ilter, D. A., Tekce, I., Kula, B., & Dönmez, D. (2017). Utilizing indoor localization technologies for occupant feedback collection. In *7th international congress on construction management-IMO*, *Istanbul* (pp 6-7).

Gao, Y., Mahmoodi, M., & Zoughi, R. (2022). Design of a novel frequency-coded chipless RFID Tag. *IEEE Open Journal of Instrumentation and Measurement*, *1*, 8000109. Retrieved from https://doi.org/10.1109/OJIM.2022.3175249

Gunawardena, T., Karunaratne, R., Mendis, P., & Ngo, T. (2016, December). Prefabricated construction technologies for the future of Sri Lanka's construction industry. In *Proceedings of the 7th international conference on sustainable built environment (ICSBE), Kandy, Sri Lanka*,16-18 December 2016 (pp. 16-18).

Gaith, F. (2012). Application and efficacy of information technology in construction industry. *Scientific Research and Essays*, *7*(38), 3223–3242. Retrieved from https://doi.org/10.5897/SRE11.955

Haddara, M., & Staaby, A. (2018). RFID Applications and adoptions in healthcare: A review on patient safety. *Procedia Computer Science*, *138*, 80–88. Retrieved from https://doi.org/10.1016/j.procs.2018.10.012

Hamadneh, S., Keskin, E., Alshurideh, M., Al-Masria, Y., & Al Kurdi, B. (2021). The benefits and challenges of RFID technology implementation in supply chain: A case study from the Turkish construction sector. *Uncertain Supply Chain Management*, *9*(4), 1071–1080. Retrieved from https://doi.org/10.5267/j.uscm.2021.x.006

Holt, E. A., Benham, J. M., & Bigelow, B. F. (2015, June). Emerging technology in the construction industry: Perceptions from construction industry professionals. In *2015 ASEE Annual Conference & Exposition, Seattle, Washington*, 14-17 June 2015. (pp. 26.595.1 - 26.595.10). https://doi.org/10.18260/p.23933

Huang, R., Tsai, T.-Y., & Wang, H.-H. (2019). Developing an RFID-based tracking system to improve the control of construction surplus soil disposal in Taiwan. *Journal of the Chinese Institute of Engineers*, *42*(2), 175-188. Retrieved from https://doi.org/10.1080/02533839.2018.1553629

Jayasena, H., & Weddikkara, C. (2012, June 28). *Building information modelling for Sri Lankan construction industry*. World Construction Conference 2012 – Global Challenges in Construction Industry, Colombo, Sri Lank. https://docs.suranga.net/publications/2012_bim4sl.pdf

Kasim, N., Ahmad Latiffi, A., & Fathi, M. S. (2013). RFID technology for materials management in construction projects – A Review. *International Journal of Construction Engineering and Management*, *2*, (4A), 7-12. Retrieved from https://doi.org/10.5923/s.ijcem.201309.02

Kereri, J. O., & Adamtey, S. (2019). RFID use in residential/commercial construction industry. *Journal of Engineering, Design and Technology*, *17*(3), 591–612. Retrieved from https://doi.org/10.1108/JEDT-07-2018-0118

Kozlovska, M., Klosova, D., & Strukova, Z. (2021). Impact of industry 4.0 platform on the formation of construction 4.0 concept: A literature review. *Sustainability*, *13*(5), 2863. Retrieved from https://doi.org/10.3390/su13052683

Lake C, & Jaselskis E. (2000, July 31). *RFID applications for owners and contractors*. Procurement Construction Industry Institute Annual Conference, Nashville, Tennessee. https://www.construction-institute.org/rfid-applications-for-owners-and-contractors

Lanko, A., Vatin, N., & Kaklauskas, A. (2018). Application of RFID combined with blockchain technology in logistics of construction materials. *MATEC web of conferences*, (Vol 170, p.03032). https://doi.org/10.1051/matecconf/201817003032

Li, N., & Becerik-Gerber, B. (2011). Life-Cycle approach for implementing RFID technology in construction: Learning from academic and industry use cases. *Journal of Construction Engineering and Management*, *137*(12), 1089–1098. Retrieved from https://doi.org/10.1061/(ASCE)CO.1943-7862.0000376

Lu, W., Huang, G. Q., & Li, H. (2011). Scenarios for applying RFID technology in construction project management. *Automation in Construction*, *20*(2), 101–106. Retrieved from https://doi.org/https://doi.org/10.1016/j.autcon.2010.09.007

Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2023). Assessment of critical factors influencing the performance of labour in Sri Lankan construction industry. *International Journal of Construction Management*, *23*(1), 144–155. Retrieved from https://doi.org/10.1080/15623599.2020.1854042

Munmulla, T., Hidallana-Gamage, H. D., Navaratnam, S., Ponnampalam, T., Zhang, G., & Jayasinghe, T. (2023). Suitability of modular technology for house construction in Sri Lanka: A survey and a case study. *Buildings*, *13*(10). Retrieved from https://doi.org/10.3390/buildings13102592

Patil P, & Shelake A. (2021). Application of RFID Technology to improve material management on construction sites. *International Research Journal of Engineering and Technology (IRJET)*, *8*(2), 1000–1003.

