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Safety-Enabled and Sustainable Facilities

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Editors:
**Prof. Nayanthara De Silva
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Conference Proceedings

**The International Conference on
Facilities Management Futures (FMF) 2025:
Safety-Enabled and Sustainable Facilities**

Editors

Prof. Nayanthara De Silva

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Foreword by the Conference Chairs

We are deeply honoured to extend a warm welcome to you at the inaugural edition of the Facilities Management Futures (FMF) Conference, proudly organised by the Department of Facilities Management at the University of Moratuwa. This landmark event marks the beginning of an inspiring journey in advancing research in the field of Facilities Management.

This conference brings together academics, researchers, practitioners, and students to share knowledge, exchange ideas, and engage with new trends and critical themes in the field. The conference theme, "Safety-Enabled and Sustainable Facilities," reflects the increasing significance of safety and sustainability in shaping how facilities are designed, operated, and maintained.

We are pleased to present a collection of double-blind peer-reviewed papers covering a wide spectrum of topics relevant to the Safety-Enabled and Sustainable Facilities. These contributions share the latest research through presentations and discussions, supporting academic and professional development.

On behalf of the organising committee, we would like to express our sincere appreciation to all authors and presenters for their contributions, the keynote speakers for honouring us with their insightful speeches, the scientific committee for their thoughtful engagement throughout the review process, and distinguished guests for gracing the event. We are also grateful to the organising committee, sponsors, and all who have supported the successful realisation of this event.

We sincerely hope that FMF 2025 will serve as a cornerstone for an enduring platform dedicated to research, dialogue, and collaboration in facilities management and safety and health, fostering meaningful advancements in the field for years to come.

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Keynote Address

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Establishment of Decision-Support System for Smart Retrofitting for Office Buildings

With global buildings aging and climate challenges intensifying, there is an urgent need for smart retrofitting (SR), the integration of smart building technologies into existing structures to enhance energy efficiency, occupant comfort, and operational resilience. This presentation introduces a structured smart retrofitting decision-support system (SRDSS) developed to guide the optimal selection of SR alternatives. The system model integrates the Analytic Network Process (ANP), the Entropy method and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to capture both expert judgment and objective data within a holistic multi-criteria decision-making framework. Developed through a rigorous process involving a systematic literature review, focus group validation, questionnaire survey, expert interviews and real-world case studies from Hong Kong and Sri Lanka, the model addresses the complexities of SR decision-making in both developed and developing regions. An electronic tool that operates the SRDSS for practical use by facility managers and decision-makers has also been developed. The presentation concludes with a discussion of necessary future enhancements, offering both academic and practical contributions of the SRDSS to sustainable building management.

Keynote Address

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Empowering Sustainability: Tech-Driven Revolution for Safety-Enabled Facilities Management

Facilities Management is evolving beyond environmental responsibility to embrace occupational health and safety as a fundamental pillar. As workplaces and technological landscapes transform, integrating health and safety initiatives into digital frameworks is no longer just an advancement; it is an imperative. This shift is about more than compliance; it is about fostering environments where efficiency and well-being coexist seamlessly. By embedding occupational health and safety into the core of technological innovation, the future is being shaped where workplaces not only enhance productivity but also nurture resilience, security, and human potential.

In the era of hybrid work, where employees may not be present in the office consistently, our approach should include flexible monitoring solutions that address the dynamic nature of modern workplaces. By leveraging IoT devices and AI analytics, we need to aim to continuously monitor workplace conditions. These initiatives are designed to create a more resilient and supportive work environment, contributing to both environmental goals and human capital well-being.

Furthermore, the emergency response strategies to accommodate the fluid nature of hybrid work settings ensure rapid and effective responses even when the same individuals aren't consistently present. By sharing expertise and resources, we can accelerate the development and deployment of groundbreaking technologies that benefit both the environment and the people within it. Therefore, the integration of facilities management, occupational health, and emergency preparedness makes a meaningful impact on the global stage.

Table of Contents

Scientific Papers

DEVELOPING EVALUATION CRITERIA FOR ASSESSING THE PERFORMANCE OF SMART RETROFITTING OF EXISTING BUILDINGS	1
TOWARDS EFFECTIVE FM OUTSOURCING: BARRIERS AND STRATEGIC INTERVENTIONS FROM THE SRI LANKAN SERVICE PROVIDER’S PERSPECTIVE.....	14
INTERVENTIONS FOR CHANGING BEHAVIOUR OF STAKEHOLDERS FOR CIRCULAR ECONOMY ADOPTION IN CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT	29
ASSESSING THE READINESS TO ADOPT THE DIGITAL TWIN ENABLED FACILITIES MANAGEMENT TO REVAMP THE BUILDING OPERATION AND MAINTENANCE IN SRI LANKA	41
SAFETY RISK OF INDUSTRIAL LIQUEFIED PETROLEUM GAS INSTALLATIONS OF THE HOTEL SEGMENT IN SRI LANKA	57
UTILISING AUTOMATION SOLUTIONS TO MINIMISE OCCUPATIONAL SAFETY AND HEALTH ISSUES IN PORTS.....	74
BIRD NESTING AND DROPPINGS IN HIGH-RISE BUILDINGS: A LITERATURE REVIEW ..	90
ADAPTATION OF AUTOMATED DEMAND RESPONSE (ADR) TECHNOLOGY TO REDUCE PEAK ENERGY DEMAND IN SRI LANKAN COMMERCIAL BUILDINGS	103
ADOPTING CONCEPT OF BIOPHILIC DESIGN TO ENHANCE HEALTHY INDOOR: AN EXPERIMENT ON MOSS-BASE FOR TROPICAL BUILDING	116
AN OBSERVATIONAL STUDY ON RISKS IN FILM AND TELEVISION PRODUCTIONS; SPECIAL REFERENCE TO ART DEPARTMENT WORKFLOWS	133
GUIDELINES FOR OPTIMISING ENERGY CONSUMPTION OF HVAC AIR-SIDE SYSTEMS IN COMMERCIAL BUILDINGS IN SRI LANKA.....	146
ADDITIVE MANUFACTURING FOR ZERO WASTE APPAREL MANUFACTURING INDUSTRY IN SRI LANKA: A LITERATURE REVIEW.....	159
ENHANCING ENVIRONMENTAL, SOCIAL, AND GOVERNANCE (ESG) PERFORMANCE THROUGH BUILDING AUTOMATION SYSTEMS (BAS)	174
BARRIERS IN IMPLEMENTING THE CIRCULAR ECONOMY MODEL IN APPAREL WASTE MANAGEMENT IN SRI LANKA	188
GLOBAL RESEARCH TREND EVOLUTION IN OCCUPATIONAL HEALTH AND SAFETY OVER THE PAST DECADE	200
MANAGING BARRIERS AFFECTING TO IMPLEMENT SUSTAINABLE CONSTRUCTION WOOD WASTE MANAGEMENT IN SRI LANKA	212
THE IMPACT OF POWER INTERRUPTIONS ON MULTI-STOREY COMMERCIAL BUILDINGS IN SRI LANKA.....	221

THE IMPACT OF LIGHT AND HEAT LEVELS IN THE WORKING ENVIRONMENT ON WORKERS' SAFETY	235
DECISION-MAKING CRITERIA FOR BOILER MAINTENANCE: AN EMPIRICAL STUDY...	244
A FRAMEWORK FOR EFFECTIVE MANAGEMENT OF JANITORIAL SERVICE CONTRACTS IN SRI LANKAN COMMERCIAL BUILDINGS: A BILATERAL PERSPECTIVE.....	255
EFFECTIVENESS OF FACILITIES MANAGEMENT PERFORMANCE DURING OCCUPANCY PHASE OF CONDOMINIUM BUILDINGS IN SRI LANKA	268
PRIORITISATION OF MITIGATION STRATEGIES TO OVERCOME THE HEALTH AND SAFETY RISKS ASSOCIATED WITH E-WASTE RECYCLING WORKERS IN SRI LANKA	277
CONSTRAINTS FOR REDUCING CARBON EMISSIONS AND ENERGY CONSUMPTION IN BUILDINGS - A SYSTEMATIC REVIEW	290
USE OF THE INTERNET OF THINGS FOR WATER CONSUMPTION MONITORING IN APPAREL INDUSTRY.....	302
BEHIND THE WASTE: A SYSTEMATIC REVIEW OF LEADING CAUSES CONTRIBUTING TO OCCUPATIONAL HEALTH AND SAFETY ISSUES AMONG MUNICIPAL SOLID WASTE HANDLERS.....	316
DIGITALISED FACILITIES ASSET MANAGEMENT: A CASE STUDY	335
Technical Papers	
ENHANCING SAFETY IN FACILITIES MANAGEMENT: A BID MANAGEMENT APPROACH	348
A STUDY OF HUMAN ERROR FACTORS ON TRANSPORTATION ACCIDENTS IN CONTAINER TERMINALS IN SRI LANKA.....	354

SCIENTIFIC PAPERS

DEVELOPING EVALUATION CRITERIA FOR ASSESSING THE PERFORMANCE OF SMART RETROFITTING OF EXISTING BUILDINGS

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Abstract. The existing building sector is contributing to high energy consumption and CO₂ emissions worldwide. Therefore, building practitioners should commit to adopting energy-conserving practices and minimizing CO₂ emissions. Consequently, the adoption of smart retrofitting (SR) in existing buildings is one of the easiest and cheapest ways to achieve energy efficiency and reduce CO₂ emissions. In Sri Lanka, SR adaptation was at a low level. However, there is a shortage of research and studies concerning assessing the performance of the SR of existing buildings in Sri Lanka after its implementation. Therefore, the purpose of this research is to develop an assessment model to assess the performance of the SR of existing buildings for the post-installation phase in Sri Lanka. A qualitative research method was used in this research to identify factors to develop an SR performance assessment model for existing buildings. Semi-structured expert interviews were conducted to validate the identified factors and obtain additional information related to the SR assessment, and the data collected was analysed through manual content analysis. As a result, a total of 39 factors were identified, which fell into seven categories: technical adaptability, human comfort, economic adaptability, energy management, environmental sustainability, safety and security, and compliance. Finally, the SR performance assessment model is developed.

Keywords. Smart Retrofits, Existing Buildings, Assessment Model

1. Introduction

Global energy consumption has grown dramatically during the past few years, and the rate of global energy consumption is expected to increase by another 30% by 2040 (Dilogini et al., 2021). According to the European Union, the existing building in the EU accounts for 40% of the total energy consumption and 36% of the total CO₂ emissions worldwide (Balaras et al., 2023). Specifically, the construction and maintenance of conventional buildings consume about 30- 40% of energy consumption and are subject to releasing high levels of greenhouse gases (Ejidike & Mewomo, 2023). However, existing buildings should have to be modernized on a large scale to become decarbonization (Naimoli, 2020). Meanwhile, the existing buildings sector has reasonably high energy consumption compared with the new buildings in the built environment (Madushika et al., 2023). To this end, the EU has committed to reducing domestic greenhouse gas emissions and CO₂ emissions by 80% by 2050 to improve energy conservation (Aldakheel, 2021).

Due to these reasons, the retrofitting concept was introduced as the most suitable solution for achieving energy efficiency and reducing CO₂ emissions by remodeling buildings with the aim of sustainability (Gleeson et al., 2011). In recent years, the integration of smart features with retrofitting in existing buildings has been the subject of research in the current Industry 4.0 era (Newman et al., 2021). Similarly, the adoption of Smart Retrofitting (SR) in existing buildings is one of the easiest and cheapest ways to enhance and modernize building performance and attain sustainability (Farahani et al., 2019; Jayarathne & De Silva, 2022; Luddeni et al., 2018).

In this research, SR is described as the process of converting an existing building through the integration of new technologies, supporting the transition towards smart buildings to be able to sense, interpret, communicate, monitor and control building systems and actively respond to building and occupant needs to achieve energy saving, occupant comfort, safety and security, technical, economic and environmentally feasible.

On a similar note, it is observed that SR in building stock make a considerable contribution to the national CO₂ emission reduction, accounting for 61% of the total reduction (Hirvonen et al., 2021). As energy savings and carbon reduction are one of the main drivers of SR, SR reduces energy consumption while improving the building's smartness (Peiris et al., 2023). Out of these in the building sector, the SR concept creates a more comfortable, convenient, and flexible environment by reducing maintenance and operating expenditures, which enables organisations to boost their productivity and increase their marketability (Huseien & Shah, 2022). There are a variety of reasons that hinder SR implementation, such as risk associated with cyber-attacks in communication networks (Lawrence et al., 2016), lack of knowledge of new technologies, and specific legal obstacles (Aldakheel et al., 2020), lack of IOT experience between facility management (Pašek & Sojková, 2018). However, it is a known fact that a lack of knowledge and experience is a challenge that may hinder retrofitting (Aldakheel et al., 2020; Ibaseta et al., 2021).

Being a developing country, the adoption of the smart building concept in Sri Lanka is still novel to industry experts and researchers due to a lag behind in the integration with new technologies (Dilogini et al., 2021; Waidyasekara & Madhusanka, 2019). Similarly, in Sri Lanka, several studies have been conducted related to smart buildings and service preferences (Weerawardhana et al., 2024); some studies consider focusing on green retrofits (Periyannan et al., 2023) or energy retrofits (Amjath et al., 2021). In addition, it is obvious that several studies concerning the developing criteria for selecting the best suitable smart retrofit option for buildings (Jayarathne & De Silva, 2022; Peiris et al., 2023).

Even though there are several studies on SR in the Sri Lankan context, there is a shortage of research and studies concerning assessing the performance of SR in the post-installation stage of existing buildings in Sri Lanka. Therefore, this research aims to develop an assessment model to assess the performance of the SR of existing buildings in Sri Lanka after its installation. The introduced model can be used by industry professionals to measure the effectiveness of SR projects in their buildings, while policymakers can use this model to select the most suitable SR methods for different types of buildings when implementing organisational and national-level energy policies.

2. Literature Review

2.1 EXISTING ASSESSMENT MODEL AND RATING SYSTEMS RELATED TO SMART BUILDINGS AND SMART RETROFITTING

Concerning assessing the performance of buildings, the focus of this work is to develop a performance assessment model by identifying a set of factors to assess the building performance in existing buildings. Accordingly, several building performance assessment schemes have contributed to assessing the Smart Buildings (SB) and SR performance as mentioned below.

According to Kelly et al. (2012), building performance is crucial for assessing and estimating energy efficiency, cost-saving enhancements, and quantifying the overall emissions in a built environment. Post occupancy assessment (POE), benchmarking, building in use (BIU), quality assessment, balanced scorecards, and facility performance measures are several building performance assessment schemes developed in literature studies. (Islam et al., 2019).

Accordingly, several smart building performance assessment schemes have been developed in the past few years (Apanaviciene et al., 2020). Kolokotsa et al. (2007) developed a matrix tool giving importance to 25 sub-performance indicators that were categorized into five key criteria: responsiveness, functionality, economic issues, suitability, and environment to assess the performance of intelligent buildings. Further study by Arditi et al. (2015) proposed a smartness index considering the issues related to smart buildings under three main categories: energy, economic, and occupant comfort issues to assess the smartness of the building. Gunatilaka et al. (2021) proposed several aspects that need to be included to assess the level of smartness in Commercial Buildings in Sri Lanka. The author developed a scoring system forming six main Assessment criteria (occupancy comfort, communication and data sharing, energy management, health, safety, building automation, and sustainability features) and 31 sub-criteria for assessing the level of smartness from a commercial building's perspective.

Extending the review further, MATOOL, developed by Building Research Establishment, BIQ (Building Intelligence Quotient), IBI (Intelligent Building Index) and TIBA (Taiwan Intelligent Building Association) are several frameworks which highly developed based on the application of smart building concepts (Affonso et al., 2024).

Within this reference, it can be revealed that some existing building assessment frameworks are mostly focused on sustainability approaches: mainly a 'three pillar' framework to assess the sustainable impact of smart buildings (Crespi, 2018). In addition to that Green Building Assessment Tool (GBTool), Green Star, BREEAM (The Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design) in the USA, and CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), considered as mostly used environmental performance assessment schemes to assess the performance of buildings (Arditi et al., 2015; Gunatilaka et al., 2021). However, it is obvious that these tools are focused on specific areas: sustainable environmental aspects and do not prioritize occupant satisfaction in terms of assessing building performance (Das, 2012). Accordingly, Hassanain et al. (2022) conducted the POE process model to assess user satisfaction with smart buildings and found that user responsiveness is an essential feature of smart buildings.

Moreover, Aldakheel (2021) proposed key performance indicators (KPIS) to assess the SR in residential buildings under three main categories: energy performance, grid performance, and technological performance. In addition, Apostolopoulos et al. (2022) used the smart readiness indicator (SRI) to investigate the cost estimation and smartification of SR in typical residential buildings.

2.2. PARAMETERS FOR ASSESSING SMART RETROFITTING OF BUILDINGS

The selection of smart retrofit measures for a particular building is a complex process. (Peiris et al., 2023). Further, the author developed decision-making criteria for making decisions on suitable smart retrofit measures. The author highlighted that when selecting various SR measures, the decision maker should consider financial, technical, environmental, legal, and human criteria to choose optimum SR solutions. Energy-saving, human comfort, and green attributes can be considered as SR performance benchmarks of buildings (Jayarathne & De Silva, 2022).

According to the literature findings, most of the authors and existing smart building assessment schemes identified the most frequently used factors: green, safety, energy, economic, occupant comfort, environment, technological, sustainability, automation, health and safety. In addition to that, papers on retrofit decision-making criteria focus on technical, financial, environmental, legal, human, energy saving, human comfort, and green attributes. Within the list of identified factors, the development of a new assessment model to assess the performance of SR in existing buildings is presented in Figure 1.