Perera, R., Wickramasinghe, L. K., & Perera, S. (2020). Drone technology adoption in the construction industry: a Sri Lankan perspective. *Engineering, Construction and Architectural Management*, *27*(4), 769–785.

Piramuthu, S. (2008). Adaptive framework for collisions in RFID tag identification. *Journal of Information & Knowledge Management (JIKM)*, *07*(01), 9–14. Retrieved from https://EconPapers.repec.org/RePEc:wsi:jikmxx:v:07:y:2008:i:01:n:s0219649208001890

Rajakaruna, R., Bandara, K., & Silva, N. De. (2008). Challenges faced by the construction industry in Sri Lanka: Perspective of clients and contractors. In R. Haigh, D. Amarathunga (Eds.), *Proceedings from international conference on building education and research (BEAR)* 11-15 February 2008, (pp. 158-169), School of the Built Environment, University of Salford, UK.

Roh, J. J., Kunnathur, A., & Tarafdar, M. (2009). Classification of RFID adoption: An expected benefits approach. *Information & Management*, *46*(6), 357–363. Retrieved from https://doi.org/https://doi.org/10.1016/j.im.2009.07.001

Ruchiranga, N., & Samarasekara, N. A. (2018). Feasibility of implementing RFID technology in the warehousing sector of Sri Lanka: a literature review. In Gunaruwan. T.L. (Ed.), *Proceedings of 3rd international conference on research for transport and logistics industry 2018* (pp. 9–12). Sri Lanka Society of Transport and Logistics.

Santoso, D. S., & Gallage, P. G. M. P. (2020). Critical factors affecting the performance of large construction projects in developing countries. *Journal of Engineering, Design and Technology*, *18*(3), 531–556. Retrieved from https://doi.org/10.1108/JEDT-05-2019-0130

Sudarshan S, Shantanu B S, Srivaths S, Neethu S, & Manjunatha C. (2022). Recent advances in nanomaterials used for RFID technology and their applications. *ECS Transactions*, *107*(1), 12189–12199.

Suresh, S., & Chakaravarthi, G. (2022). RFID technology and its diverse applications: A brief exposition with a proposed machine learning approach. *Measurement*, *195*, 111197. Retrieved from https://doi.org/https://doi.org/10.1016/j.measurement.2022.111197

Tan, W. C., & Sidhu, M. S. (2022). Review of RFID and IoT integration in supply chain management. *Operations Research Perspectives*, *9*, 100229. Retrieved from https://doi.org/https://doi.org/10.1016/j.orp.2022.100229

Toit, J. (2012). A typology of designs for social research in the built environment. *International Journal of Social Research Methodology*, *16*(2), 125-139 Retrieved from. https://doi.org/10.1080/13645579.2012.657013

Valero, E., & Adán, A. (2016). Integration of RFID with other technologies in construction. *Measurement*, *94*, 614–620. Retrieved from https://doi.org/10.1016/j.measurement.2016.08.037

Valero, E., Adán, A., & Cerrada, C. (2015). Evolution of RFID Applications in Construction: A literature review. *Sensors*, *15*(7), 15988–16008. Retrieved from https://doi.org/10.3390/s150715988

Waidyasekara, A., Gamlath, M., & Pandithawatta, S. (2020). Application of Robotic Technology for the Advancement of Construction Industry in Sri Lanka: A Review In K. Panuwatwanich, C.H. Ko (Eds.), *The 10th international conference on engineering, project, and production management* (pp. 43-54). Springer Singapore.

Wang, L.-C. (2008). Enhancing construction quality inspection and management using RFID technology. *Automation in Construction*, *17*(4), 467–479. Retrieved from https://doi.org/10.1016/j.autcon.2007.08.005

World bank. (2021). *Sri Lanka - Country Snapshot*. (Report No. 120478) https://data.worldbank.org/country/sri-lanka

Zhu, X., Mukhopadhyay, S. K., & Kurata, H. (2012). A review of RFID technology and its managerial applications in different industries. *Journal of Engineering and Technology Management*, *29*(1), 152–167. Retrieved from https://doi.org/10.1016/J.JENGTECMAN.2011.09.011

Guruge, K., Waidyasekara, K.G.A.S., Jayasena, H.S. and Manewa, R.M.A.S., 2024. Unveiling the potential of design for deconstruction in the circular economy. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 1101-1111. DOI: https://doi.org/10.31705/WCS.2024.87. Available from: https://ciobwcs.com/papers/

UNVEILING THE POTENTIAL OF DESIGN FOR DECONSTRUCTION IN THE CIRCULAR ECONOMY

Kavini Guruge[1], K.G.A.S. Waidyasekara[2], H.S. Jayasena[3], and R.M.A.S. Manewa[4]

ABSTRACT

The construction industry plays a vital role in fostering sustainability through various concepts and strategies being implemented globally. Among these, Circular Economy (CE) stands out as a prominent approach to enhancing sustainability. CE aims to move the industry away from the traditional linear model (i.e., build-use-demolish) towards a more sustainable circular approach. In the built environment, the 'Design for Deconstruction' (DfD) aims to integrate planning for a building's end-of-life disassembly and material/component salvaging into the design process, thereby promoting sustainability through waste minimisation. However, the relationship between DfD and circularity is less evident. For example, most of the literature about DfD explains the potentials of end-of-life disassembly is limited in terms of discussion on the second life (potential reuse) of those disassembled materials/components. This research aims to bridge this gap. A detailed literature review has been undertaken to establish the status of DfD within the construction industry, including principles, practices, advantages, and barriers of DfD and its contribution to CE. The findings confirm that the blurred link between DfD and CE, and the required improvements in standardisation, awareness, and deconstruction information model/databases are the key priorities to enhance the circularity through DfD.

Keywords: *Circular Economy; Construction Industry; Design-for-Deconstruction; Sustainability.*

1. INTRODUCTION

The construction industry plays a crucial role in the global economy. It is a major consumer of raw materials and contributes to generating significant amounts of waste, which led environmental degradation. This has led to a quest for a sustainable environment achieved through Sustainable Construction (SC) globally (Oke et al., 2019). Sustainability in construction has been enhanced through various concepts and innovative practices in the recent past (Lima et al., 2021).

[1] Student, Department of Building Economics, University of Moratuwa, Sri Lanka, kviniveenadhi1997@gmail.com

[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk

[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, suranga@uom.lk

[4] Senior Lecturer, School of Civil Engineering and Built Environment, Liverpool John Moores University, UK, R.M.Manewa@ljmu.ac.uk

The circular economy offers a new way of thinking about construction that can help to reduce waste and conserve resources. It is an economic system that reconsiders the way resources are used, placing a major focus on waste reduction, resource efficiency, and the development of a resilient and regenerative economic system (Yu et al., 2021). CE conceptualises a closed-loop economy that minimises waste generation and treats any waste as a valuable resource. In this context, the concepts of DfD, aim at designing construction assets (buildings, infrastructure) that can be easily reused or repurposed, using recycled materials and elements, and minimising waste during construction and demolition. In foresight, this paper explains the potential of DfD in promoting circularity in the built environment.

2. RESEARCH METHOD

Sylvester et al., (2013) explain that a literature review is required to identify any gap in the knowledge and a successful researcher claims a gap in the existing knowledge with evidence. This paper is based on a detailed literature review part of an ongoing MPhil research, which is aimed at developing a Deconstruction Information Model for Design Decisions in Construction Assets. As the research is in its initial stages, the analysis is purely based on a review of current literature revealing the existing gap in the knowledge, principles and practices of DfD and its contribution to enhancing CE. Mainly, literature evidence was taken referring to journal articles, books, published and unpublished bibliographies, conference proceedings, and documents. During the literature review, key terms including; circular economy, design for deconstruction, design for disassembly, benefits, barriers, and construction were used (Sylvester et al., 2013).

3. DESIGN FOR DECONSTRUCTION (DfD)

Rios, et al. (2015) stated that DfD, is a well-known practice within the construction industry to make the deconstruction process much easier through the procedure of planning and designing (Cruz et al., 2015). DfD has its own set of key principles which can be aligned with the process of Reduce, Reuse and Recycle as the functions; 3R processes as mentioned by various authors. According to Akanbi et al., (2019), to promote the practice of design for deconstruction, corresponding techniques to overcome obstacles to design for deconstruction and materials reuse were established.

Tleuken et al. (2022) stated that Design for Deconstruction (DfD) is the concept that considers the final demolition stage during initial design and planning. DfD focuses on saving the value that has been put into the building material or structural elements even after the buildings end-of-use. As mentioned previously, the deconstruction process can be predicted at the planning stage of a construction process (Akanbi et al., 2019). Therefore, this concept can result in several advantages economically, environmentally and socially (Akinade et al., 2020). For example, if the buildings are initially designed for deconstruction, it will significantly improve the environmental effect due to the possibility recover almost 95% savings of the embodied energy of the construction materials and up to 50% of the total building's life cycle energy (Tleuken et al., 2022). Moreover, it would also decrease waste management issues.

DfD has its own set of principles that are supposed to follow when its practices it is implemented. Literature promotes reducing the number of materials and components used; choosing materials that are possible for reusing and recycling; using visible and reachable building elements connections; using simple (yet strong) and connections that are easy to deconstruct, e.g., dry connections, dissolvable chemical or reversible welding connections; and practising utilisation of building modules that are robust, substitutable and convenient for transportation (Akinade et al., 2020).