2.2.1 Technical Adaptability

The adoption of SB technologies has enabled us to control and inspect remotely and operate in a shared network when compared with traditional buildings, which operate independently (Froufe et al., 2020). According to the authors, building automation systems and their inherent components (actuators and sensors) monitor and control interconnected services, enable remote monitoring, and manage multiple building operations automatically (Baig et al., 2017; Gunatilaka et al., 2021). Moreover, a high degree of automation characteristic of SB technologies can facilitate predictive maintenance approaches of existing systems (Moretti et al., 2021).

Accordingly, the inclusion of technology and automation into a reality in a common building will result in improving the value and life span of the building with the help of real-time updates and maintenance approaches (Froufe et al., 2020). Under this category, the study identified six (6) factors that are essential in assessing the performance of SR, including system interoperability, integrating BMS with existing controls, maintenance fault prediction capabilities, real-time monitoring and control, compatibility with existing systems, and flexibility to adopt changes.

2.2.2 Energy Management

Energy management is a prominent factor in optimum energy efficiency due to the use of information communication technology and advanced computing (Aslam et al., 2017; Mir et al., 2021). The adoption of SR technologies is becoming progressively meaningful for buildings to consider that they could decrease their energy costs (Crespi, 2018). Examples include the use of smart metering with an energy management system (Mbungu et al., 2020), smart grid (Mbungu et al., 2020), and integration with machine learning technologies to detect and predict anomalies in power consumption (Eini et al., 2021) are considered. Through building intelligent controls and management features, the SB energy management system can make intelligent, real-time decisions and manage building energy consumption by exploiting the information from IOT sensors and smart grids

(Froufe et al., 2020). Under this category, the study identified (6) factors that are essential in assessing the performance of SR including intelligent controls and energy management capabilities, energy efficiency improvements and saving capabilities, demand management capabilities, prediction of energy consumption, onsite renewable energy generation capabilities, and accuracy of smart metering capturing and monitoring real-time energy consumption.

2.2.3 Human Comfort

Parkinson et al. (2023) mentioned that human comfort is a fundamental factor that needs to be considered in buildings. Further study pinpointed sources for customer dissatisfaction: acoustics, temperature, noise level, visual privacy and air quality. This evidence should motivate building owners to respond proactively by adopting SB technologies to prioritize a comfortable indoor environment for occupant satisfaction (Daissaoui et al., 2020). Examples include controlling temperature and ventilation based on implementing SB technologies in HVAC retrofits make user satisfaction while maintaining an acceptable indoor air quality with high ventilation rates (Rodriguez & Fumo, 2024; Sieber et al., 1996). However, SR measures lead to complying with health certifications and standards that promote the health and well-being of the occupants: ASHRAE standard 62.1 (Rodriguez & Fumo, 2024). Under this category, the study identified four (4) factors that are essential in assessing the performance of SR, including maintaining indoor air quality, the ability to optimize thermal comfort, the ability to optimize visual comfort, and effective space utilization.

2.2.4 Safety and Security

Studies indicate that incorporation of SB technology and systems that are interconnected can provide a dual benefit, ensuring data security and privacy, ensure data security and privacy (Peiris et al., 2023). Security and access control have become critical functions in modern buildings, with the combination of sensors and other control devices to control and monitor the building's indoor and outdoor environment (Bhatt & Verma, 2015). These techniques include smart access control, CCTV, intrusion detection devices, and audio surveillance to enhance the safety and security of the buildings (Ciholas et al., 2019). Furthermore, through their smart safety and security systems SR contributes to building cybersecurity through the integration of IOT (Peiris et al., 2023), providing faster evacuation in an emergency by integration of a sensor-based emergency alert system (Costa et al., 2019), and integration of fire monitoring system provide accurate detection of potential fire incidents at early stage increasing occupant safety and resilience (Baek et al., 2021). Under this category, the study identified four (4) factors that are essential in assessing the performance of SR, including cyber-physical systems, emergency response with BMS capabilities, smart access control and surveillance capabilities and fire detection and response capabilities.

2.2.5 Environmental Adaptability

Over the past decades, most countries and organizations have been concerned with approaches and guidelines to minimize building energy consumption and achieve environmental sustainability goals (Periyannan et al., 2023). Furthermore, buildings that contribute to producing considerable amounts of greenhouse gas emissions have become a global issue (Chen & Ng, 2016; Truong et al., 2016). Respectively,

SR has been identified as an alternative solution in building sustainability to minimize energy consumption and prevent greenhouse gas emissions (Haidar et al., 2018). Moreover, the attainment of sustainable certifications such as the Building Research Establishment Environmental Assessment Method (BREEAM) and Energy and Environmental Design (LEED) can be identified as a crucial criterion for assessing the SR in buildings (Fasna & Gunatilake, 2019). Under this category, the study identified two (2) factors that are essential in assessing the performance of SR, including water conservation and decarbonizing. Figure 1 shows the summary of the literature findings.

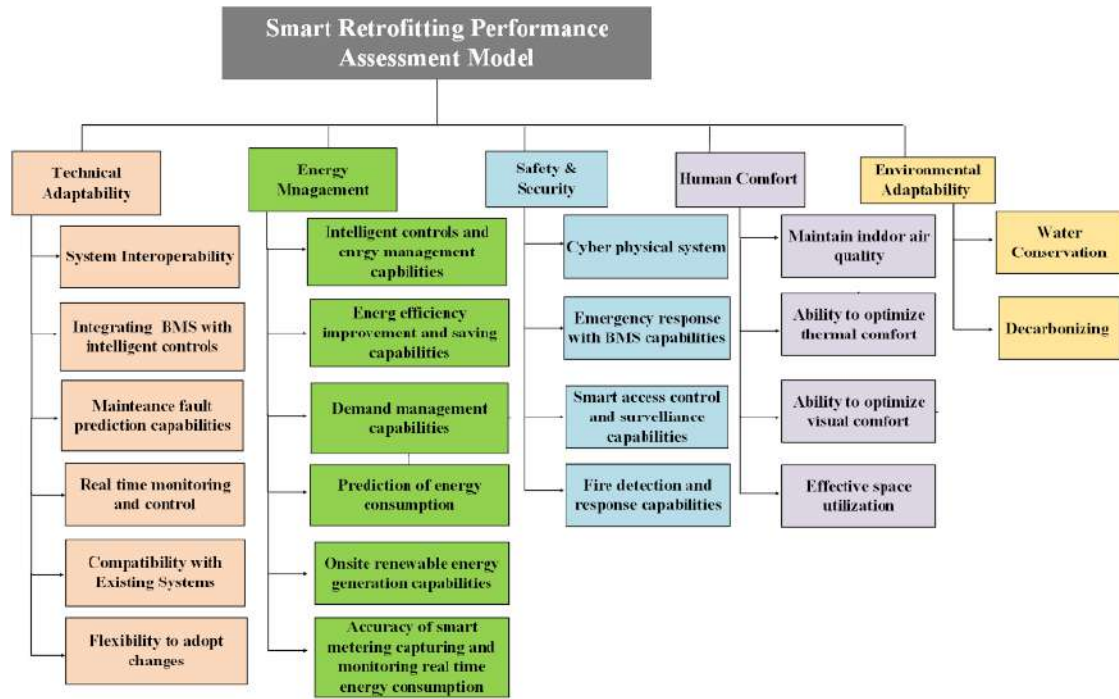


Figure 1: Developed SR performance assessment model from literature

According to the findings of the literature review, the existing SR performance assessment models focus on selecting suitable SR methods. This model provides several factors to be considered for the assessment of post post-implementation stage of SR in conventional buildings in Sri Lanka. It helps to measure the effectiveness of the implemented SR measures and to make informed decisions on the continuation of those measures. To make the assessment process easier, all factors have been divided into 7 categories.

3. Research Methodology

In the first stage of research, a comprehensive literature review was carried out to identify the factors that affect assessing SR in existing buildings through journals, books, and conference proceedings. Subsequently, a qualitative approach was carried out to collect in-depth information and learn about respondents' thoughts and opinions based on their experience and opinions involved in integrating SR. Interviews have been identified as one of the best options for data collection to carry out an in-depth inquiry regarding the survey findings, and they mainly fall within the qualitative research (De La Croix et al., 2018). Further expert interviews are best suited to gather the data by investigating the experience and perspectives of the interviewees (Döringer, 2020). Therefore, expert interviews were carried out

to validate the data generated through the literature. Apart from verifying the relevance of the proposed SR assessment model identified through the literature, respondents were invited to make changes and modifications to the developed SR performance assessment model. The semi-structured interviews are the most widely used qualitative research data collection method in which predefined guidelines are used, but they allow the researcher to explore the issue or response with diversity (Islam & Aldaihani, 2022). Therefore, semi-structured interviews were carried out to extract relevant information from the experts. Manual content analysis was used for interpreting and analyzing the details from the semi-structured interviews. Table 1 illustrates the profile of the respondents for semi-structured interviews.

Table 1: Profile of the respondents

Expert Code	Designation	Years of experience in the built environment
E1	Head of Facilities Management	12 years of working experience in leading commercial sector buildings
E2	Ph.D. Candidate	5 years of working experience in SR in office buildings
E3	Building Automation Engineer	10 years of working experience in building automation projects
E4	Manager Engineering	11 years of working experience in commercial and office buildings
E5	MEP and Facility consultant	16 years of working experience in commercial and office buildings
E6	Engineer in Facility Management and commissioning	10 years of working experience in building automation projects

According to Table 1, the experts who were chosen by purposive sampling and further evaluated using several other additional factors, including possessing a degree in facilities management (FM)/engineering field, possessing a professional qualification in the facilities management/engineering field, possessing theoretical knowledge about new technology and in SR. Further, it is mandatory to have a minimum of 4 years of experience in SR practice or research and at least 5 years of experience in FM practice or research. Due to the lack of more experienced experts in the field of smart SR, the sample was limited to 6.

4. Findings and Data Analysis

Expert interviews were conducted to confirm the accuracy of the information obtained from the literature. With the help of additional information obtained through the expert interviews, the objectives of the study, which had been partially outlined by the literature review, were strengthened and completed. This phase involved six experts in total. In addition, experts interpreted factors and additional main criteria for the SR performance assessment of existing buildings.

All the experts confirmed all the factors mentioned in the technical adoption performance assessment through the literature review findings. In addition, the experts advised that the phrase 'Automated maintenance prediction capabilities' needs to be changed to 'Automated maintenance management' because the SB system supports not only predictive maintenance, but also corrective maintenance, and preventive maintenance activities point out that "trends, multi-trends supported for predictive and preventive maintenance, while real-time monitoring and alarming support corrective maintenance". The experts also highlight the need for real-time monitoring and controlling, which ensures the successful implementation of the SR project. On the other hand, experts emphasized the importance of IoT integration as a performance assessment criterion in the post-performance stage, enabling SB operation to sense, communicate, exchange data, and analyze data in real-time. Another technical assessment criterion for SR is integration with AI applications to enhance building performance through predictive fault detection using real-time data from IOT sensors. Experts further stated that successful SR projects are dependent on the user-friendliness of humans and their willingness to adopt new technologies.

All six experts confirmed the energy management criteria in the assessment of SR, as identified by the literature findings. The experts commented that the SR concept is progressively adopted by existing buildings due to the Energy efficiency improvements. In addition, E3 revealed that the "ability to facilitate onsite renewable energy generation has limitations because the criteria rely on the renewable energy generation connected to the smart energy management systems, BMS system or integrated into the smart grid". E1, E4, and E5 experts revealed that the 'prediction of energy consumption' phrase needs to be changed to 'Prediction of Energy Consumption and variations' to strengthen the meaning of the criteria. Two primary factors are disclosed by experts to assess the assessment of SR practices including 'System accuracy for optimized saving' as a new energy management criterion to ensure systems function accurately and maximize energy efficiency and 'energy benchmarking' as part of the criteria as it helps determine if SR implementation results in significant savings, energy goals are achieved as they expected. Experts agree that SR is a sustainable approach to decarbonization and water conservation, which is identified in the literature. In addition to that, E5 proposed Material conservation as a new criterion for sustainability performance by stating, "Some countries utilized recycled materials in electrical components". Although the experts revealed that the 'environmental adaptability' criteria need to be changed to 'environmental sustainability' to strengthen the meaning of the criteria

All experts agreed with the criteria for comfort, health and well-being that are found in the literature. Experts agreed on the importance of maintaining indoor air quality, optimising thermal comfort, and optimising visual comfort. They also highlighted that occupancy sensors are crucial for efficient space management and minimizing occupancy complaints. Other than that, experts revealed the need to address occupant satisfaction and enhance indoor air quality and temperature controls for increased productivity. In addition to these factors, experts emphasized that occupant satisfaction is a crucial factor of smart retrofits that should be considered when assessing performance. Under this occupant experience about their convenience, timesaving after the SR implementation needs to be addressed. The

literature review identified four functions for assessing performance, safety and security in retrofit buildings that are agreed upon by all the experts. Cybersecurity is becoming increasingly important for enhancing privacy and data security. Factors such as fault detection accuracy, response time, smart access control, and fire detection and response capabilities are crucial for assessing SR performance.

Nevertheless, experts commented that regulatory compliance was noted to assess the performance of SR implementation. These included guidelines established by professional organizations, such as achieving environmental sustainability certification, supporting human health certification, achieving operations standards and certifications (ISO), and complying with government codes and regulations, are the crucial factors that need to be considered to assess the performance.

In addition to these criteria, all the experts revealed economic adaptability as a new criterion for assessing the performance of SR. Most of the research has demonstrated that the payback period and return on investment of retrofits are more important to assess economic viability. Another economically sustainable criterion to assess SR is the operation cost by disclosing as lower operating costs are anticipated by building owners with the highest quality level in their retrofit projects. In addition to that, experts emphasize the importance of SR implementation for operational efficiency, cost savings, and asset value enhancement. Besides that, experts emphasized the importance of increasing asset value and brand image as a performance assessment criterion in the post-performance stage. Thus, it improves occupancy rates and tenant retention, enhancing market competitiveness.

5. Developed Assessment Model

The SR Assessment model is developed by considering the literature and experts' opinions to assess the performance of SRs. According to literature findings and based on the experts' opinions, 39 SR performance Assessment criteria were identified; and these fall under six main categories, such as technical adaptability, human comfort, health and well-being, economic adaptability, environmental sustainability, safety and security, and compliance. Figure 2 illustrates the developed Assessment model. When assessing the effectiveness of SR, industry practitioners can use the criteria in this model.

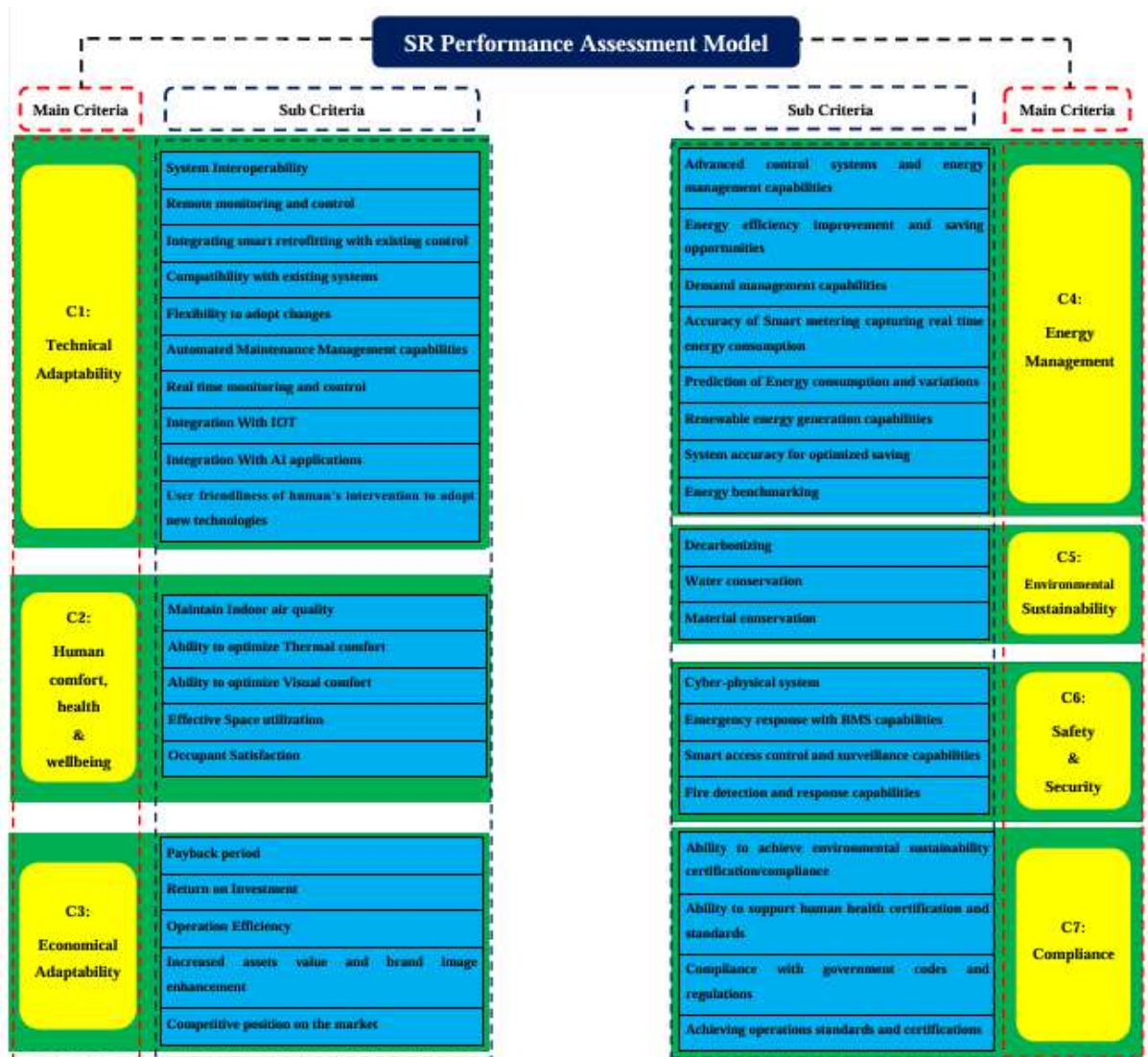


Figure 2: Developed SR performance assessment model

6. Conclusion

This study aims to assess the performance of implementing the SR concept in existing buildings. Initially, an in-depth literature review was carried out to identify the factors for assessing the performance of the SR concept, highlighting a focus on technical adaptability, energy management, human comfort, safety and security, environmental sustainability, economic adaptability, and compliance. According to literature findings and based on the experts' opinions, 39 SR performance Assessment criteria were identified, and these fall under seven main categories. Finally, a framework was developed that supports building practitioners in assessing the performance of their SR implementation.