3.1 DECONSTRUCTION OF COMPONENTS/ MATERIALS

As stated by Thomsen et al., (2011), 'Deconstruction' is generally a positive notion, an opposite practice of demolition, which is based on the process of taking apart and compressing a building and disposing the waste as landfill. In addition, past studies identified that deconstruction can explained under two different phases; firstly the careful planning and highly controlled deconstruction process producing a differentiated assortment of components and materials, and secondly, continued use of the deconstructed components and materials in other buildings or other functions at the highest possible level, to avoid down cycling, energy transformation and deposit into landfill as much as possible (Davila et al., 2019). Deconstruction is a present practice with various implications in the construction industry adopting the above-mentioned two phases. Some similar practices would include the planning stage associated with the selective deconstruction of the existing building asset, followed by the planning of the construction works for the redevelopment, adaptation, and in some cases the expansion of the building asset (Sanchez et al., 2019). When a building reaches the end of its useful life (economic or physical), deconstruction enables the recovery of building components for building relocation, component reuse, recycling, or remanufacturing (Akinade et al., 2020). The consideration of DfD practices within the early stages of construction (planning, design, procurement etc.) will promote efficient building recovery as opposed to the deconstruction processes of conventional buildings. However, the reusability of the deconstructed materials at their end of life is less evident.

3.2 APPLICATIONS OF DESIGN FOR DECONSTRUCTION

DfD is one of the most popular concepts in the global construction industry (Bertino et al., 2021) and there is less evidence of absorption of such practices within the Asian construction sector (Tleuken et al., 2022). Nevertheless, there are no standard practices or any certain regulatory concepts or frameworks to enhance DfD practices within the construction industry, efficient building recovery at the end-of-life can only be made possible when the need for deconstruction has been considered from the design stage (Ganiyu et al., 2020). Moreover, in the perspective of reusing Construction and Demolition Waste (C&DW), as an example, there are practices in maximisation of high-quality recycled aggregate, and further, according to the researchers, 'Reuse'; the third 'R' principle is still in its earliest stage of implementation (Tleuken et al., 2022).

In support of DfD, the production of Demolition and Refurbishment Information Datasheets (DRIDS) has improved the possibility of material reuse, recycling, reclamation and waste diversion from landfills (Akanbi et al., 2019). DRIDS provides a publicly accessible database that helps identify building elements that could be reclaimed for reuse and recycling and those that must be sent to landfills. When it comes to cost, companies attempt to use materials that are as durable as possible and have the right certifications (Tleuken et al., 2022). Usage of easily dis-assimilable structures as construction structures is common practice in the industry. Further to that, researchers have found that DfD concepts are being used in the adaptive reuse of buildings as well.

In its design process, the designers bear the responsibility of arriving at a cost-effective and useful adaptive reuse design. A typical construction asset may have multiple adaptive reuse designs, planning for the targeted components' disassembly will vary depending on the design. It is feasible to carry out the deconstruction planning in detail using a proposed disassembly plan, including scheduling the deconstruction works, estimating resource allocation, and calculating the related budget (Sanchez et al., 2019). A study by Roxas et al. (2023) summarised DfD guidelines under three major themes i.e. (i) Simplification of building design, (ii) Materials and connections, and (iii) Deconstruction details and information, for the adopting process of DfD in the construction industry, particularly during the planning stage. Moreover, Zoghi et al., (2022) propose a method for selecting the suitable construction material based on DfD factors.

Table 1: DfD principles (Adapted- Roxas et al., 2023)

Themes	Principles
Simplification of Building Designs	Minimise the number of building components and component types
	Modularisation
	Standardisation
	Use of off-site construction and prefabrication
	Use of lightweight components
	Use of tools and equipment
	Reduction in the number of structural systems
	Utilisation of dry construction
	Realisation of accessible technical installations
	Utilisation of an open building design
	Incorporation of a structural grid
	Consider the interchangeability of building components
Materials and Connections	Use of reusable materials
	Use of environmentally safe materials
	Simplification of the connections
	Utilisation of mechanical connections
	Ease of removal of connections
	Minimise the number of connections and connection types
	Design materials and connections for longevity and durability
	Accessibility of components and connections
	Determine the performance of each material at the building's end-of-life
	Avoid applying secondary finishes
	Storage of spare parts for unforeseen minor revisions
	Determine and apply the optimal material size
	Identify the lifespan of each material
	Reduce the different types of materials
	Use of non-hazardous material
	Avoid using composite materials
Deconstruction Details and information	Documentation of technical plans, drawings, and pictures
	Database of materials, components, and building information

Themes	Principles
	Instructions for materials to be reused and recycled
	Incorporate the type and method of deconstruction in the design
	Viewing a building as a multi-layered structure possessing distinct lifespans
	Determine the parts of the building system to be deconstructed
	Consideration of parallel disassembly in the design
	Allow easy accessibility to the entire building
	Create a deconstruction and waste management plan

Consequently, DfD has both opportunities as well as barriers (Tleuken et al., 2022).

The study done by Aidana et al., (2022) states some of the basic benefits such as DfD in the industrial market are reducing the time required for building demolition and labour involved in demolition works. DfD will bring economic incentives.

3.2.1 Advantages of DfD Applications

Research studies have consistently viewed DfD as a fundamental concept for developing circular economy practices in the construction sector. As such, they are advantageous for sustainable building and circularity techniques. Given that, these applications both directly and indirectly address the circular economy's guiding concepts and guidelines (Wuni & Shen, 2020). Despite this, some of the most significant benefits of DfD fall into one of four broad categories i.e., (i) social, (ii) economic, (iii) environmental, and (iv) strategic (Andrade & Bragana, 2019). Table 2 provides a summary of the advantages of DfD applications identified by different authors along with an overview of the bibliographical analysis on the positive effects of DfD applications.

Table 2: Advantages of DfD applications

Advantages	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Resource Efficiency		√			√		√	√		√	
Cost Savings	√		√	√	√	√		√			√
Environmental Benefits	√	√	√		√	√	√	√	√		√
Flexibility and Adaptability	√		√						√	√	
Improved Safety			√				√	√		√	
Regulatory Compliance		√			√		√		√		
Enhanced Reputation and Marketability	√			√		√		√			√

A1-(Cruz et al., 2015), A2-(Sanchez et al., 2019), A3-(Akanbi et al., 2019), A4-(Akinade et al., 2020), A5-(Bertino et al., 2021), A6-(Dams et al., 2021), A7-(Roxas et al., 2023), A8-(Thormark, 2007), A9-(Roberts et al., 2023), A10-(Salama, 2017), A11-(Ostapska et al., 2021)

According to the authors, DfD applications can be identified with many advantages, where DfD focuses on designing buildings and structures with the end of their lifecycle in mind. This approach allows for the efficient recovery and reuse of materials, reducing the overall demand for raw materials and minimising waste generation. It has directly impacted resource efficiency and DfD supports cost perspectives. By designing structures that are easier to deconstruct and dismantle, DfD can lower the costs associated with demolition, waste disposal, and material procurement for future projects. Additionally, salvaged materials can often be sold or reused, providing additional revenue streams (Thormark, 2007). Moreover, DfD contributes to environmental sustainability by reducing the environmental impact associated with construction activities. It minimises the consumption of natural resources, decreases energy consumption, and lowers greenhouse gas emissions by reducing the need for new material production and waste disposal. Additionally, DfD encourages modular construction techniques and the use of standardised components, making it easier to modify, expand, and/or repurpose structures in response to changing needs or preferences. This flexibility enhances the longevity and adaptability of buildings, reducing the need for new construction projects and conserving resources. Apart from that, adopting DfD principles demonstrates a commitment to sustainability and responsible resource management, which can enhance an organisation's reputation and attract environmentally conscious clients, investors, and stakeholders. DfD can differentiate construction projects in the marketplace, offering a competitive advantage in an increasingly sustainability-focused industry (Salama, 2017).

In summary, DfD applications offers numerous benefits to the construction industry, ranging from cost savings and environmental sustainability to improved safety and marketability. By prioritising the efficient use of resources and the reduction of waste, DfD contributes to a more sustainable and resilient built environment.

3.2.2 Barriers and Strategies in Implementing DfD Applications

The literature identifies the barriers to the implementation of DfD applications in the construction industry. Accordingly, the comprehensive study conducted by Akinade et al., (2020), has identified 26 barriers to implementing DfD in the construction industry and those barriers have been classified under five major categories as stated in Table 3.

Table 3: Barriers to DfD applications (Adapted- Akinade et al., 2020)

Categories	Barriers
Lack of stringent legislation for DfD	Lack of Government legislation for deconstructed facilities.
	Design codes generally favour specifying new materials
	Low Building Research Establishment Environmental Assessment Method (BREEAM) point for DfD
Lack of adequate information in building design	Lack of information about recoverable materials
	Lack of disassembly information
	Inadequate information about cost-effective material separation methods
Lack of a large enough market for recovered components	No standardisation and grading system for salvaged materials
	Perceived perception and risks associated with second-hand materials
	Low-performance guarantees for recovered materials
	Degraded aesthetics of salvaged materials
	Damaged or Contaminated materials during recovery
	Storage consideration for recovered materials
	Transportation considerations for recovered materials
	No information exchange system for salvaged materials

Categories	Barriers
Difficulty in developing a business case for DfD	Cost of product re-certification
	The additional cost of design that makes the project more expensive
	Insurance constraints and legal warranties of reclaimed materials
	DfD will increase the design time
	Changing industry standards and construction methodology
	Believe that DfD could compromise building aesthetics and safety
	The overall benefit of DfD may not happen after a long time
Lack of effective DfD tools	Lack of DfD analysis methodologies
	Existing DfD tools are not BIM-compliant
	No tools for identifying and classifying salvaged materials at the end-of-life
	Performance analysis tools for end-of-life scenarios are lacking
	Limited visualisation capability for DfD

Apart from the above-mentioned barriers: uncertainty about the quality of the reused material, low demand due to users' negative perception, financial profitability of demolition practices rather than disassembly, earthquake risks when using bolting connections, high risks of reinforced concrete corrosion can be identified as basic barriers to DfD applications (Tleuken et al., 2022). Moreover, DfD in construction faces challenges due to budget constraints, technology limitations, and lack of collaboration amongst construction participants. Conventional methods are preferred for their cost-effectiveness, while DfD can be more successful if its economic profit is quantifiable. In practice, contractors are prone to make decisions at construction sites without much regard for DfD applications. Implementing DfD into construction regulations could address these barriers irrespective of the individual aims of the parties involved (Tleuken et al., 2022). Overcoming barriers to the implementation of Design for Deconstruction (DfD) in the construction industry requires a combination of strategies aimed at addressing various challenges (van Buren et al., 2016). Table 4 summarises different approaches suggested by various authors to overcome the barriers to DfD implementation in the construction industry.