Prior studies have focused on SR decision-making to select an appropriate smart retrofit option. However, it is difficult to assess the level of SR performance in existing buildings in Sri Lanka without a robust SR assessment model due to the lack of SR performance assessment models and the lack of SR-experienced building practitioners. In Sri Lanka adoption of SR is very rare. Hence, the developed model provides an assessment criterion to assess the performance of

SR in existing buildings after its implementation stage from a Sri Lankan point of view. The developed model will enable building practitioners to systematically assess the performance of their smart retrofit outcomes in terms of technical adaptability, energy management, human comfort, safety and security, environmental sustainability, economic adaptability, and compliance. Also, the outcome of this study serves as a benchmarking and KPIs evaluation tool, which can help facilities managers in making informed decisions regarding SR techniques that have been implemented.

7. References

- Affonso, E. O. T., Branco, R. R., Guedes, A. L. A., Chinelli, C. K., Tam, V. W. Y., Haddad, A. N., & Soares, C. a. P. (2024). Framework for assessing the smart buildings intelligence degree. *International Journal of Construction Management*, 1–23. <https://doi.org/10.1080/15623599.2024.2400809>
- Al Dakheel, J., Del Pero, C., Aste, N., & Leonforte, F. (2020). Smart buildings features and key performance indicators: A review. In *Sustainable Cities and Society* (Vol. 61). Elsevier Ltd. <https://doi.org/10.1016/j.scs.2020.102328>
- Apanaviciene, R., Vanagas, A., & Fokaides, P. A. (2020). Smart Building Integration into a Smart City (SBISC): Development of a New Evaluation Framework. *Energies*, 13(9), 2190. <https://doi.org/10.3390/en13092190>
- Arditi, D., Mangano, G., & De Marco, A. (2015). Assessing the smartness of buildings. *Facilities*, 33(9/10), 553–572. <https://doi.org/10.1108/f-10-2013-0076>
- Aslam, S., Iqbal, Z., Javaid, N., Khan, Z., Aurangzeb, K., & Haider, S. (2017). Towards Efficient Energy Management of Smart Buildings Exploiting Heuristic Optimization with Real Time and Critical Peak Pricing Schemes. *Energies*, 10(12), 2065. <https://doi.org/10.3390/en10122065>
- Baek, J., Alhindi, T. J., Jeong, Y. S., Jeong, M. K., Seo, S., Kang, J., & Heo, Y. (2021). Intelligent Multi-Sensor Detection System for Monitoring Indoor Building Fires. *IEEE Sensors Journal*, 21(24), 27982–27992. <https://doi.org/10.1109/JSEN.2021.3124266>
- Baig, Z. A., Szewczyk, P., Valli, C., Rabadia, P., Hannay, P., Chernyshev, M., Johnstone, M., Kerai, P., Ibrahim, A., Sansurooah, K., Syed, N., & Peacock, M. (2017). Future challenges for smart cities: Cyber-security and digital forensics. *Digital Investigation*, 22, 3–13. <https://doi.org/10.1016/j.diin.2017.06.015>
- Balaras, C. A., Dascalaki, E. G., Patsioti, M., Droutsas, K. G., Kontoyiannidis, S., & Cholewa, T. (2023). Carbon and Greenhouse Gas Emissions from Electricity Consumption in European Union Buildings. *Buildings*, 14(1), 71. <https://doi.org/10.3390/buildings14010071>
- Bhatt, J., & Verma, H. K. (2015). Design and development of wired building automation systems. *Energy and Buildings*, 103, 396–413. <https://doi.org/10.1016/j.enbuild.2015.02.054>
- Chen, Y., & Thomas Ng, S. (2016). Factoring in embodied GHG emissions when assessing the environmental performance of building. *Sustainable Cities and Society*, 27, 244–252. <https://doi.org/10.1016/j.scs.2016.03.015>
- Ciholas, P., Lennie, A., Sadigova, P., & Such, J. M. (2019). The Security of Smart Buildings: a Systematic Literature Review. <http://arxiv.org/abs/1901.05837>
- Costa, D. G., Vasques, F., Portugal, P., & Aguiar, A. (2019). A distributed Multi-Tier emergency alerting system exploiting Sensors-Based event detection to support smart city applications. *Sensors*, 20(1), 170. <https://doi.org/10.3390/s20010170>
- Crespi, M. (2018). An economic feasibility study of smart building investments: the Italian scenario.

- Ejidike, C. C., & Mewomo, M. C. (2023). Benefits of adopting smart building technologies in building construction of developing countries: review of literature. *SN Applied Sciences*, 5(2). <https://doi.org/10.1007/s42452-022-05262-y>
- Daissaoui, A., Boulmakoul, A., Karim, L., & Lbath, A. (2020). IoT and Big Data Analytics for Smart Buildings: A Survey. *Procedia Computer Science*, 170, 161–168. <https://doi.org/10.1016/j.procs.2020.03.021>
- Dilogini, R. A. A., Sridarran, P., & Mahedrarajah, G. (2021). Enhancing the integration of smart features in commercial buildings to conserve energy: A framework. *World Construction Symposium*, 302–313. <https://doi.org/10.31705/WCS.2021.26>
- Eini, R., Linkous, L., Zohrabi, N., & Abdelwahed, S. (2021). Smart building management system: Performance specifications and design requirements. *Journal of Building Engineering*, 39, 102222. <https://doi.org/10.1016/j.jobee.2021.102222>
- Froufe, M., Chinelli, C., Guedes, A., Haddad, A., Hammad, A., & Soares, C. (2020). Smart buildings: systems and drivers. *Buildings*, 10(9), 153. <https://doi.org/10.3390/buildings10090153>
- Gunatilaka, R. N., Abdeen, F. N., & Sepasgozar, S. M. E. (2021). Developing a Scoring System to Evaluate the Level of Smartness in Commercial Buildings: A Case of Sri Lanka. *Buildings*, 11(12), 644. <https://doi.org/10.3390/buildings11120644>
- Farahani, A., Wallbaum, H., & Dalenbäck, J. O. (2019). The importance of life-cycle based planning in maintenance and energy renovation of multifamily buildings. *Sustainable Cities and Society*, 44, 715–725. <https://doi.org/10.1016/j.scs.2018.10.033>
- Fasna, M. F. F., & Gunatilake, S. (2019). The effective outsourcing of building retrofitting: key decisions and motivators. *Journal of Facilities Management*, 17(4), 371–384. <https://doi.org/10.1108/JFM-01-2019-0003>
- Gleeson, C., Yang, J., & Lloyd-Jones, T. (2011). European Retrofit Network: Retrofitting Evaluation Methodology Report. http://www.betterbuildingspartnership.co.uk/download/bbp_low_carbon_retrofit_toolkit.pdf
- Haidar, N., Attia, M., Senouci, S. M., Aglzim, E. H., Kribeche, A., & Asus, Z. B. (2018). New consumer-dependent energy management system to reduce cost and carbon impact in smart buildings. *Sustainable Cities and Society*, 39, 740–750. <https://doi.org/10.1016/j.scs.2017.11.033>
- Hirvonen, J., Heljo, J., Jokisalo, J., Kurvinen, A., Saari, A., Niemelä, T., Sankelo, P., & Kosonen, R. (2021). Emissions and power demand in optimal energy retrofit scenarios of the Finnish building stock by 2050. *Sustainable Cities and Society*, 70. <https://doi.org/10.1016/j.scs.2021.102896>
- Huseien, G. F., & Shah, K. W. (2022). A review on 5G technology for smart energy management and smart buildings in Singapore. In *Energy and AI* (Vol. 7). Elsevier B.V. <https://doi.org/10.1016/j.egyai.2021.100116>
- Ibaseta, D., García, A., Álvarez, M., Garzón, B., Díez, F., Coca, P., Pero, C. Del, & Molleda, J. (2021). Monitoring and control of energy consumption in buildings using WoT: A novel approach for smart retrofit. *Sustainable Cities and Society*, 65. <https://doi.org/10.1016/j.scs.2020.102637>
- Kolokotsa, D., Sutherland, G., Stavarakakis, G., Karatassou, S., & Santamouris, M. (2007). A matrix tool for assessing the performance of intelligent buildings. *Management of Environmental Quality an International Journal*, 18(1), 36–49. <https://doi.org/10.1108/14777830710717703>
- Lawrence, T. M., Boudreau, M. C., Helsen, L., Henze, G., Mohammadpour, J., Noonan, D., Patteeuw, D., Pless, S., & Watson, R. T. (2016). Ten questions concerning integrating smart buildings into the smart grid. *Building and Environment*, 108, 273–283. <https://doi.org/10.1016/j.buildenv.2016.08.022>

- Luddeni, G., Krarti, M., Pernigotto, G., & Gasparella, A. (2018). An analysis methodology for large-scale deep energy retrofits of existing building stocks: Case study of the Italian office building. *Sustainable Cities and Society*, 41, 296–311. <https://doi.org/10.1016/j.scs.2018.05.038>
- Madushika, U. G. D., Ramachandra, T., Karunasena, G., & Udakara, P. A. D. S. (2023). Energy Retrofitting Technologies of Buildings: A Review-Based Assessment. In *Energies* (Vol. 16, Issue 13). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/en16134924>
- Mir, U., Abbasi, U., Mir, T., Kanwal, S., & Alamri, S. (2021). Energy Management in Smart Buildings and Homes: Current Approaches, a Hypothetical Solution, and Open Issues and Challenges. *IEEE Access*, 9, 94132–94148. <https://doi.org/10.1109/ACCESS.2021.3092304>
- Moretti, N., Blanco Cadena, J. D., Mannino, A., Poli, T., & Re Cecconi, F. (2021). Maintenance service optimization in smart buildings through ultrasonic sensors network. *Intelligent Buildings International*, 13(1), 4–16. <https://doi.org/10.1080/17508975.2020.1765723>
- Mbungu, N. T., Bansal, R. C., Naidoo, R. M., Bettayeb, M., Siti, M. W., & Bipath, M. (2020). A dynamic energy management system using smart metering. *Applied Energy*, 280, 115990. <https://doi.org/10.1016/j.apenergy.2020.115990>
- Naimoli, S. (2020). THE ISSUE Climate Solutions Series Decarbonizing the Built Environment THE CHALLENGE.
- Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W. D., & Rillie, I. (2021). 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>
- Pašek, J., & Sojková, V. (2018). Facility management of smart buildings. *International Review of Applied Sciences and Engineering*, 9(2), 181–187. <https://doi.org/10.1556/1848.2018.9.2.15>
- Peiris, S., Lai, J., & M Kumaraswamy, M. (2023). Establishing criteria for smart retrofitting decision-making for buildings. *IOP Conference Series: Earth and Environmental Science*, 1176(1). <https://doi.org/10.1088/1755-1315/1176/1/012004>
- Periyannan, E., Ramachandra, T., & Geekiyanage, D. (2023). Assessment of costs and benefits of green retrofit technologies: Case study of hotel buildings in Sri Lanka. *Journal of Building Engineering*, 78. <https://doi.org/10.1016/j.job.2023.107631>
- POLITECNICO DI MILANO “An economic feasibility study of Smart Building investments: the Italian scenario.” (n.d.).
- Rodriguez, J., & Fumo, N. (2024a). Simultaneous thermal zoning and demand control ventilation. *Energy Reports*, 11, 4412–4422. <https://doi.org/10.1016/j.egyr.2024.04.025>
- Rodriguez, J., & Fumo, N. (2024b). Simultaneous thermal zoning and demand control ventilation. *Energy Reports*, 11, 4412–4422. <https://doi.org/10.1016/j.egyr.2024.04.025>

TOWARDS EFFECTIVE FM OUTSOURCING: BARRIERS AND STRATEGIC INTERVENTIONS FROM THE SRI LANKAN SERVICE PROVIDER'S PERSPECTIVE

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Abstract. Facilities management (FM) refers to the management of non-core business activities to support the core activities. FM outsourcing has been established as one of the successful methods for FM procurement because of its benefits. In the FM operation, various challenges have arisen from various perspectives. Referring to that, the aim of this study is to investigate requirements for maintaining an effective FM outsourcing contract by the service provider company. The research scope was limited to challenges to FM service providers and strategies that are used by them to overcome challenges within the Sri Lankan context in a situation where the contract has already been formed. Accordingly, a qualitatively based extensive literature synthesis has been conducted concerning the FM outsourcing concept and challenges in maintaining FM contracts. Following the qualitative approach, data were collected through nine (9) semi-structured interviews with FM service providers. The findings revealed that in the Sri Lankan context, FM service providers are facing various challenges, knowing them and making strategies to overcome them will be the key to the continuity of the contract with the client. Prioritizing clients' needs, defining proper standing operation procedures, having separate service coordinators, frequent meetings with the client and subcontractors, understanding the client's language and nonverbal communication, and forming communication strategies were mainly used as strategies. The framework has been developed based on the above-mentioned key findings, including key determinants to be considered.

Keywords. Facilities Management, Outsourcing, Service Provider, Contracts

1. Introduction

FM provides business-improving solutions for organizations that are looking for solutions to the problems occurring in their business (Fajrillah et al., 2022). Further, it has been defined as the strategic management of non-core activities (Parry & Collins, 1993). The growing awareness and recognition of FM and the role of FM for business performance in the public sector and the corporate sector have gradually grown with competitive strategies (Riratanaphong et al., 2012). Ikediashi et al. (2014) stated that as organizations increasingly recognize the strategic value of FM, many are re-evaluating how these services are delivered to maximize efficiency and effectiveness. This shift has led to a growing interest in alternative delivery models, among which outsourcing has emerged as a prominent approach (Pratap, 2014). Outsourcing has gained traction as it allows organizations to tap into external expertise and streamline their operations (Ikediashi, 2014). This trend reflects a broader move toward more agile and cost-effective management of non-core functions. Accordingly, three main reasons have been identified for outsourcing to become increasingly popular in organizations that are integrating with the best practices: achieving optimum cost discipline, improving managerial skills for better performance, and enabling a stronger focus on core competencies of the organization (Ikediashi et al., 2014).

Outsourcing the FM functions allows management to spend more time and pay attention to core business activities (Vetr et al., 2013). The new generation debate, however, is that it is not only about outsourcing facilities management but about

how it should be managed effectively (BOOTY, 2009). Several factors have been identified that influence FM outsourcing decisions, including increasing flexibility and profitability, solving capacity problems, making costs more transparent, and reducing operational expenses (Iqbal, 2013). This highlights a growing need to shift from simply outsourcing FM functions to strategically managing outsourced contracts to ensure value delivery. Although there are various methods of outsourcing, the expected value will be gained or achieved only through effective restructuring of the rigid property portfolio as per the business needs (Soili Nystén-Haarala, 2010). Such contradictions between the expected benefits and actual outcomes suggest a lack of clarity on the conditions under which FM outsourcing becomes successful (Ikediashi et al., 2014).

To address this, there must be proper commitment from top and middle management to understand how business operations flow from strategic to operational levels (Wauters, 2017). When considering the main areas of concern for FM outsourcing companies, customer satisfaction, sustainability, energy management solutions, key performance indicators, and better risk-sharing are seen as key factors (Rimbalová & Vilčeková, 2013).

In Sri Lanka, although demand for FM services is growing, the property market expects teams that are specialized and trained to meet this increasing demand (Research and Professional Development Center, 2016). However, challenges such as shortage of skilled human resources, benchmarking, and the level of quality of FM service providers and suppliers continue to affect service reliability (Dissanayake & Weerasinghe, 2015). Therefore, proper integration between the FM service provider and the client organization is essential (ISS, 2016). Some studies have found some cases related to the failures in outsourcing arrangements because of not having properly administered strategies (Amos & Gadzekpo, 2016).

While several studies have explored FM outsourcing risks and practices in countries like Nigeria (I. Ikediashi et al., 2014; Ikediashi et al., 2012) and Uganda (Natukunda et al., 2013), there is a notable lack of research in the Sri Lankan context. This absence limits the understanding of local challenges and stakeholder dynamics in FM outsourcing. This study, therefore, aims to critically examine the key challenges of successful FM outsourcing in the Sri Lankan context and propose strategies for improving contract performance. By addressing contextual limitations in current literature in Sri Lankan context, this research seeks to bridge the gap between FM outsourcing theory and its practical application in Sri Lanka.

2. Literature Review

2.1 CONCEPT OF FACILITIES MANAGEMENT (FM) OUTSOURCING

The Centre for Facilities Management, Strathclyde Graduate Business School, defined facilities management as “the process by which an organization delivers and sustains a quality working environment and delivers quality support services to meet organization objectives at the best cost” (Kurdia et al., 2011). According to Lok and Baldry (2015), facilities management (FM) outsourcing is the process of delegating facility-related services to external service providers instead of managing them in-house. This practice has evolved as organizations seek to focus on their core competencies while improving efficiency and cost-effectiveness in non-core activities (Wang et al., 2020). FM outsourcing can involve either partial or

complete externalization of a process that was previously managed within the organization.