Table 4: Strategies to overcome barriers to DfD implementations

Strategies	A1	A2	A3	A4	A5	A6	A7	A8	A9
Education and Awareness	√	√		√	√	√	√	√	
Regulatory Support		√	√			√		√	√
Financial Incentives			√	√	√		√		√
Supply Chain Collaboration	√			√		√	√		
Technology Integration	√		√	√				√	
Demonstration Projects					√	√		√	
Collaborative Design Processes	√	√				√			√

Strategies	A1	A2	A3	A4	A5	A6	A7	A8	A9
Lifecycle Assessment	√	√		√		√		√	√
Industry Standards and Best Practices			√				√		
Continuous Improvement and Evaluation		√			√	√			

A1-(Silva et al., 2019), A2-(Akinade et al., 2020), A3-(Salama, 2017), A4-(Tleuken et al., 2022), A5-(Charef & Emmitt, 2021), A6-(Pittri et al., 2024), A7-(Anastasiades et al., 2023), A8-(Munaro & Tavares, 2023), A9-(Raja Ghazilla et al., 2015)

According to Table 4, ten strategies have been identified by researchers which can be implemented to overcome the barriers to DfD implementation in the construction industry. Most researchers in their studies imply that educating and making the industry aware of DfD practices is the most viable way of overcoming barriers in this regard and regulatory support and technological integration would further support the cause.

3.3 DFD AND BIM

As stated earlier, there is a relationship between DfD and the circular economy concept (Akinade et al., 2020). According to the findings and statements provided by past researchers, DfD needs to be standardised to achieve circular economic goals. After addressing the barriers to implementing DfD, it is necessary to pay attention to how to evaluate DfD performances and quantify the benefits of DfD concepts. As per the study done by Obi et al. (2021), deconstruction-related practices can be managed by implementing BIM based methodologies, such as BIMfD (BIM for deconstruction). In the same study, authors have stated that BIMfD is still at the earliest stage of it being practised. Specifically in the above study, Obi et al., (2021) have provided a hierarchical BIMfD implementation factor model to support improved deconstruction practices in the construction industry of the UK.

Moreover, in a recent study conducted by Kim and Kim, (2023), stated that there is a lack of tools and methods for evaluating the DfD performances. According to the researchers, there is a specific necessity for a tool for the proper implementation of design for deconstruction concepts rather than using the BIM software as a practice. Additionally, Charef et al., (2019) have come up with a suggestion of a model for deconstruction, named DIM in their proposed conceptual framework for the building life cycle. Therefore, rather than practising DfD along with the BIM, it would be more efficient if there was a specific information model for the deconstruction processes of constructed buildings.

4. CONTRIBUTION FROM DfD TO A CIRCULAR ECONOMY

Circular economy is an innovative concept which has gained much global attention recently (Dwivedi et al., 2020). The concept is popular within the business world and governments of many countries as a possible way to deal with business objectives and a sustainable environment simultaneously (Pomponi & Moncaster, 2017). This concept aims to lessen the strain on natural resources and to develop a more sustainable method of managing useful and valuable materials (Casiano Flores et al., 2018). The general perspective of circular economy is mostly used in construction, waste minimisation and recycling (Hart et al., 2019), resource optimisation (Mhatre et al., 2021) and reusing materials from wrecked or removing structures (Bertino et al, 2021). Yu et al. (2022) explain the historical evidence of the application of CE practices in construction, where the concept was not implemented conceptually with the exact terminologies and procedures as in the current practice.

The literature further explains that waste-to-energy supply chain (Pan et al., 2015), eco-industrial park, waste-to-resource supply chain, cradle-to-cradle, industrial ecology regenerative design (Mahpour, 2018), product-service-system, blue economy, design-for-deconstruction (Akanbi et al., 2019) are used to form the circular economy concept. As noted above, the DfD approach moves beyond traditional demolition methods by intentionally planning buildings for easier disassembly at the end of their lifespan and then reuse in their second life. By using standardised components, and readily accessible connections, most of the valuable materials/components can be separated, salvaged, and reintroduced into new construction projects. This not only reduces the need for virgin materials and lowers environmental impact, yet creates a valuable resource pool for the construction industry, fostering a more circular and sustainable building life cycle. However, there is a lack of awareness of such practices, and regulations and a limited number of information models to understand the deconstruction possibility of materials and their reusability.