The concept of FM outsourcing gained prominence in the USA during the 1970s when large and medium-sized firms started contracting out their FM services to specialized facilities management companies (Parry & Collins, 1993). This trend later expanded to Britain in the 1990s and has since continued to grow globally (Jensen, 2017). Studies indicate that even during financial crises, the tendency for FM outsourcing has increased, with 63% of organizations opting for outsourced FM services despite a slight reduction in FM turnover (Jensen, 2017). Outsourcing FM functions allows organizations to concentrate on their core business activities while benefiting from specialized service providers' expertise (Lok, So, et al., 2021). By outsourcing, companies can achieve better cost management, enhance service quality, and optimize operational efficiency (Lok, Smith, et al., 2021). Furthermore, FM outsourcing supports business rationalization by optimizing costs, improving flexibility, and ensuring better management of facilities (I. Ikediashi et al., 2014).

2.1.1 Key Strategies in FM Outsourcing

FM outsourcing is guided by two primary strategies: core competency focuses and outsourcing non-core activities (Opoku & Lee, 2022). The first strategy emphasizes leveraging the organization's internal resources and investments for critical business functions. The second strategy involves outsourcing activities where the organization lacks specialized capabilities (Pratap, 2014). Organizations must carefully evaluate their resource base and internal staff capabilities before deciding to internalize or outsource FM services (Pratap, 2014).

In addition to outsourcing non-core activities, organizations must also consider intangible resources such as information technology management and process knowledge (Hoxha et al., 2022). Effective outsourcing requires careful decision-making at every stage, from the tendering process to contract management and long-term service evaluation (Pratap, 2014). Different FM outsourcing models have been identified in the literature. According to Jensen (2017), FM outsourcing can be categorized into four sourcing models:

1. In-house/own production – Organizations manage FM services internally.
2. Single services – Outsourcing specific FM services to external providers.
3. Bundled services – Grouping multiple FM services under one contract with a service provider.
4. Integrated Facilities Management – A comprehensive outsourcing approach where all FM functions are handled by a single provider.

Organizations often adopt a combination of these models depending on their operational requirements and strategic objectives (Lok, Smith, et al., 2021). The selection of the appropriate model depends on factors such as service scope, geographical coverage, relationship management, and decision-making structures (Wang et al., 2020). FM outsourcing contracts generally span three to four years, during which organizations and service providers must maintain strong collaboration to achieve the desired outcomes (Kurdi et al., 2011). Moreover, balancing in-house and outsourced FM services is a critical decision, as

organizations need to assess whether outsourcing will provide the expected benefits while maintaining operational control (Opoku & Lee, 2022). The Balanced Scorecard method has been suggested as a tool for evaluating FM performance and procurement decisions (Hoxha et al., 2022). Additionally, maintaining long-term relationships with service providers is essential to ensure service quality and operational efficiency (Jensen, 2017).

Despite the numerous benefits of FM outsourcing, organizations frequently face a range of challenges that can compromise the success and continuity of the outsourced delivery service. These challenges are not limited to clients alone but significantly impact service providers, who must navigate issues such as maintaining consistent service quality, adapting to evolving client expectations, managing resource constraints, and aligning their operations with contractual obligations. Identifying and understanding these specific challenges from the service provider's perspective is essential to improving long-term outsourcing relationships and ensuring the sustainability of FM contracts.

2.2 CHALLENGES TO THE FM SERVICE PROVIDER FOR CONTINUING FM OUTSOURCING CONTRACT

Outsourcing in FM has grown significantly as organizations seek to improve operational efficiency and reduce costs. However, several challenges continue to impact the effective implementation of outsourced FM services. These challenges can be grouped into key areas: strategic, operational, and relational challenges, which can hinder the success of outsourcing arrangements.

2.2.1 Strategic Challenges

The alignment of outsourcing strategies with the organization's long-term goals is often a significant hurdle. A study by Lilly et al. (2020) suggests that many organizations struggle to integrate FM outsourcing into their core business strategies. This misalignment can lead to difficulties in ensuring that the outsourced services contribute to the organization's overarching objectives. Furthermore, a lack of clarity in the selection of service providers may result in the wrong choice of partners, compromising the quality and efficiency of services (Amos & Gadzekpo, 2016).

2.2.2 Operational Challenges

On the operational side, managing day-to-day operations becomes complex as FM services are outsourced to third parties. According to Teo et al. (2025), managing the coordination between internal teams and external service providers can lead to communication gaps and inefficiencies. Additionally, issues such as poor contract management, unclear service level agreements (SLAs), and inadequate performance monitoring can lead to operational disruptions (Moseley & Thomann, 2021). These challenges are particularly pronounced in long-term contracts where expectations evolve.

2.2.3 Relational Challenges

The relationship between the client and the service provider is central to successful outsourcing. One of the most significant challenges is building and maintaining trust. A study by Brito et al. (2024) found that a lack of trust and poor

communication between stakeholders can create a toxic environment that undermines collaboration. Furthermore, issues related to cultural differences, particularly when the service provider is from a different region or country, can exacerbate misunderstandings and negatively impact service delivery (Lai et al., 2025).

2.2.4 Technology and Innovation Challenges

As technology continues to advance, the incorporation of smart building technologies and integrated FM systems has become increasingly important. However, many organizations face challenges in adopting new technologies due to the high costs, complexity of integration, and resistance to change from internal staff (Koo & Jeong, 2024). Furthermore, service providers may not always have the technical expertise required to implement innovative solutions, thereby hindering the potential benefits of outsourcing in terms of technology adoption.

2.2.5 Financial and Risk Management

One of the primary reasons for outsourcing is the financial savings it offers. However, without proper risk management frameworks in place, organizations may find themselves exposed to financial risks. According to D'Andrea et al. (2023), hidden costs, such as the need for additional monitoring and administrative support, can erode the financial benefits of outsourcing. Furthermore, the reliance on a third-party provider for critical services creates vulnerability in case of service disruptions or non-compliance with contractual obligations.

2.2.6 Quality Control and Performance Management

Maintaining service quality is a perennial issue in outsourcing arrangements. Studies by Ikediashi et al. (2014) emphasize that without effective performance management systems in place, outsourced FM services may fail to meet the required standards. Poor performance in facilities management can lead to dissatisfaction among employees and tenants, affecting the overall organizational environment and productivity.

Table 1: Challenges to FM service providers

Challenges to the FM Service Provider		
Management Challenges		
1	Not being able to provide the learning and development to the staff	(Capizzi, 2018)
2	Not being able to manage the risks of the operation	(Sillanpää & Junnonen, 2012)
3	Being unable to manage the sub-contractors accordingly to overcome the required qualitative and quantitative outcomes	(Patacas et al., 2020), (Sarshar, 2006)
4	Being unable to ensure a smooth transition	(Sarshar, 2006)
5	Not paying attention to the issues at the right time	(Sillanpää & Junnonen, 2012)
Challenges because of the client's mindset		

6	Restrictions on the sacrifice of short-term cost benefits to achieve long-term cost benefits	(Kurdia et al., 2011)
7	The decision to go with multiple contractors for various hard FM and soft FM functions.	(Pratap, 2014)
8	That outsourcing is an automatic ticket to success	(Campbell, 2006)
Expertise Challenges		
9	Not having sufficient technological expertise to overcome the technological issues	(Ikediashi, 2014), (Kurdia et al., 2011), (Iqbal, 2013)
10	The shortage of experienced and effective managers	(Lok & Baldry, 2015), (Amos & Gadzekpo, 2016), (Ikediashi, 2014)
Challenges due to lack of management in sub-contracting		
11	Being unable to manage the sub-contractors accordingly to overcome required qualitative and quantitative outcomes	(Lok & Baldry, 2015), (Ventovuori & Lehtonen, 2006), (Patacas et al., 2020)
External environmental challenges		
12	Economic demand becomes less due to the economic crises	(Riratanaphong et al., 2012), (Capizzi, 2018)
Challenges in relationship management		
13	Not being able to correctly engage with the co creation process has been led to many issues	(Ikediashi et al., 2012)
14	Situations where the contract value exceeds the risks associated with the business process	(Performance Transparency Drives, 2016)

3. Research Methodology

The research approach can be defined as plans and procedures for conducting research that cover the progression from general hypotheses to specific techniques for data collecting, analysis, and interpretation. The qualitative research approach has been used for this study because it can thoroughly analyse ideas, models, and frameworks with a theoretical foundation (Creswell, 2014). This paper addressed the research problem:

RQ: What are the main challenges in outsourcing facilities management services, and how can they be mitigated for better outcomes?

Exhaustive literature research was conducted by reviewing conference papers, journal articles, e-books, and other publications to access knowledge on evaluating the concept of FM outsourcing, concerns in FM outsourcing, such as importance and key considerations, and challenges in FM outsourcing contracts. Thus, there is a knowledge gap in comprehensively identifying the strategies that have been taken to overcome the challenges faced to get a good platform to fulfill the expected objectives from this study, to develop guidelines for service provider companies to overcome those identified challenges and keep continuing the FM contract. Semi-structured interviews were carried out to collect qualitative data on practitioners lived experiences, observations, and opinions on the contexts of FM contracts.

Although various outsourcing models exist within the industry, the interview guide was intentionally designed to extract views on challenges and strategies that are commonly encountered regardless of the specific outsourcing model adopted. Therefore, the challenges and mitigation strategies identified in this study are intended to reflect universal issues experienced across different FM outsourcing models, making the findings broadly relevant and applicable.

Data analysis is an important activity in the process of the data through the most appropriate information-gathering methodologies to provide the expected results of the research process. Manual content analysis was conducted to identify the strategies to overcome the challenges faced. There are no closely defined rules when selecting a sample size for qualitative research (Baum, 2000; Patton, 2002). However, according to Huberman and Miles (1994), qualitative research generally relies on small numbers to study in-depth and detailed detail. Hence, for this study, the snowball sampling technique was used to select the sample. This method was an easy and fast way to select a suitable sample from the population. Accordingly, as mentioned above, the initial sample was limited to interviews of nine respondents who were saturated after the seventh interview. Table 2 summarizes the profile of the interviewees.

Table 2: Profiles of interviewees

Interviewee code	Profession	Designation	Years of experience
R1	FM function manager	Property Manager	9
R2	Facilities Executive	Facilities Executive	6
R3	FM executive	FM executive	9
R4	Facilities manager	Facilities manager	16
R5	FM Manager	FM Manager	7
R6	FM executive	FM executive	24
R7	Senior Facilities Manager	Senior Facilities Manager	10
R8	Hard FM Manager	Hard FM Manager	26
R9	Soft FM executive	Soft FM executive	7

4. Research Findings

The data collected was the opinions of the experts on the generic factors that were identified as related to outsourcing FM. The data collected was analyzed through manual content analysis. Consequently, the findings from the conducted expert interviews have been discussed as follows.

4.1 CHALLENGES TO THE FM SERVICE PROVIDER FOR CONTINUING FM OUTSOURCING CONTRACT

All the challenges identified in the literature review were checked with the respondents' opinions. All the respondents were asked whether the identified

challenges in the literature review are valid for the Sri Lankan context. The respondents were asked to give additional challenges they have experienced or known. Consequently, no additional challenges were identified by the respondents. Further, their experience with each challenge was analyzed. Table 3 illustrates the findings through expert interviews.

Table 3: Challenges to the FM Service Provider

Challenges to the FM Service Provider		R1	R2	R3	R4	R5	R6	R7	R8	R9
Management Challenges										
1	Not being able to provide the learning and development to the staff.	✓	✓	x	✓	✓	x	✓	✓	✓
2	Not being able to manage the risks of the operation.	x	✓	✓	✓	x	✓	✓	✓	✓
3	Being unable to manage the sub-contractors accordingly to overcome required qualitative and quantitative outcomes	✓	✓	x	✓	✓	✓	✓	✓	x
4	Being unable to ensure a smooth transition	x	✓	x	✓	x	✓	✓	✓	✓
5	Not paying attention to the issues at the right time.	✓	✓	✓	✓	✓	✓	✓	x	✓
Challenges because of the client's mindset										
6	Restrictions on the sacrifice of short-term cost benefits to achieve long-term cost benefits	✓	✓	✓	✓	✓	x	✓	✓	x
7	The decision to go with multiple contractors for various hard FM and soft FM functions.	✓	x	✓	✓	✓	✓	✓	✓	✓
8	That outsourcing is an automatic ticket to success	✓	✓	✓	✓	x	✓	✓	✓	✓
Expertise Challenges										
9	Not having sufficient technological expertise to overcome technological issues.	✓	✓	x	✓	✓	✓	✓	✓	✓
10	The shortage of experienced and effective managers	x	✓	✓	✓	✓	✓	✓	✓	✓
Challenges due to a lack of management in sub-contracting										
11	Being unable to manage the sub-contractors accordingly to overcome the required qualitative and quantitative outcomes	x	✓	✓	✓	✓	✓	✓	✓	✓
External environmental challenges										
12	Economic demand becomes less due to the economic crisis.	x	✓	✓	✓	✓	✓	✓	✓	✓
Challenges in relationship management										
13	Not being able to correctly engage with the co-creation process has led to many issues	✓	✓	✓	✓	✓	✓	✓	x	✓
14	In situations where the contract value exceeds, the risks associated with the business process	✓	✓	✓	✓	✓	✓	x	✓	x

The **management challenges** identified by respondents highlight several key issues affecting service delivery. One major concern is the lack of learning and development for staff, where R1 mentioned, "There is no proper staff training and upskill within the organization, which leads to inefficiencies in service delivery." Similarly, risk management deficiencies were raised by R3, who noted, "Most service providers do not conduct risk assessments properly, which causes issues in service quality and safety." Additionally, subcontractor management remains a significant hurdle, as R5 explained, "The biggest challenge we face is managing subcontractors effectively. Sometimes, they do not meet the required quality standards". Another critical issue is ensuring a smooth transition when new contracts begin, with R7 stating, "When a new contract begins, there is no proper transition plan, and it affects service continuity." Furthermore, delayed attention to operational issues creates unnecessary disruptions, as R8 pointed out, "Sometimes, the response time for addressing operational issues is too slow, creating unnecessary disruptions."

Challenges also arise due to the **client's mindset**, particularly regarding cost considerations and expectations. Many clients tend to prioritize **short-term cost savings over long-term benefits**, which affects the overall efficiency and quality of service. R9 explained this by stating, "Clients mainly look at short-term cost reductions rather than investing in sustainable solutions that could provide long-term benefits." This approach often results in lower service quality and increased long-term operational costs.

Another major category of challenges relates to **contractual and compliance issues**, which affect the smooth execution of service agreements. Several respondents highlighted difficulties in contract enforcement and the rigidity of contractual terms. R4 emphasized, "Some contract terms are too rigid, leaving little room for flexibility when unexpected issues arise." Similarly, R2 pointed out issues in defining the scope of work, stating, "Ambiguities in the contract lead to disputes because different parties interpret the scope differently." Compliance with regulatory requirements also poses a challenge, as R6 noted, "Meeting all the compliance and regulatory requirements adds extra workload and sometimes causes delays in service execution."

Additionally, **financial constraints and budget limitations** create significant barriers to effective service delivery. R5 explained, "Budget cuts often lead to reduced service quality since we have to compromise on materials or resources." The issue of delayed payments further complicates operations, as R3 stated, "Late payments from clients affect cash flow, making it difficult to manage resources efficiently." This problem is compounded by unrealistic pricing structures in tenders, with R7 adding, "Sometimes, contracts are awarded to the lowest bidder, which forces service providers to cut costs, ultimately affecting quality."

In terms of **operational challenges**, many respondents pointed out inefficiencies in resource allocation and workforce management. R1 mentioned, "There is often a mismatch between the workload and the available workforce, leading to delays and inefficiencies." Similarly, R8 highlighted the difficulty in retaining skilled employees, stating, "High staff turnover is a major issue because we constantly have to train new employees, which disrupts workflow." A related concern is the

lack of proper technology adoption, as R9 explained, "We are still relying on outdated systems, which reduces efficiency and makes it harder to track progress in real-time."

Communication gaps between stakeholders also contribute to operational inefficiencies. R6 pointed out, "Miscommunication between different parties leads to mistakes and delays in decision-making." This issue is particularly evident in coordination between contractors and clients, as R2 stated, "Sometimes, clients do not provide timely feedback, which affects project timelines and deliverables."

Lastly, challenges related to **external factors and environmental conditions** were also raised by respondents. R4 highlighted unpredictable weather conditions, explaining, "Extreme weather events sometimes disrupt our operations, and there are no proper contingency plans in place." Additionally, supply chain disruptions due to global uncertainties were a concern for R3, who noted, "Material shortages and supply chain disruptions have become more common, making it difficult to maintain schedules."

4.2 STRATEGIES TO MAINTAIN AN EFFECTIVE FM OUTSOURCING CONTRACT

To address the identified challenges in FM outsourcing contracts, a set of strategic approaches has been outlined to ensure smooth operations, better coordination, and overall efficiency. These strategies align with key challenge categories and focus on practical solutions that can enhance service delivery and contract performance.

Management challenges in FM outsourcing arise due to inefficiencies in staff training, risk management, subcontractor coordination, and transition planning. To overcome these issues, FM service providers must prioritize learning and development programs for staff to enhance skills and ensure alignment with client requirements. Proper risk assessment and mitigation strategies should be implemented to manage operational risks effectively. R4 emphasized the importance of structured subcontractor management, stating, "Defining proper SOPs, conducting regular evaluations, and ensuring continuous supervision help subcontractors meet both qualitative and quantitative expectations." Additionally, a smooth transition process can be achieved through thorough site assessments and timely communication between outgoing and incoming contractors. Another key issue is delayed response to problems. As R3 pointed out, "Paying attention to operational challenges at the right time prevents disruptions and ensures service continuity."

Clients often struggle to balance short-term cost savings with long-term benefits, leading to financial constraints in FM operations. To mitigate this, FM service providers should educate clients on the financial advantages of strategic FM outsourcing. R6 suggested, "Demonstrating cost-benefit analysis with real case studies can help clients see the long-term financial and operational advantages." In cases where clients choose multiple contractors for different FM functions, better coordination and integration strategies must be established to prevent inefficiencies. As R2 mentioned, "Standardizing service coordination among multiple contractors ensures seamless integration and minimizes operational conflicts." Clients sometimes assume that outsourcing guarantees success without

active involvement. To counter this, FM providers should involve clients in key decision-making processes and ensure clear role distribution.

A major issue in FM outsourcing is the lack of technological expertise and experienced managers to handle operations effectively. To overcome this, companies should invest in training programs, workshops, and certifications to enhance the technological capabilities of FM teams. R7 highlighted, "Adopting new technologies and integrating Building Management Systems (BMS) and Computer-Aided Facility Management (CAFM) software can improve efficiency and service delivery." To address the shortage of experienced managers, companies should develop leadership programs and mentorship initiatives to nurture managerial talent internally. R5 emphasized, "Proper supervision and hands-on training can help new managers gain expertise and confidence in handling FM operations."

Subcontractor management is a critical aspect of FM outsourcing, and inefficiencies in this area can lead to poor service delivery. Strategies to enhance subcontractor management include clearly defining SOPs and performance standards, regular performance reviews and site inspections, and assigning a dedicated coordinator to oversee subcontracted services. R1 mentioned, "Continuous evaluation and direct supervision ensure that subcontractors align with FM service quality expectations." By ensuring better accountability and communication, FM providers can enhance the performance of subcontractors.

Economic instability and external market conditions pose significant challenges to FM service providers. To mitigate risks associated with economic downturns, companies should adopt a proactive approach by forecasting financial trends and adjusting contract terms accordingly. R9 emphasized, "Monitoring economic trends and adapting cost structures help FM providers remain competitive even during financial crises." Additionally, FM providers should explore cost optimization strategies such as resource efficiency, energy-saving initiatives, and sustainable practices to reduce operational expenses.

Building strong relationships among FM service providers, clients, and subcontractors is essential for contract success. One major challenge is engaging effectively in co-creation, which involves collaborative problem-solving. R3 pointed out, "Active engagement and open discussions between FM teams and clients improve service innovation and efficiency." Another critical issue is contract value escalation and associated business risks. To address this, FM providers must ensure transparent financial reporting and regular cost assessments. R8 suggested, "Having justifications for cost escalations and maintaining an open dialogue with clients can prevent disputes over contract values."

5. Discussion

The study identifies key challenges in FM outsourcing, categorizing them into management inefficiencies, client-related constraints, expertise limitations, subcontractor management issues, external environmental impacts, and relationship management complexities. Addressing these challenges requires strategic interventions that align with industry best practices and empirical evidence. For instance, proper change management strategies (Jensen, 2017) and continuous staff training (Dixit et al., 2019) are crucial to improving operational

efficiency. Additionally, ensuring coordinated subcontractor management enhances service quality, as improper oversight often leads to performance inconsistencies.

Client mindset is another determinant of FM contract success, where short-term cost-saving decisions often undermine long-term benefits (Al-Najjar, 2021). Educating clients on the advantages of integrated FM services can mitigate such challenges. Furthermore, technology adoption in FM operations (Kamarazaly et al., 2013) addresses expertise gaps, enhancing decision-making and resource optimization. External economic and environmental factors, although beyond direct control, necessitate proactive financial and strategic planning (Shohet & Lavy, 2004).

Effective relationship management is critical in mitigating contractual disputes and ensuring co-creation (Grimshaw et al., 2015). Establishing transparent communication channels fosters trust and facilitates adaptive service models. By implementing these strategic responses, FM outsourcing can transition from reactive problem-solving to a proactive, value-driven approach.

6. Conclusion

This study underscores the multifaceted challenges in FM outsourcing and the necessity of structured strategies to ensure contract efficiency. Management inefficiencies, inadequate client engagement, and subcontractor mismanagement are key barriers that hinder service optimization. Addressing these issues requires prioritizing learning and development, enhancing risk management strategies, and adopting advanced technologies to bridge expertise gaps. Economic and environmental uncertainties remain external risks, emphasizing the need for adaptive financial planning and regulatory compliance. Client reluctance to invest in long-term FM benefits further challenges service providers, making awareness-building initiatives essential. Additionally, stronger contractual frameworks and clearer role definitions can minimize ambiguities and improve service delivery. The findings highlight the critical role of co-creation and stakeholder collaboration in achieving sustainable FM outsourcing models. Future research should explore data-driven decision-making tools and AI integration in FM to enhance predictive analytics and operational resilience. By aligning FM strategies with evolving industry standards, outsourcing contracts can deliver sustained value, operational efficiency, and long-term cost savings.

7. References

- Al-Najjar, A. (2021). Full life cycle assessment of a cross laminated timber modular building in Sweden. Linnaeus University, Faculty of Technology.
- Amos, D., & Gadzekpo, A. (2016). Cost of in-House Vs Outsourced Facilities Management Services in Public Polytechnics in Ghana.
- Baum, F. (2000). The new public health. (Issue Ed. 4). Oxford University Press.
- Booty, F. (2009). FACILITIES MANAGEMENT HANDBOOK.
- Brito, C., Pereira, S., Martins, S., Monteiro, A., Moutinho-Pereira, J. M., & Dinis, L. (2024). Strategies for achieving the sustainable development goals across the wine chain: A review. *Frontiers in Sustainable Food Systems*, 8, 1437872.
- Campbell, F. (2006). Occupational stress in the construction industry. Chartered Institute of Building (CIOB), 1–16.

<http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Occupational+Stress+in+the+Construction+Industry#0>

- Capizzi, F. (2018). FM Provider Management: A Source of Innovation? Zurich University of Applied Sciences.
- Creswell, J. W. (2014). Research Design: Qualitative, Quantitative and Mixed Methods Approaches. In Notes and Queries (Vols. s4-I, Issue 25). <https://doi.org/10.1093/nq/s4-I.25.577-c>
- D'Andrea, A., Grifoni, P., & Ferri, F. (2023). FADM: A feasible approach to disaster management. *Development Policy Review*, 41(2), e12633.
- Disanayake, P., Weerasinghe D, A. A. (2015). Industry Attractiveness of Outsourced Facilities Management Services in Sri Lanka. July.
- Dixit, M. K., Venkatraj, V., Ostadalimakhmalbaf, M., Pariafsai, F., & Lavy, S. (2019). Integration of facility management and building information modeling (BIM) A review of key issues and challenges. *Facilities*, 37(7/8), 455–483.
- Fajrillah, A. A. N., Lubis, M., & Syam, I. (2022). Organizational Architecture and Service Delivery Re-Alignment based on ITIL and TOGAF: Case Study of the Provincial Development Bank. *International Journal of Advanced Computer Science and Applications*, 13(4).
- Grimshaw, K. E., Bryant, T., Oliver, E. M., Martin, J., Maskell, J., Kemp, T., ... & Roberts, G. (2015). Incidence and risk factors for food hypersensitivity in UK infants: results from a birth cohort study. *Clinical and translational allergy*, 6, 1-13
- Hoxha, V., Hoxha, D., & Hoxha, J. (2022). Current situation, challenges and future development directions of facilities management in Kosovo. *Property Management*, 40(3), 343–369.
- Huberman, A. M., & Miles, M. B. (1994). An Expanded Source Book: Qualitative Data Analysis. In SAGE publications London: Vol. 2nd ed.
- Ikediashi, D., O. Ogunlana, S., & Boateng, P. (2014). Determinants of outsourcing decision for facilities management (FM) services provision. *Facilities*, 32(9/10), 472–489.
- Ikediashi, D. I. (2014). A framework for outsourcing facilities management services in Nigeria's public hospitals. PhD Thesis, Heriot Watt University, 271.
- Ikediashi, D. I., Ogunlana, S. O., Boateng, P., & Okwuashi, O. (2012). Analysis of risks associated with facilities management outsourcing: a multivariate approach. *Journal of Facilities Management*, 10(4), 301–316.
- Iqbal, Z. A. M. D. (2013). Outsourcing : A Review of Trends, Winners & Losers and Future Directions. *International Journal of Business and Social Science*, 4(8), 91–107.
- ISS, W. B. (2016). ISS 2020 Vision Future of Outsourcing and Perspectives for Facility Management.
- Jensen, P. A. (2017). Strategic sourcing and procurement of facilities management services. *Journal of Global Operations and Strategic Sourcing*, 10(2), 138–158.
- Kamarazaly, M. A., Mbachu, J., & Phipps, R. (2013). Challenges faced by facilities managers in the Australasian universities. *Journal of Facilities Management*, 11(2), 136–151.
- Koo, J.-I., & Jeong, S.-J. (2024). Improved technology readiness assessment framework for system-of-systems from a system integration perspective. *IEEE Access*, 12, 23827–23853.
- Kurdia, M. K., Abdul-Tharim, A. H., Jaffar, N., Azli, M. S., Shuib, M. N., & Ab-Wahid, A. M. (2011). Outsourcing in facilities management-A literature review. *Procedia Engineering*, 20, 445–457.

- Lai, D. W. L., Zhou, J.-J., Bai, X., Lam, R. Y. K., & Li, Y.-Z. (2025). Intergenerational engagement and challenges: Participants' perspectives on intergenerational activities in Hong Kong. *Journal of Intergenerational Relationships*, 23(1), 30–49.
- Lilly, S. M., Deshmukh, A. J., Epstein, A. E., Ricciardi, M. J., Shreenivas, S., Velagapudi, P., & Wyman, J. F. (2020). 2020 ACC expert consensus decision pathway on management of conduction disturbances in patients undergoing transcatheter aortic valve replacement: a report of the American College of Cardiology Solution Set Oversight Committee. *Journal of the American College of Cardiology*, 76(20), 2391–2411.
- Lok, K. L., & Baldry, D. (2015). Facilities management outsourcing relationships in the higher education institutions. *Facilities*, 33(13/14), 819–848.
- Lok, K. L., Smith, A., Opoku, A., & Chen, C. (2021). The challenges of sustainable development on facilities management outsourcing services: an investigation in educational facilities. *Sustainability*, 13(15), 8156.
- Lok, K. L., So, A., Opoku, A., & Chen, C. (2021). A sustainable facility management outsourcing relationships system: Artificial neural networks. *Sustainability*, 13(9), 4740.
- Moseley, A., & Thomann, E. (2021). A behavioural model of heuristics and biases in frontline policy implementation. *Policy & Politics*, 49(1), 49–67.
- Natukunda, C. M., Pitt, M., & Nabil, A. (2013). Understanding the outsourcing of facilities management services in Uganda. *Journal of Corporate Real Estate*, 15(2), 150–158.
- Opoku, A., & Lee, J. Y. (2022). The future of facilities management: Managing facilities for sustainable development. In *Sustainability* (Vol. 14, Issue 3, p. 1705). MDPI.
- Parry, B., & Collins, B. (1993). Where is facilities management going? *International Journal of Contemporary Hospitality Management*, 5(2).
- Patacas, J., Dawood, N., & Kassem, M. (2020). BIM for facilities management: A framework and a common data environment using open standards. *Automation in Construction*, 120, 103366. <https://doi.org/https://doi.org/10.1016/j.autcon.2020.103366>
- Patton, M. Q. (2002). *Qualitative research & evaluation methods*. sage.
- Performance Transparency Drives. (2016). What Are the Pitfalls of Outsourcing Your Facilities Management?
- Pratap, S. (2014). Towards a framework for performing outsourcing capability. *Strategic Outsourcing*, 7(3), 226–252. <https://doi.org/10.1108/SO-04-2014-0004>
- Research and Professional Development Center. (2016). Contribution of Real Estate on Socio-Economic Development of the Country". 2nd National Symposium On Real Estate Management and Valuation.
- Rimbalová, J., & Vilčeková, S. (2013). The Proposal of Key Performance Indicators in Facility Management and Determination the Weights of Significance. *Selected Scientific Papers - Journal of Civil Engineering*, 8(2), 73–84. <https://doi.org/10.2478/sspjce-2013-0020>
- Riratanaphong, C., van der Voordt, T., & Sarasoja, A. L. (2012). Performance measurement in the context of CREM and FM. *Added Value of Facilities Management, Concepts, Findings and Perspectives*, 123–145.
- Sarshar, M. (2006). Improving service delivery in FM: case study of a UK hospital facilities directorate. *Journal of Facilities Management*, 4(4), 271–285.
- Shohet, I. M., & Lavy, S. (2004). Healthcare facilities management: state of the art review. *Facilities*, 22(7/8), 210–220.
- Sillanpää, E., & Junnonen, J. (2012). Factors affecting service innovations in FM service sector. *Facilities*, 30(11/12), 517–530.
- Teo, J. S., Mohd Aini, A., & Zyed, Z. A. S. (2025). Exploring performance measurement practices in public housing tenancy management in Malaysia. *Property Management*.

- Ventovuori, T., & Lehtonen, T. (2006). Alternative models for the management of FM services: An empirical investigation. *Journal of Corporate Real Estate*, 8(2), 73–90.
- Vetr, M., Potk, M., & The, H. (2013). Outsourcing of facility management. *Economic Management*, January.
- Wang, M. W. C., Tan, C. L., & Wahid, N. A. (2020). Service Quality, Facilities Management Practices and Outsourcing Service Provider Capabilities: A Critical Review and Conceptual Framework for Facilities Management Companies. *Global Business & Management Research*, 12(2).
- Wauters, B. (2017). Strategic management in the public sector: a tool for improving performance of ongoing operations or for redefining performance to meet new challenges? Report to the European Commission's Public Administration and Governance Network, 29(March), 1–118. <https://doi.org/10.1108/09513559010138316>

INTERVENTIONS FOR CHANGING BEHAVIOUR OF STAKEHOLDERS FOR CIRCULAR ECONOMY ADOPTION IN CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT

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Abstract. Stakeholder resistance to change remains one of the primary challenges in adopting Circular Economy (CE) principles for construction and demolition waste management (CDWM). While behaviour of stakeholders is dynamic and can be influenced by various interventions, there has been limited research on which interventions are commonly used to derive behavioural change. At the same time, CE is emerging as a promising approach to addressing inefficiencies in current CDWM practices by promoting resource efficiency, waste minimisation, and material reuse. However, for CE to be effectively implemented, it is crucial to understand what interventions can facilitate behaviour change and overcome resistance. This study aims to bridge this gap by identifying commonly used interventions to change the behaviour of stakeholders in adopting CE for CDWM. This paper employs a literature review to identify behavioural barriers and interventions. Pareto analysis is used to identify the most used interventions to adopt CE in CDWM. The results indicate that policy and regulations are the most widely used interventions, followed by stakeholder engagement and education, economic incentives and market development, technological advancements and innovation, and design and construction practices. However, the effectiveness of these interventions has not been extensively tested in real-world applications. The findings offer valuable insights for policymakers, industry professionals, and researchers to revisit their policies, design new practices, and design and implement interventions for changing the behaviour of stakeholders to adopt CE in CDWM.

Keywords. Circular Economy, Construction and Demolition Waste, Interventions, Behaviour of Stakeholders

1. Introduction

The construction sector is a major global resource consumer, utilizing approximately 30% of raw materials, 40% of energy, 25% of water sources, and 12% of land (Bilal et al., 2020). Consequently, C&D waste accounts for a significant portion of global waste, contributing over 30% to total waste generation (Wu et al., 2019). The continuous extraction of natural resources to support construction activities accelerates environmental degradation, resource depletion, and greenhouse gas emissions, while also exerting pressure on landfill capacities and ecosystems (Ma et al., 2020; Zhang et al., 2021). Alarming, C&D waste generation is expected to increase by 70% by 2050 if immediate measures are not taken (Kaza et al., 2018).

In response to these challenges, the CE has emerged as a viable solution to mitigate the environmental and economic impacts of C&D waste. CE principles focus on resource efficiency by minimizing waste, promoting recycling, and extending material lifespans (Benachio et al., 2020). The construction sector was the largest contributor, accounting for 38.4% of total waste, followed by mining and quarrying (22.7%), waste and water services (10.5%), manufacturing (10.4%), and households (8.9%) (Eurostat, 2024). Similarly, countries like China and Brazil produced 2.3 billion tons and 100 MT of C&D waste, respectively (Zhao, 2021). In Australia, approximately 75.8 MT of waste was generated in 2020/21,

with construction and demolition materials constituting 25.1 MT (Pickin et al., 2022).

Despite the growing global recognition of CE, its implementation remains hindered by multiple barriers, including stringent regulatory requirements, high costs of recycled materials, lack of market incentives, and stakeholder resistance to change (Urbinati et al., 2021). Stakeholder behaviour is a key determinant of CE adoption, influencing compliance, investment in sustainable practices, and overall industry transformation (Shooshtarian et al., 2022). Factors such as perceived behavioural control, awareness of environmental benefits, and financial constraints play significant roles in shaping stakeholder decisions (Ajzen, 1991; Adabre et al., 2022). While government regulations and policy frameworks aim to facilitate the transition to CE, stakeholders often show reluctance due to economic and operational uncertainties (Bilal et al., 2020).

To overcome these barriers, targeted interventions are required to influence stakeholder behaviour and drive the adoption of CE principles in CDWM. Interventions such as policy incentives, economic instruments, technological innovations, and education programs can play a crucial role in modifying stakeholder perceptions and enabling structural changes within the industry (Shooshtarian et al., 2021). However, there is a lack of comprehensive analysis on which interventions are most effective in changing stakeholder behaviour and overcoming the barriers to CE adoption.

This study aims to fill this gap by identifying the commonly used interventions that change the behaviour of stakeholders in CDWM. Hence, the research provides insights into strategic measures that can accelerate CE adoption, reduce C&D waste, and promote long-term sustainability. The findings will support policymakers, industry practitioners, and researchers in designing tailored interventions to change the behaviour of stakeholders to adopt CE.