5. CONCLUSIONS AND THE WAY FORWARD

In conclusion, this paper provides a detailed explanation of the concept of DfD and circular economy within the construction industry, encompassing its principles, current practices, applications, advantages and implementation barriers, along with strategies to overcome said barriers. Accordingly, this study identifies 37 principles, categorised into three themes, and highlights seven advantages across various categories. Additionally, it identifies 26 barriers grouped into five major categories. Finally, the study outlines ten key strategies proposed to address these barriers and facilitate the successful implementation of DfD in the construction industry. The paper suggests a clear consideration of the potential second use of the materials/components during the design phase will promote a circular economy within construction instead of limiting the component/material life at the deconstruction phase. Moreover, the study indicates the requirement of a standard practice to evaluate the DfD implementations in the construction industry and the current knowledge of it.

This paper looks at theoretical aspects to produce a conceptual framework as the next step of the study which can be used to develop a DIM for Design Decisions integrating CE in Built Assets. Further, this paper motivates future research on eco-industrial parks, blue economy etc. and other supportive concepts of CE in the construction industry.

6. REFERENCES

Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Davila Delgado, J. M., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production*, *223*, 386–396. https://doi.org/10.1016/j.jclepro.2019.03.172

Akinade, O., Oyedele, L., Oyedele, A., Davila Delgado, J. M., Bilal, M., Akanbi, L., Ajayi, A., & Owolabi, H. (2020). Design for deconstruction using a circular economy approach: barriers and strategies for improvement. *Production Planning and Control*, *31*(10), 829–840. https://doi.org/10.1080/09537287.2019.1695006

Anastasiades, K., Dockx, J., van den Berg, M., Rinke, M., Blom, J., & Audenaert, A. (2023). Stakeholder perceptions on implementing design for disassembly and standardisation for heterogeneous construction components. *Waste Management and Research*, *41*(8), 1372–1381. https://doi.org/10.1177/0734242X231154140

Andrade, J. B., & Bragana, L. (2019). Assessing buildings' adaptability at early design stages. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012012

Bertino, G., Kisser, J., Zeilinger, J., Langergraber, G., Fischer, T., & Österreicher, D. (2021). Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials. *Applied Sciences (Switzerland)*, *11*(3), 1–31. https://doi.org/10.3390/app11030939

Charef, R., Alaka, H., & Ganjian, E. (2019). A BIM-based theoretical framework for the integration of the asset End-of-Life phase. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012067

Charef, R., & Emmitt, S. (2021). Uses of building information modelling for overcoming barriers to a circular economy. *Journal of Cleaner Production*, *285*, 124854. https://doi.org/10.1016/j.jclepro.2020.124854

Cruz, F., Chong, W. K., & Grau, D. (2015). Design for disassembly and deconstruction - challenges and opportunities. *International Conference on Sustainable Design, Engineering and Construction*, *118*, 1296–1304. https://doi.org/https://doi.org/10.1016/j.proeng.2015.08.485

Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P., & Emmitt, S. (2021). A circular construction evaluation framework to promote designing for disassembly and adaptability. *Journal of Cleaner Production*, *316*, 128122. https://doi.org/10.1016/j.jclepro.2021.128122

Davila, D., Manuel, J., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M., & Owolabi, H. (2019). Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. *Journal of Building Engineering*, *26*, 100868. https://doi.org/10.1016/j.jobe.2019.100868

Ganiyu, S. A., Oyedele, L. O., Akinade, O., Owolabi, H., Akanbi, L., & Gbadamosi, A. (2020). BIM competencies for delivering waste-efficient building projects in a circular economy. *Developments in the Built Environment*, *4*(December), 100036. https://doi.org/10.1016/j.dibe.2020.100036

Kim, S., & Kim, S. (2023). A design support tool based on building information modeling for design for deconstruction : A graph-based deconstructability assessment approach. *Journal of Cleaner Production*, *383*, 135343. https://doi.org/10.1016/j.jclepro.2022.135343

Lima, L., Trindade, E., Alencar, L., Alencar, M., & Silva, L. (2021). Sustainability in the construction industry : A systematic review of the literature. *Journal of Cleaner Production*, *289*, 125730. https://doi.org/10.1016/j.jclepro.2020.125730

Mahpour, A. (2018). Prioritizing barriers to adopt circular economy in construction and demolition waste management. *Resources, Conservation and Recycling*, *134*, 216–227. https://doi.org/10.1016/j.resconrec.2018.01.026

Munaro, M. R., & Tavares, S. F. (2023). Design for adaptability and disassembly: guidelines for building deconstruction. *Construction Innovation*. https://doi.org/10.1108/CI-10-2022-0266

Obi, L., Osobajo, O., Awuzie, B., Obi, C., Oke, A., & Omotayo, T. (2021). BIM for deconstruction : An interpretive structural model of factors influencing implementation. *Buildings*, *11*(227). https://doi.org/https://doi.org/10.3390/buildings11060227

Oke, A., Ferrão, P., Oke, A., & Aghimien, D. (2019). Sustainable Construction Practices the Zambian Construction Industry Assessing the feasibility of using the heat demand-outdoor Drivers of Practices, and demand temperature for a district heat forecast C. *Energy Procedia*, *158*, 3246–3252. https://doi.org/10.1016/j.egypro.2019.01.995