2. Literature Review

2.1. BEHAVIOURAL CHANGE

Individual behaviour change is a complex process influenced by a variety of factors that can significantly impact environmental and societal outcomes (Schultz et al., 2018). Behaviour change refers to the modification of human actions and habits, often in response to internal motivations or external stimuli (Michie et al., 2011; Kolb, 1987). Understanding what drives behaviour change is essential for developing effective interventions. In addition, to effectively influence stakeholder behaviour, it is essential to understand the theoretical foundations that explain how and why individuals change their behaviours (Michie et al., 2011). There are approximately 60 behaviour change models, with many of them sharing similar frameworks (Darnton, 2008). Behaviour change models can be categorised into two categories. One category aims on how individual behaviour is shaped by attitudes and beliefs. The second type of model emphasizes how individual behaviour evolves. The first type, which focuses on beliefs and attitudes, is known as knowledge-attitude-behaviour (KAB) models or cognitive decision models. The

latter are referred to as stages of change models or diffusion models. These models are suitable for situations where individuals' beliefs and attitudes evolve, or where individuals progress through various stages and can be categorized within a target population. Numerous models and theories are employed to alter individual behaviour, and the most adopted ones are discussed in Table 1.

Table 1: Behavioural change theories

Theories	Key concepts	Connections to CE interventions	Authors
Health Belief Model (HBM)	Decisions are influenced by perceived threats, benefits, and self-efficacy.	Public awareness campaigns and stakeholder engagement programs to enhance knowledge and perceive benefits of CE adoption.	[1]
Transtheoretical Model (TTM)	Behavior change occurs in stages, from awareness to active adoption.	Training programs, certification schemes, and structured incentives to guide stakeholders through progressive CE adoption.	[2]
Diffusion of Innovation Theory	Describes how new ideas, behaviors, or technologies spread within a population.	Economic incentives, technological innovations, and regulatory frameworks encouraging early adopters and industry-wide uptake.	[3]
Evolutionary Game Theory (EGT)	Decision-making is influenced by strategic interactions within a competitive environment.	Financial subsidies, landfill levies, and digital material tracking to create incentives for cooperative waste management.	[4], [5], [6]
Kotter's 8-Step Change Model	Organizational change follows eight structured steps, from creating urgency to embedding new behaviors.	Phased implementation of CE strategies, policy enforcement, and industry-wide incentives to sustain long-term adoption.	[7]
Lewin's Change Management Model	Change occurs in three phases: Unfreeze (prepare), Change (implement), and Refreeze (stabilize).	Stepwise transition towards CE adoption through regulatory frameworks, training programs, and incentive-based interventions.	[8]
Elaboration Likelihood Model (ELM)	Persuasive communication influences behavior through central and peripheral processing routes.	Tailored communication strategies to address different stakeholder groups and drive CE adoption in CDWM.	[9]
[1] (Glanz & Rimer, 2005); [2] (Prochaska & DiClemente, 1970); [3] (Rogers & Smith, 1962); [4] (Osborne & Rubinstein, 1994); [5] (Kahan, 2014); [6] (Camerer, 2003); [7] (Kotter, 1996); [8] (Lewin, 1947); [9] (Petty & Cacioppo, 1986)			

Each of these theories provides a fundamental understanding of how behaviour change occurs and can be influenced. HBM suggests that individuals are more likely to act when they perceive a risk and recognize the benefits of a new behaviour. Applied to CE and CDWM, this means that increasing awareness of the

environmental and economic consequences of construction waste can drive stakeholders toward more sustainable practices. Public awareness campaigns, stakeholder engagement initiatives, and transparent communication of CE benefits align with this model by ensuring that stakeholders understand the importance of waste reduction and resource efficiency. The TTM describes behaviour change as a gradual process, moving through stages from pre-contemplation to maintenance. In the context of CE, stakeholders may initially resist circular practices due to unfamiliarity or perceived complexity. Interventions such as structured training programs, phased certification schemes, and policy incentives ensure a progressive transition, supporting stakeholders at different levels of readiness. By acknowledging that change does not happen instantly, this model supports the need for long-term engagement and reinforcement mechanisms in CE adoption. The Diffusion of Innovation Theory explains how new ideas and practices spread within a community or industry. Early adopters play a critical role in influencing broader adoption, and this is particularly relevant for CE in CDWM. Regulatory interventions, financial incentives, and the promotion of successful case studies help drive the diffusion of circular construction practices. Technologies such as BIM for waste tracking and digital platforms for secondary materials enable industry-wide knowledge sharing and standardization, accelerating the adoption curve. The EGT emphasizes that stakeholder decisions are influenced by competitive interactions and strategic incentives. In CE and CDWM, companies are more likely to adopt sustainable practices if they see economic advantages or reputational benefits. Government-led incentives, such as tax benefits for circular construction, competitive grants, and procurement policies favouring sustainable projects, ensure that adopting CE principles becomes the most beneficial strategy in the long run. Market-driven interventions, such as waste exchange platforms and financial rewards for recyclers, further create a system where circular behaviours are advantageous and self-sustaining. Kotter's 8-Step Change Model provides a structured approach to organizational transformation, making it highly relevant for implementing CE interventions in industries resistant to change. The staged approach of creating urgency, gaining stakeholder buy-in, and embedding CE practices into company policies ensures long-term success. Lewin's Change Management Model simplifies behaviour change into three phases: unfreezing existing practices, implementing change, and reinforcing new behaviours. This model is useful for phased CE implementation, where regulatory frameworks, education, and incentives are introduced progressively to support stakeholder transition. The ELM emphasizes the role of persuasive communication in shaping stakeholder behaviour. Targeted awareness campaigns using both logical (central route) and emotional (peripheral route) appeals can effectively influence different stakeholder groups, increasing CE adoption in CDWM.

Theories highlight that a multi-dimensional intervention approach is necessary to change stakeholder behaviour effectively. Studies emphasize that interventions are crucial in modifying individuals' behaviour (Zhang et al., 2023; Shooshtarian et al., 2021). These interventions are categorized into five key areas: (1) Policy and Regulatory Measures, influencing stakeholder behaviour through legal mandates and waste management regulations; (2) Stakeholder Engagement and Education, fostering awareness and participation through training programs and communication strategies; (3) Economic Incentives and Market Development, utilizing financial support, tax benefits, and funding to encourage sustainable

practices; (4) Technological Advancements and Innovation, integrating digital tools and material tracking technologies to improve efficiency; and (5) Design and Construction Practices, promoting circular design principles to minimize waste. Table 2 highlights the diverse range of interventions implemented globally for CE adoption in CDWM.

Table 2: Interventions to change behaviour of stakeholders to adopt CE in CDWM

Common Category	Interventions	Countries	Authors
Policies and Regulatory Measures	Mandatory waste segregation laws, landfill taxes, recycling targets	EU, Australia, China	[1], [2], [3]
Stakeholder Engagement and Education	Stakeholder training programs, public awareness campaigns	UK, Germany, Australia	[4], [5], [6]
Economic Incentives and Market Development	Tax credits for recycled material use, grants for CE projects, reduced landfill fees	USA, Australia, EU	[3], [7], [8]
Technological Advancements and Innovation	BIM for waste tracking, digital waste exchange platforms, advanced recycling technologies	Japan, EU, China	[9], [10], [11]
Design and Construction Practices	Designing for deconstruction, modular construction, use of recyclable materials	Netherlands, Germany, UK	[12], [13], [14]
1] (Alhawamdeh et al., 2024); [2] (Ma & Hao, 2024); [3] (Shooshtarian et al., 2022); [4] (Almeida et al., 2022); [5] (Ferriz-Papi et al., 2024); [6] (Ramos & Martinho, 2023); [7] (Tanthanawiwat et al., 2024); [8] (Ghafoor et al., 2022); [9] Karanafti et al., 2024); [10] (Swarnakar & Khalfan, 2024); [11] (Cocco & Ruggiero, 2023); [12] (Antunes et al., 2024); [13] (Santos et al., 2021); [14] (Lederer et al., 2020)			

3. Methodology

A literature review was conducted using Web of Science and Scopus, two widely recognized academic databases. The literature search was carried out using keywords such as Circular Economy, Construction and Demolition Waste Management, Stakeholder Behaviour, and Interventions. The keyword search was conducted across the article title, abstracts, and keywords. Following the initial retrieval, full-text screening was carried out to confirm the inclusion of studies that met the review criteria. A total of 33 papers were initially identified through comprehensive searches in Scopus (29 papers) and Web of Science (4 papers) using the keywords: "Circular economy" OR "CE" AND "Construction and demolition waste management" OR "CDWM" AND "Interventions". This process initially identified 210 records. After removing 35 duplicates, 175 unique papers remained. Titles and abstracts were screened for relevance, followed by full-text screening of 67 papers. Only peer-reviewed journal articles and conference papers published within the last 10 years (2014–2024) were included, thus, 34 papers were excluded due to being outside the date range or not directly addressing behavioural interventions in CE for CDWM. As a result, 33 studies were included in the final analysis. The last 10 years have seen significant advancements and policy developments in CE and CDWM, making recent studies more pertinent to the current research context (Geissdoerfer et al., 2017). In addition to peer-reviewed

literature, several government reports and policy documents from different countries were analysed to identify interventions implemented at various levels. These reports provided insights into policy frameworks, regulatory measures, and financial incentives to promote CE adoption in CDWM.

The selected literature and policy documents were analysed using a Pareto analysis to determine the commonly used interventions to adopt CE in CDWM. This approach helped identify the most used interventions that facilitate stakeholder behaviour change. Pareto analysis was employed as a statistical technique based on the 80/20 principle (Powell and Sammut-Bonnici, 2015). This principle suggests that 80% of the effects come from 20% of the causes, meaning that a small number of key interventions contribute to most of the stakeholder behaviour change in CE adoption. The literature review provided the basis for classifying interventions into five key categories: Policy and Regulatory Measures, Stakeholder Engagement and Education, Economic Incentives and Market Development, Technological Advancements and Innovation, and Design and Construction Practices. The frequency of each intervention was manually recorded across the 33 selected studies. The frequency refers to the number of studies (out of the 33 reviewed) in which each intervention explicitly appeared as a recommended or implemented strategy to CE adoption in CDWM. A relative frequency analysis was conducted using the formula:

A cumulative percentage was then calculated to determine the proportion of interventions contributing to the overall impact:

The results were visualized using a Pareto chart as shown in Figure 1, where interventions were sorted in descending order of frequency on the X-axis, while the Primary Y-axis represented the number of occurrences, and the Secondary Y-axis depicted the cumulative percentage. The threshold for identifying the most significant interventions was set using the 80/20 rule, where interventions contributing to approximately 80% of the cumulative frequency were considered the most impactful.

4. Findings and Discussion

Pareto analysis was employed in this study, as shown in Figure 1, to prioritize the most used interventions for CE adoption in CDWM. Given the wide range of interventions identified in the literature, it was essential to determine which interventions are commonly used to change the behaviour of stakeholders to adopt CE in CDWM. By applying Pareto analysis, the study was able to highlight the most frequently appeared interventions from the selected 33 papers and assess their cumulative influence. This is evident from the chart, where the first few categories, such as Policy and Regulations, Stakeholder Engagement, and Economic Incentives, account for a significant portion of the cumulative percentage. The orange cumulative line helps identify the threshold where approximately 80% of the total impact is achieved, highlighting the most critical interventions.

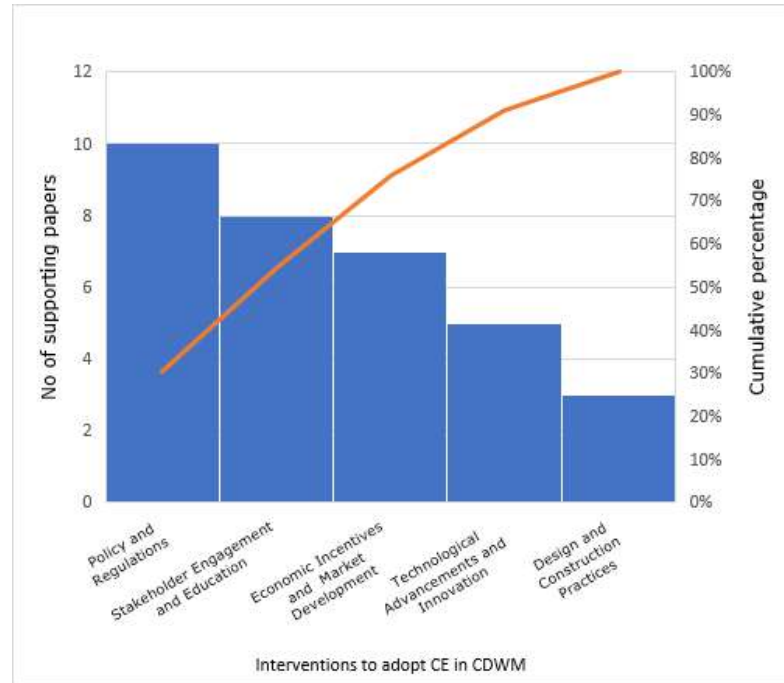


Figure 1: Interventions for CE adoption

4.1 POLICY AND REGULATIONS

This category, supported by 10 papers, was identified as the most significant intervention. This alone accounts for a significant proportion of the total impact, contributing to the highest cumulative percentage on the Pareto chart. Policies and regulatory frameworks are critical in driving CE adoption as they establish the necessary legal and institutional infrastructure to support circular practices. Several countries have implemented regulatory measures to promote CE adoption in CDWM. In the European Union, the Waste Framework Directive enforces waste hierarchy principles, encouraging recycling and reuse (Ferriz-Papi et al., 2024). China has introduced mandatory construction waste sorting policies, which require developers to separate and recycle materials on-site (Ma & Hao, 2024). Australia has adopted landfill levies and extended producer responsibility (EPR) schemes, making it more expensive to dispose of materials in landfills while encouraging product stewardship (Shooshtarian et al., 2022). These interventions primarily address regulatory barriers, such as the lack of policies and standards concerning recovered and recycled materials (Ramos et al., 2023). By enforcing mandatory recycling policies and waste diversion targets, governments create a structured regulatory environment that compels industry compliance. Additionally, these policies mitigate economic barriers, particularly the high cost of recycling, by providing financial incentives for businesses to invest in sustainable practices (Alhawamdeh et al., 2024).

4.2 STAKEHOLDER ENGAGEMENT AND EDUCATION

With support from 8 papers, this category emerged as the second most critical intervention. Countries like the Netherlands and Sweden have implemented public awareness campaigns and professional training programs to encourage circular

construction practices (Gherman et al., 2023). Singapore has introduced mandatory training for construction professionals, ensuring they are equipped with knowledge of sustainable building materials and deconstruction methods (Martin et al., 2024). The UK has integrated CE education into university curricula, ensuring future professionals adopt circular principles early in their careers (Karanafti et al., 2024). Educational programs, workshops, and stakeholder forums help disseminate knowledge about the benefits and practicalities of CE adoption. Almeida et al. (2022) demonstrated that stakeholder training initiatives in Europe led to higher acceptance and implementation of CE practices in the construction sector. These interventions address the lack of technical knowledge, misconceptions about CE benefits, and limited collaboration among stakeholders. Effective stakeholder engagement ensures that all parties, from project planners to waste managers, are informed and motivated to participate in circular practices, thereby promoting a culture of sustainability. These interventions directly address behavioural barriers, including a lack of awareness about CE benefits and negative perceptions about recycled materials (Soto-Paz et al., 2023). By increasing education and engagement, stakeholders are more likely to adopt CE principles and support sustainable waste management practices.

4.3 ECONOMIC INCENTIVES AND MARKET DEVELOPMENT

This category, highlighted in 7 papers, plays a vital role in mitigating financial barriers. Economic incentives play a pivotal role in overcoming the financial barriers associated with CE adoption, particularly the high initial costs and perceived lack of financial returns. Germany has successfully implemented tax reductions on recycled materials, making them more competitive with virgin materials (Tanthanawiwat et al., 2024). In Japan, the government provides subsidies for construction companies that integrate recycled aggregates and low-carbon materials into projects (Almeida et al., 2022). Australia's waste levy schemes make it economically unviable to send construction waste to landfills, pushing companies to adopt circular strategies (Wu et al., 2022). Interventions such as tax incentives for using recycled materials, grants for CE projects, and reduced landfill fees lower the financial burden on construction firms, encouraging them to invest in sustainable practices. Shooshtarian et al. (2022) found that economic incentives in Australia stimulated market demand for recycled construction materials, making circular practices financially attractive. These incentives address behavioural barriers like reluctance to invest in new practices due to financial uncertainty and perceived economic disadvantages of CE materials compared to virgin resources. Moreover, economic instruments promote a competitive market for recycled products, encouraging innovation and fostering a circular supply chain. However, the study by Ramos and Martinho (2021) emphasizes that for economic interventions to be effective, they must be easily accessible and substantial enough to offset the initial costs of CE adoption.

4.4 TECHNOLOGICAL ADVANCEMENTS AND INNOVATION

Supported by 5 papers, technological advancements such as Building Information Modelling (BIM), material recovery facilities, and digital platforms for waste exchange enhance operational efficiency and material reuse. Karanafti et al. (2024) emphasized that BIM facilitates accurate material tracking and management,

reducing waste and enabling efficient recycling. South Korea has adopted Building Information Modelling (BIM) tools, enabling real-time tracking of materials and their potential for reuse (Cocco & Ruggiero, 2023). In Finland, automated waste sorting technology helps separate and recover valuable construction materials, reducing waste sent to landfills (Karanafti et al., 2024). China has developed digital marketplaces for surplus construction materials, allowing contractors to buy and sell reclaimed materials efficiently (Ramos et al., 2023). These technological interventions address operational and site constraints, including lack of time for waste management and limited space for material sorting and storage (Cocco & Ruggiero, 2023). By automating sorting and improving material traceability, technology makes CE adoption more feasible and scalable in construction projects. However, the adoption of these technologies requires significant investment and technical expertise, highlighting the need for supportive policies and training programs.