Ostapska, K., Gradeci, K., & Ruther, P. (2021). Design for disassembly (DfD) in construction industry: A literature mapping and analysis of the existing designs. *Journal of Physics: Conference Series*, *2042*(1). https://doi.org/10.1088/1742-6596/2042/1/012176

Pittri, H., Godawatte, A. G. R., Agyekum, K., Botchway, E. A., Dompey, A. M. A., Oduro, S., & Asamoah, E. (2024). Examining the barriers to implementing design for deconstruction in the construction industry of a developing country. *Construction Innovation*. https://doi.org/10.1108/CI-09-2023-0239

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Raja Ghazilla, R. A., Sakundarini, N., Taha, Z., Abdul-Rashid, S. H., & Yusoff, S. (2015). Design for environment and design for disassembly practices in Malaysia: A practitioner's perspectives. *Journal of Cleaner Production*, *108*, 331–342. https://doi.org/10.1016/j.jclepro.2015.06.033

Roberts, M., Allen, S., Clarke, J., Searle, J., & Coley, D. (2023). Understanding the global warming potential of circular design strategies: Life cycle assessment of a design-for-disassembly building. *Sustainable Production and Consumption*, *37*, 331–343. https://doi.org/10.1016/j.spc.2023.03.001

Roxas, C. L. C., Bautista, C. R., Cruz, O. G. Dela, Leoric, R., Cruz, C. Dela, Pedro, J. P. Q. De, Dungca, J. R., Lejano, B. A., & Ongpeng, J. M. C. (2023). Design for Manufacturing and Assembly (DfMA) and design challenges, trends and developments. *Buildings*, *13*(5), 1164. https://doi.org/https://doi.org/10.3390/buildings13051164

Salama, W. (2017). Design of concrete buildings for disassembly: An explorative review. *International Journal of Sustainable Built Environment*, *6*(2), 617–635. https://doi.org/10.1016/j.ijsbe.2017.03.005

Sanchez, B., Rausch, C., & Haas, C. (2019). "Deconstruction programming for adaptive reuse of buildings." *Automation in Construction*, *107*, 102921. https://doi.org/10.1016/j.autcon.2019.102921

Silva, F. C., Shibao, F. Y., Kruglianskas, I., Barbieri, J. C., & Sinisgalli, P. A. A. (2019). Circular economy: analysis of the implementation of practices in the Brazilian network. *Revista de Gestao*, *26*(1), 39–60. https://doi.org/10.1108/REGE-03-2018-0044

Sylvester, A., Tate, M., & Johnstone, D. (2013). Beyond synthesis: Re-presenting heterogeneous research literature. *Behaviour and Information Technology*, *32*(12), 1199–1215. https://doi.org/10.1080/0144929X.2011.624633

Thomsen, A., Schultmann, F., & Kohler, N. (2011). Deconstruction, demolition and destruction. *Building Research and Information*, *39*(4), 327–332.

Thormark, C. (2007). Motives for design for disassembly in building construction. *Portugal SB 2007 - Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millennium*, *June*, 607–611.

Tleuken, A., Torgautov, B., Zhanabayev, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2022). Design for deconstruction and disassembly: Barriers, opportunities, and practices in developing economies of Central Asia. *Procedia CIRP*, *106*, 15–20. https://doi.org/10.1016/j.procir.2022.02.148

van Buren, N., Demmers, M., van der Heijden, R., & Witlox, F. (2016). Towards a circular economy: The role of Dutch logistics industries and governments. *Sustainability (Switzerland)*, *8*(7), 1–17. https://doi.org/10.3390/su8070647

Wuni, I. Y., & Shen, G. Q. (2020). Critical success factors for modular integrated construction projects: a review. *Building Research and Information*, *48*(7), 763–784. https://doi.org/10.1080/09613218.2019.1669009

Yu, Y., Yazan, D. M., Bhochhibhoya, S., & Volker, L. (2021). Towards circular economy through industrial symbiosis in the Dutch construction industry: A case of recycled concrete aggregates. *Journal of Cleaner Production*, *293*, 126083. https://doi.org/10.1016/j.jclepro.2021.126083

Zoghi, M., Rostami, G., Khoshand, A., & Motalleb, F. (2022). Material selection in design for deconstruction using Kano model, fuzzy-AHP and TOPSIS methodology. *Waste Management and Research*, *40*(4), 410–419. https://doi.org/10.1177/0734242X211013904

The 12th World Construction Symposium - 2024

Empowering Construction Industry:
Towards Sustainable Development Goals

Organizers

CEYLON INSTITUTE OF BUILDERS (CIOB) SRI LANKA

DEPARTMENT OF BUILDING ECONOMICS UNIVERSITY OF MORATUWA

Associate Partners

Principal Sponsor

TOKYO CEMENT GROUP

Gold Sponsor

ALUMEX
ULTIMATE IN ALUMINIUM PROFILES

Silver Sponsors

Industry Sponsors

Convention Partner

Ceylon Institute of Builders

No.4-1/2, Bambalapitiya Drive, Colombo 04.
Tel : +94 (0) 112 508 139 | E : info@ciob.lk
W : www.ciobwcs.com