4.5 DESIGN AND CONSTRUCTION PRACTICES

Although supported by only 3 papers, this category remains critical. The Pareto analysis demonstrated that while fewer studies highlighted this intervention, its impact on design-related barriers is significant. Denmark has led the way with modular construction techniques, where buildings are designed for easy disassembly and reuse (Santos et al., 2021). In Canada, sustainable design guidelines promote the use of low-impact and recycled materials in building projects (Lederer et al., 2020). Austria has mandated pre-demolition audits, requiring developers to assess materials for potential reuse before demolition (Bao & Lu, 2020). These interventions address design-related barriers like lack of circularity in construction designs and limited use of recyclable materials. By integrating circular principles from the project inception, construction firms can ensure that materials are reused and recycled efficiently at the end of a building's lifecycle. However, widespread adoption of circular design practices requires changes in design standards, professional training, and industry-wide collaboration.

5. Conclusion

This study provides a comprehensive analysis of interventions aimed at promoting CE adoption in CDWM. By employing systematic literature review and conducting a Pareto analysis, the study identifies key intervention categories, including policies and regulatory measures, stakeholder engagement and education, economic incentives and market development, technological advancements and innovation, and design and construction practices. The top three intervention categories, policies and regulations (supported by 10 papers), stakeholder engagement and education (8 papers), and economic incentives and market development (7 papers) are cumulatively represented around 80% of the intervention frequency across the 33 selected studies. These are the most used interventions, addressing major behavioural barriers such as resistance to change, lack of awareness, and financial constraints. Technological innovations and sustainable design practices further support CE adoption by enhancing operational efficiency and promoting material reuse. The findings emphasize the need for an integrated approach that combines

regulatory frameworks, economic support, technological solutions, and stakeholder collaboration to achieve sustainable CDWM practices. This study contributes to the existing body of knowledge by outlining the most used interventions and providing insights into overcoming behavioural barriers, thereby facilitating the transition to a circular economy in the construction sector. A key limitation of this study is that it is based solely on a systematic literature review and does not involve testing the identified interventions using real-life data. As such, while the frequency analysis highlights which interventions are most proposed in literature, it does not confirm their effectiveness or impact in practice. Future research can focus on empirical validation of the identified interventions through stakeholder surveys or simulation-based methods. This would allow researchers to assess not only the theoretical relevance of each intervention but also its practical influence on stakeholder behaviour to adopt CE in CDWM.

6. References

- Adabre, M. A., Chan, A. P., Darko, A., & Hosseini, M. R. (2023). Facilitating a transition to a circular economy in construction projects: intermediate theoretical models based on the theory of planned behaviour. *Building Research & Information*, 51(1), 85-104.
- Alhawamdeh, M., Ferriz-Papi, J. A., & Lee, A. (2024). Examining the drivers to support improved construction and demolition waste management for a circular economy: A comprehensive review using a systematic approach. *Sustainability (Switzerland)*, 16(14), 6014.
- Almeida, F., Vieira, C. S., Carneiro, J. R., & de Lurdes Lopes, M. (2022). Drawing a path towards circular construction: An approach to engage stakeholders. *Sustainability (Switzerland)*, 14(9), 5314.
- Antunes, A., Costa, H., Carmo, R., & Júlio, E. (2024). Circular rehabilitation methodology-sustainable construction and demolition waste management. *fib Symposium*, 1159-1166.
- Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, 50(2), 179-211.
- Bao, Z., & Lu, W. (2020). Developing efficient circularity for construction and demolition waste management in fast emerging economies: Lessons learned from Shenzhen, China. *Science of the Total Environment*, 724, 138264.
- 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>
- 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>.
- Camerer, C. F. (2003). Behavioural studies of strategic thinking in games. *Trends in cognitive sciences*, 7(5), 225-231.
- Cocco, P. L., & Ruggiero, R. (2023). From rubbles to digital material bank: A digital methodology for construction and demolition waste management in post-disaster areas. *Environmental Research and Technology*, 6(2), 151-158.
- Darnton, A. (2008). Reference report: An overview of behaviour change models and their uses. Government Social Research Unit.
- Eurostat. (2024). Waste statistics. Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics.
- Ferriz-Papi, J. A., Lee, A., & Alhawamdeh, M. (2024). Examining the challenges for circular economy implementation in construction and demolition waste management: A comprehensive review using systematic methods. *Buildings*, 14(5), 1237.
- Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy-A new sustainability paradigm?. *Journal of cleaner production*, 143, 757-768.

- Ghafoor, S., Shooshtarian, S., Maqsood, T., & Wong, P. S. P. (2022). Assessment of public opposition to construction and demolition waste facilities: A case study in Australia. *Recycling*, 7(5), 62.
- Gherman, I.-E., Lakatos, E.-S., Clinci, S. D., Cioca, L. I., & Rada, E. C. (2023). Circularity outlines in the construction and demolition waste management: A literature review. *Recycling*, 8(5), 69.
- Glanz, K. A. R. E. N., Rimer, B. K., & Viswanath, K. (2015). Health behavior. Theory, research, and practice, 5.
- Kahan, J. P., & Rapoport, A. (2014). Theories of coalition formation. Psychology Press.
- Karanafti, A., Trubina, N., Giarma, C., Tsikaloudaki, K., & Theodosiou, T. (2024). Integrating BIMs in construction and demolition waste management for circularity enhancement: A review. *Lecture Notes in Civil Engineering*, 489, 669–678.
- Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications.
- Kolb, B., & Walkey, J. (1987). Behavioural and anatomical studies of the posterior parietal cortex in the rat. *Behavioural brain research*, 23(2), 127-145.
- Kotter, J. P. (1996). Leading change. Harvard Business Review Press.
- Lederer, J., Gassner, A., Kleemann, F., & Fellner, J. (2020). Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: A case study from Vienna. *Resources, Conservation and Recycling*, 161, 104942.
- Lewin, K. (1947). Frontiers in group dynamics: Concept, method and reality in social science; social equilibria and social change. *Human Relations*, 1(1), 5-41.
- Ma, W., & Hao, J. L. (2024). Enhancing a circular economy for construction and demolition waste management in China: A stakeholder engagement and key strategy approach. *Journal of Cleaner Production*, 450, 141763.
- Martin, H., Chebrolu, D., Chadee, A., & Brooks, T. (2024). Too good to waste: Examining circular economy opportunities, barriers, and indicators for sustainable construction and demolition waste management. *Sustainable Production and Consumption*, 48, 460–480.
- Michie, S., Hyder, N., Walia, A., & West, R. (2011). Development of a taxonomy of behaviour change techniques used in individual behavioural support for smoking cessation. *Addictive behaviors*, 36(4), 315-319.
- Petty, R. E., & Cacioppo, J. T. (1986). The elaboration likelihood model of persuasion. Academic Press.
- Pickin, J., Wardle, C., O'Farrell, K., Stovell, L., Nyunt, P., Guazzo, S., Lin, Y., Caggiati-Shortell, G., Chakma, P., Edwards, C., Lindley, B., Latimer, G., & Downes, J. (2022). National Waste Report 2022 (Version 1.2). Department of Climate Change, Energy, the Environment and Water. <https://www.dcceew.gov.au/sites/default/files/documents/national-waste-report-2022.pdf>
- Prochaska, J. O., & DiClemente, C. C. (1983). Stages and processes of self-change of smoking: Toward an integrative model of change. *Journal of Consulting and Clinical Psychology*, 51(3), 390-395.
- Powell, T., & Sammut-Bonnici, T. (2015). Pareto analysis. In C. L. Cooper (Ed.), *Wiley encyclopedia of management* (Vol. 12). John Wiley & Sons.
- Ramos, M., & Martinho, G. (2021). Influence of construction company size on the determining factors for construction and demolition waste management. *Waste Management*, 136, 295–302.
- Ramos, M., Martinho, G., & Pina, J. (2023). Strategies to promote construction and demolition waste management in the context of local dynamics. *Waste Management*, 162, 102–112.
- Rogers, E. M., & Smith, L. (1962). Bibliography on the Diffusion of Innovations. Department of Communication, Michigan State University.
- Santos, M. M., Lanzinha, J. C. G., & Ferreira, A. V. (2021). Proposal for a methodology for sustainable rehabilitation strategies of the existing building stock—the ponte gêa neighborhood. *Designs*, 5(2), 26.

- Schultz, P. W., Nolan, J. M., Cialdini, R. B., Goldstein, N. J., & Griskevicius, V. (2018). The constructive, destructive, and reconstructive power of social norms: Reprise. *Perspectives on psychological science*, 13(2), 249-254.
- Shooshtarian, S., Caldera, S., Zaman, A., & Newman, P. (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.
- Soto-Paz, J., Arroyo, O., Torres-Guevara, L. E., Parra-Orobio, B. A., & Casallas-Ojeda, M. (2023). The circular economy in the construction and demolition waste management: A comparative analysis in emerging and developed countries. *Journal of Building Engineering*, 78, 107724.
- Swarnakar, V., & Khalfan, M. (2024). An analysis of circular economy adaptation in construction and demolition waste management sector: A systematic literature review and conceptual implementation framework. *Smart and Sustainable Built Environment*.
- Tanthanawiwat, K., Gheewala, S. H., Nilsalab, P., Schoch, M., & Silalertruksa, T. (2024). Environmental sustainability and cost performances of construction and demolition waste management scenarios: A case study of timber and concrete houses in Thailand. *Journal of Cleaner Production*, 436, 140652.
- Urbanati, A., Franzò, S., & Chiaroni, D. (2021). Enablers and barriers for circular business models: An empirical analysis in the Italian automotive industry. *Sustainable production and consumption*, 27, 551-566.
- Wu, H., Zuo, J., Zillante, G., Wang, J., & Yuan, H. (2019). Construction and demolition waste research: A bibliometric analysis. *Architectural Science Review*, 62(4), 354–365.
- Zhao, X. (2021). Stakeholder-associated factors influencing construction and demolition waste management: A systematic review. *Buildings*, 11(4), 149. <https://doi.org/10.3390/buildings11040149>

ASSESSING THE READINESS TO ADOPT THE DIGITAL TWIN ENABLED FACILITIES MANAGEMENT TO REVAMP THE BUILDING OPERATION AND MAINTENANCE IN SRI LANKA

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Abstract. The Facilities Management (FM) industry is undergoing a transformation with the adoption of IT technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Building Information Modelling (BIM), leading to the innovative concept of Digital Twin (DT), which is known as a dynamic virtual copy of a physical asset, process, system or environment that behaves identically to its real-world counterpart. The FM industry has seen a revolution due to DT enabled FM (DT-FM), shifting the focus from basic monitoring to advanced prediction and simulation of conditions, transforming FM activities into proactive, data-driven strategies. However, Sri Lanka has not practically adopted the DT concept for FM, even though it has numerous modern buildings with complex maintenance processes. This research was designed to assess the readiness for adopting the DT-FM for operations and maintenance (O&M) of facilities. A leading 43 modern buildings of more than 75,000 sq.ft floor area in Colombo metropolis were randomly selected for data collection. The study employed a mixed method approach, starting with qualitative data collection and analysis using expert interviews, and further followed by a quantitative phase involving a questionnaire survey. Research findings indicate that 58% of FM organisations are aware of DT-FM concept. However, willingness and readiness for adopting DT-FM are at a lower level, and this gives a strong message for facility managers to rethink how to bridge the gaps for the successful implementation of DT-FM.

Keywords. Facilities Management, Digital Twin, Operation And Maintenance, Building Information Modelling, Artificial Intelligence

1. Introduction

A transformative era in facilities management (FM) has begun with the widespread adoption of cutting-edge technologies like Artificial Intelligence (AI), Internet of Things (IoT), and Building Information Modelling (BIM) which enhance the decision-making capabilities throughout a building's life cycle and giving rise to the ground-breaking concept of Digital Twin (DT) (Pomè & Signorini, 2023). The DT serves as a virtual representation of the real-time status of objects, processes, and systems, bridging the gap between physical and digital realms by connecting digital objects, and is instrumental in integrating the physical and digital worlds (Javaid et al., 2023). According to Pomè & Signorini (2023), the FM industry has seen a revolution due to DT enabled FM (DT-FM), especially during the O&M phase, shifting the focus from basic monitoring to advanced prediction and simulation of conditions, transforming FM activities into proactive, data-driven strategies. Martin and Fjeld (2020) mentioned that DT offers capabilities such as simulation, decision assistance, automation and integration, which are necessary to move the FM industry into Industry 4.0, which entails a continuous interaction between people and technology. Real-time monitoring of assets (Eyre & Freeman, 2018), predictive maintenance of equipment (Elyasi et al., 2023), efficient energy management (Shahzad et al., 2022), improved occupant comfort (Arowoia et al., 2023), data driven decision making (Yao et al., 2023), comprehensive performance analysis (D. G. J. Opoku et al., 2022), remote monitoring and control (Elyasi et al., 2023), long

term sustainability (Omrany et al., 2023), and collaboration between stakeholders (Zhao et al., 2022) are few other benefits of DT-FM.

Groombridge (2023) predicted that by 2027, more than 40% of large enterprises globally will incorporate DT technology into their projects to drive revenue growth. Furthermore, a study conducted by Pomè and Signorini (2023), revealed that several case studies in the global proving the use of DT is supported by substantial cost savings, including a notable 15% reduction in FM expenses, 40% reduction in energy costs, and 30% reduction in operating costs, primarily attributable to optimised resource management and overall efficiency.

In the Global context, developed countries such as the UK, USA, Australia, and Italy have been the top countries in advancing DT adoption in the built environment, while developing countries like Brazil, China, and South Africa have made commendable contributions (D. G. J. Opoku et al., 2022). This is proven by successful DT integration in different countries. For instance, the Centre for Digital Built Britain (CDBB) in the UK is running the National Digital Twin Programme (NDTp) to access high quality and secure data to improve how infrastructure is built, managed, operated and decommissioned (CDBB, 2017). The Sydney Opera House restoration team in Australia created a unified central data repository utilising some DT concepts to improve O&M (Cooperative Research Centre for Construction Innovation, 2007). Further, this repository integrates data from various building systems to support more informed O&M decisions, ultimately improving the performance and longevity of the iconic structure. The framework proposed by Zhao et al. (2022) for an effective Building O&M process is another good example which integrates real-time data analytics, predictive maintenance, and automated feedback mechanisms, demonstrating how DT can transform traditional O&M practices into proactive, data-driven strategies.

The key factor driving a rise in the total life-cycle cost of a building project is the O&M phase (Yalcinkaya & Singh, 2014). Mohanta and Das (2016) state that O&M expenses account for 60% - 85% of total life cycle costs, with the remaining percentage going towards design and construction. Moreover, the conventional FM techniques frequently struggle with issues including incomplete, inadequate or outdated documentation, which makes it difficult to make effective decisions and maintenance planning regarding the facility (Chen & Tsai, 2021). Through the smooth integration of IoT sensors and data analytics, DT enabled proactive decision-making, empowering facility managers to optimise maintenance schedules, improve operational performance, save costs, increase sustainability, and offer a seamless FM experience (Elyasi et al., 2023). As a result of the creative application of DT technology, building maintenance has changed significantly in the last few years (Errandonea et al., 2020). This widespread tendency denotes a paradigm change in the upkeep of buildings.

However, while the global landscape showcases successful DT implementations, the specific readiness of Sri Lanka's building sector remains a research gap. Also, Sri Lanka has not practically adopted the DT concept for FM, even though Sri Lanka has many modern buildings with complex maintenance processes. Therefore, there is an essential need to assess the readiness to promote the successful adoption of

DT-FM unique to the Sri Lankan context. Hence, this research focused on assessing the readiness to adopt the DT-FM to revamp the building O&M in Sri Lanka.

2. Literature Review

2.1 DIGITAL TWIN (DT)

DT technology is part of the rise of new digital technologies that support digital transformation by facilitating capabilities to enable new business models and decision support systems (VanDerHorn and Mahadevan, 2021). DT has been defined in various ways in the extant literature, as per the characteristics derived from multiple use cases and the conceptual understanding of DT has continuously evolved during its development (van der Valk et al., 2020). Further, Muctadir et al. (2024) defined DT as a pairing of a physical entity and a corresponding virtual entity (VE), mimicking certain aspects of the former depending on the use case.

2.2 DT ENABLED FM (DT-FM)

A paradigm shift in FM has been brought about by the use of DT, especially in the Architectural, Engineering & Construction (AEC) sector and the O&M of built environments represent primary domains of application for DT-FM (Dixit et al., 2019). Arowoia et al. (2023) underscored that the integration of DT to FM operations aims to provide a complete and dynamic method to maximise efficiency and resource utilisation, hence greatly enhancing data-driven decision-making throughout the asset lifespan. Brilakis et al. (2019) conclude that a DT in the built environment is a 3D model-based representation of a physical asset, which may be created to serve a specific purpose in a project lifecycle and would contain the related data required to simulate the realistic characteristics of the physical twin within the defined use case of the DT.

Based on these facts, the DT-FM can be defined as a sophisticated DT technology integration into the O&M segment of the built environment in the AEC industry, imparting a sensible and comprehensive digital representation for real-time monitoring, decision making, and predictive maintenance throughout the facility's life cycle (Zhao et al., 2022).

2.2.1 Application and Benefits of DT-FM

Research conducted by Slioa (2022) found that the main applications of DT concept in FM are energy monitoring, energy savings, predictive maintenance, error detection, occupant detection, occupant prediction, comfort, and cost savings.

DT applications enable enterprises to accurately monitor and evaluate patterns of energy use within a facility, leading to effective optimisation. (Bortolini et al., 2022). Organisations may proactively identify energy-intensive activities, optimise operations, and save needless spending by integrating IoT sensors and sophisticated analytics through the DT (Omran et al., 2023). Further, Pomè & Signorini (2023) revealed that it could save the building energy cost by 40% via the use of DT enabled energy management system.

Liu et al. (2018) highlighted the usefulness of DT in predictive maintenance by explaining how these tools can be optimised to improve asset performance and resource allocation, giving facility managers the power to make well-informed decisions and promoting an efficient and sustainable built environment through the synchronised synergy between physical assets and their digital counterparts. Research conducted by Zhao et al. (2022) revealed that the main advantages of using DT in FM are real-time data gathering and monitoring, a more effective decision-making process and improved predictive maintenance.

DT transforms the comfort of facility users through occupancy prediction, energy-efficient HVAC system adjustments, and the integration of many data sources, including occupant feedback and emotion detection (Clausen et al., 2021). It allows for customised indoor environmental settings, adjusting interior conditions to suit individual preferences and effortlessly monitors temperature, humidity, and CO₂ levels, optimising air conditioning cycles to minimise the need for natural ventilation and cut down on energy waste (Desogus et al., 2021).

A recent interpretation of the DT concept within the built environment research relates it to the use of DT of an asset to provide simulations and to an information link to a real-world entity, thus enabling opportunities for data-centric decision making in asset O&M (Shahzad et al., 2022). DT technology, paired with cutting-edge Machine Learning and AI capabilities, offers to forecast future maintenance needs of built environments, preventing unplanned downtime and optimising asset performance in the field of FM (Negri et al., 2020).

DT offers a new visual for facilities monitoring with the use of BIM and XR technologies, which enables the visualisation of equipment and subsequent realisation of equipment management (Zhang et al., 2023). Further, Lu et al. (2020) suggested a Bayesian optimisation-based change point detection system to assess the DT data and find abnormalities and anomalies in the facility.

Almatared et al. (2023) mentioned the application of DT technology to fire management in the venues used for early warnings and emergency management evacuation path guidance for fire safety. The major goals of utilising DT in emergencies include fire evacuation and guidance, prevention of future cases, personalised treatment, supporting decision making, and improving visualisation (Zhang et al., 2023).

As a summary, the diverse applications and key benefits of DT-FM are indicated in Table 1.

Table 1: Application & Benefits of DT-FM

Application	Benefits	References
Energy Monitoring & Management	Optimised energy use, cost reduction up to 40%	(Bortolini et al., 2022; Pomè & Signorini, 2023; Omrany et al., 2023)
Predictive Maintenance	Reduced downtime, efficient resource allocation, extended asset life	(Liu et al., 2018; Negri et al., 2020; Zhao et al., 2022)

Occupancy Detection & Comfort	Customised indoor settings, HVAC efficiency, improved occupant satisfaction	(Clausen et al., 2021; Desogus et al., 2021)
Real-Time Monitoring & Decisions	Improved decision-making and operational efficiency	(Shahzad et al., 2022; Slioa, 2022)
Visualisation (BIM & XR)	Better equipment management and anomaly detection	(Lu et al., 2020; Zhang et al., 2023)
Emergency & Fire Management	Early warnings, evacuation planning, incident prevention	(Almatared et al., 2023; Yao et al., 2023)

2.2.2 Prerequisites for DT-FM

The essential conditions, technologies, and frameworks that must be in place to successfully implement and operate a digital replica of physical assets can be introduced as the prerequisites for DT-FM (Zhao et al., 2022).

1. Technological resources

- Data perception technologies

According to Khajavi et al. (2019), two essential technological components can be identified as the data perception for developing a DT model for a building, including the required data components from BIM or BMS and a Wireless Sensor Network (WSN). A BIM is a computable representation of all building physical and functional attributes, as well as related lifecycle information, and it serves as a repository of information for building owners and operators to maintain the systems (Edirisinghe et al., 2017). BIM is essential for DT integration due to the DT visualisation for a building can rely on 3D CAD model extracted from BIM or a custom 3D model of the building (Khajavi et al., 2019). Li et al. (2022) stated that the sensors are the 'must-have' components in every form of DTs, coupled with data transmission technologies, they guarantee that DT can realise real-time data collection and synchronisation. DT uses IoT as its primary technology in every application to sense real time building conditions, and it is predicted that more than 90% of all IoT platforms will have DT capability by 2027 (Attaran & Celik, 2023).

- Data transmission technologies

In any kind of DT, there are generally three types of connections, including the connection between the physical entity and the virtual side, the connection between the virtual side to humans and the connection from humans to the physical side (Li et al., 2022). Further, (Li et al., 2022) revealed that Big data, IoT, 5G, Wi-fi and satCom are fundamental to the connectivity of DT.

- Data storage technologies

The technology known as database technology, which oversees managing and storing data related to the DT, is facing escalating demands due to the continuous progression of continuous expansion of data volume (Zhang et al., 2023). The two most common data storage methods used for the DT concept now are cloud storage and local storage environments (Yu et al., 2021).

- Data processing technologies

The main function of data integration and analytics is to gather, process and analyse the data and in general, the virtual side is made up of sets of models with different functions, which are mainly divided into two forms, including traditional modelling methods that are mostly physics-based, and data-driven modelling (Li et al., 2022). AI can assist DT by providing an advanced analytical tool capable of automatically analysing obtained data and providing valuable insights, making predictions about outcomes, and giving suggestions as to how to avoid potential problems (Attaran & Celik, 2023). Li et al. (2022) explained that most AI applications on the virtual side reflect on using ML to create the data-driven analytical model, and these models are widely applied in diagnosis, manufacturing, and decision making due to their proven performance in classification, clustering, and generation tasks. Glaessgen and Stargel (2012) also pointed out that high-performance computers will be necessary for the construction of the high dimensional and complex DT with huge data to deal with DT related issues like handling large and noisy data, quantifying uncertainty and a huge number of equations. Cloud computing is an emerging technology and a 'good-to-have' infrastructure to meet the requirements of DTs while breaking up the limitations of local computing devices, whilst improving the overall computing capacity (Li et al., 2022). Furthermore, edge computing technology plays a more significant role in data strain in confined environments, and it will expedite reaction times and effectively reduce the time lag between data collecting and processing (Li et al., 2022).

- Data visualisation technologies

Immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are together referred to as Extended Reality (XR) and these innovations have the power to expand our perception of reality by fusing the actual and virtual realms (Stacchio et al., 2022).

2. Financial resources

Securing adequate funds and financial investment is identified as the crucial dimension for the successful adoption of DT technology in FM, as it enables the procurement of necessary resources, supports the development of infrastructure, and facilitates the implementation of DT to drive innovation and efficiency in projects (Deepu & Ravi, 2021). Further, a study conducted by Huang et al. (2023) identified that the affordability of software and hardware upgrades and maintenance costs is a crucial determinant towards the adoption of DT, as it significantly influences financial planning, resource allocation, and the overall strategy for technological investments, thereby playing a vital role in ensuring the long-term viability and efficiency of implementing DT in FM.

3. Human resources

Liu et al. (2022) highlighted that the skills and experience of the workforce regarding DT implementation are important for its successful integration. Supporting that, the Centre for Digital Built Britain (CDBB's) National Digital Twin (NDT) programme, in partnership with the Construction Innovation Hub, has released a Skills and Competency Framework to help individuals.

4. Regulatory factors

Muhlheim et al. (2022) mentioned that the industry and regulators must develop agreed-upon guidance and frameworks for the acceptance of DT applications that are consistent and explicit and that enable the use of DTs. Further, clear and robust regulations provide a framework that facilitates the safe and ethical use of DT, fostering trust among stakeholders and mitigating risks associated with breaches and misuse, thereby enhancing the overall reliability and acceptance of DT solutions in the industry.

5. Organizational support & readiness

Deepu & Ravi (2021) highlighted that top management commitment and Stakeholders' awareness of technology benefits are crucial for the successful adoption of DT for providing resources, fostering a culture of innovation, and ensuring organisational alignment with technological advancements. Supporting that, Opoku et al., (2022) pointed out that stakeholder engagement is pivotal for the adoption of DT, as it ensures collaborative support, aligns interests, and fosters a shared commitment to leveraging DT for enhanced project outcomes.

6. Data privacy, security & compliance

The adoption of DT technology in industries necessitates stringent attention to data privacy, security, and compliance, and the assurance of data privacy and security is paramount, as it protects sensitive information from unauthorised access and breaches, thereby maintaining the integrity and confidentiality of organisations (Agnusdei et al., 2021).

7. Knowledge, expertise & competencies

The availability of knowledge, skills, and competencies to adopt the technology is fundamental, as it ensures that personnel are equipped with the necessary understanding and capabilities to effectively implement and utilise DT technology (Hong et al., 2019).

8. Market & external factors

Götz et al. (2022) highlighted that market demand for the technology plays a significant role, as it drives the industry's investment and development in DT and managing industry resistance to adopting new technology is essential for overcoming uncertainty and encouraging widespread acceptance.

3. Methodology

This study aims to assess the willingness and readiness of organisations in the FM industry to adopt DT-FM for O&M. The study was carried out in multiple stages to address the research question. Initially, a comprehensive literature review was carried out on a broader perspective to review the concept of DT and its usage in the FM sector to familiarise with the research problem and identify the background of the research area.

The study employed a mixed method approach, starting with qualitative data collection and analysis, including expert interviews, and further followed by a quantitative phase involving a questionnaire survey. In the first phase, expert

interviews were conducted with five experts to validate the findings derived from the literature review on requirements for adopting DT-FM. As mentioned in the above section, the identified eight dimensions and twenty-four sub-dimensions (refer Section 2.4) that can be used to assess the readiness for adopting DT-FM were discussed by the selected experts. Manual content analysis was employed to analyse the data gathered through expert interviews. The profile of the interviewees is shown in Table 2.

Table 2: Profile of the Interviewees

No	Interviewer Code	Designation	Years of Experience
1	R1	Building Automation Manager	10 years
2	R2	Digital Transformation Practitioner	13 years
3	R3	DT Engineer	5 Years
4	R4	Lead Digital Transformation Engineer	7 Years
5	R5	Building Automation Engineer	8 Years

In the second phase, a questionnaire survey was conducted to gauge the awareness of DT-FM and their perceptions of its potential benefits and assess the existing willingness. The questionnaire was distributed among 50 organisations in the FM industry with more than 75,000 sqft of floor area. The questions based on the identified prerequisites for adopting DT-FM at the O&M phase were included with a 1-5 Likert scale. 24 sub-dimensions were organised under eight identified dimensions including (1) Technological resources, (2) Human resources, (3) Financial resources, (4) Regulatory factors, (5) Organizational resources, (6) Knowledge, Expertise and Competencies resources, (7) Market and external factors, (8) Data privacy, security and Compliance. Facility managers/Building managers/Facility engineers were invited to participate in the survey.

IBM SPSS (Statistical Package for the Social Sciences version 26) software was utilised to perform statistical analysis on the data collected under the questionnaire survey, with a one-sample t-test applied to evaluate the significance of the results.

4. Research Findings

Experts' opinions on the literature findings for DT-FM prerequisites are shown in Table 3. Since all experts believed that all literature findings were important, all twenty-four sub-dimensions under 8 dimensions were included in the questionnaire.

Table 3: Summary of Expert Responses

Dimensions	Sub dimensions	Literature	Interviewee				
			R1	R2	R3	R4	R5
Technological infrastructure	Data perception tools • BIM, BAS/BMS, WSN (EMS, CMMS)	✓	✓	✓	✓	✓	✓
	Data transmission tools • Wired, Wireless (Wi-Fi, 5G, IOT)	✓	✓	✓	✓	✓	✓
	Data storage tools • Local, Cloud	✓	✓	✓	✓	✓	✓

	Data processing technology AI, ML, DL, Cloud computing, Edge computing, HPC hardware	✓	✓	✓	✓	✓	✓
	Data visualisation tools AR, VR, Dashboards	✓	✓	✓	✓	✓	✓
Financial Resources	Availability of funds and financial investment	✓	✓	✓			
	Affordability of software and hardware upgrading and Maintenance costs	✓	✓	✓	✓	✓	✓
Human Resources	Skilled human resources	✓	✓				
	Technology operators	✓	-	✓	-	-	-
Regulatory factors	Rules and regulations provided by the Government	✓	✓				
Organisational support and readiness	Top management supportiveness	✓	✓				
	Organisation's readiness to adopt the technology	✓	✓	✓	✓	✓	✓
	Personnel readiness to change and adopt new technology	✓	✓	✓	✓	✓	✓
	Stakeholders' awareness of technology benefits	✓	✓	✓	✓	✓	✓
	Stakeholder engagement to adopt the technology	✓	✓	✓	✓	✓	✓
Knowledge, Expertise and Competencies	Availability of knowledge, skills, and competencies to adopt the technology	✓	✓				
	Availability of practical cases of the technology	✓	✓	✓	✓	✓	✓
	Continuity of research and development efforts to enhance the adaptability of the technology	✓	✓	✓	✓	✓	✓
Data privacy, security and compliance	Assurance of data privacy and security	✓	✓				
	Availability of clear project documentation and requirements	✓	✓	✓	✓	✓	✓

	Availability of standards and codes for the new technology	✓	✓	✓	✓	✓	✓
Market and External Factors	Market demand for the technology	✓	✓				
	Readiness of the industry to manage and overcome resistance to adopting technology	✓	✓	✓	✓	✓	✓
	Availability of KPIs for tracking progress	✓	✓	✓	✓	✓	✓

Out of 50, 43 respondents completed the questionnaire, accounting for an 86% response rate. Figure 1 shows the type of facilities of the respondents.

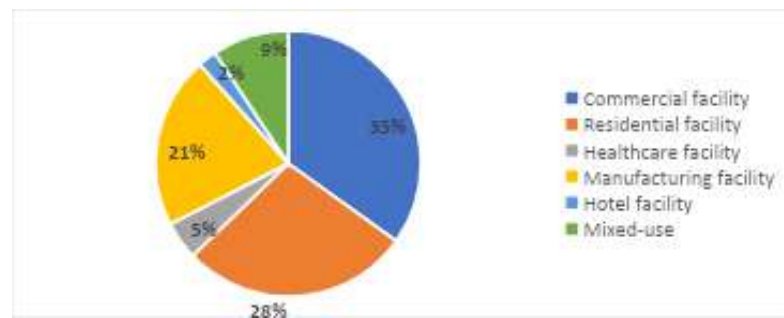


Figure 1: Type of facilities of the participating organizations

4.1 AWARENESS OF DT-FM INDUSTRY

According to the findings of the questionnaire survey, the awareness level of the FM industry towards DT-FM is demonstrated in Figure 2.

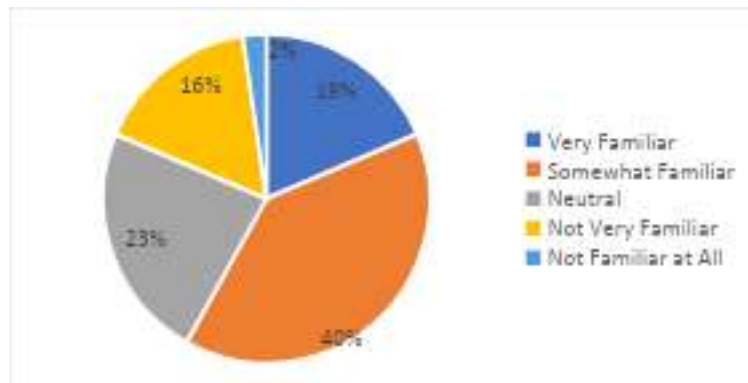


Figure 2: Awareness level of the FM industry towards DT-FM

Following the survey findings, 18.6% of stakeholders in the industry were very familiar with the concept of DT-FM. And 39.53% of Stakeholders are somewhat familiar with the concept, while 23.26% of stakeholders had neutral familiarity with DT enabled FM concept. On the other hand, 16.28% of Stakeholders in the FM industry were not very familiar with DT enabled FM concept. Further, 2.33% of stakeholders were not familiar with DT enabled FM concept. According to that,

58.13% of the building managers/ in the FM industry are aware of the DT-FM concept and it can be identified as a higher awareness level.

4.2 WILLINGNESS TO ADOPT DT -FM

Based on the questionnaire survey findings, the willingness to adopt DT-FM was assessed using a one-sample t-test. The hypotheses were defined below,

- Null Hypothesis (H_0): The willingness to adopt DT-enabled FM is not significantly different from the threshold, indicating insufficient willingness.
- Alternative Hypothesis (H_1): The willingness to adopt DT-enabled FM is significantly different from the threshold, indicating sufficient willingness.

The results of the test were tabulated in Table 4.

Table 4: Result of one-sample t-test for Level of willingness to adopt DT

Code	Level of Willingness	N	t statistic	Significance (P value)	Mean
Int	Willingness to adopt DT-enabled FM	43	-4.887	<.001	2.72

The negative T value and the P value less than 0.05 indicate that the mean willingness score is significantly below the threshold of 3.5. This result is statistically significant, suggesting a notable lack of willingness to adopt DT-enabled FM within the industry. Therefore, the null hypothesis (H_0) is accepted.

4.3 READINESS TO ADOPT DT-FM

The level of readiness in the FM industry to adopt the DT-FM was analysed via a statistical analysis through IBM SPSS 25, and the hypotheses were defined below, Null Hypothesis (H_0): The dimension is not ready for DT-enabled FM implementation.

Alternative Hypothesis (H_1): The dimension is ready for DT-enabled FM implementation. The results of the test were tabulated in Table 5.

Table 5: One-sample t-test results of DT-FM prerequisites

Code	Prerequisites for DT-FM	N	T Value	P value
Tec1	Availability of data perception tools like BIM, BMS, EMS, CMMS, IoT	43	-5.991	<.001
Tec2	Availability of data transmission tools like Wireless (WiFi, 5G, IOT) or wired data transmission	43	-12.136	<.001
Tec3	Availability of Data storage tools like Cloud Storage or Local Storage	43	-11.225	<.001
Tec4	Utilising Artificial Intelligence (AI) for O&M	43	-21.387	<.001
Tec5	Utilising Machine Learning (ML) for O&M	43	-9.487	<.001
Tec6	Utilising cloud computing and Edge computing for O&M	43	-26.536	<.001
Tec7	Utilising high-performance computer hardware for O&M	43	-9.871	<.001
Tec8	Availability of Data visualisation tools like Interface, AR, VR	43	-8.210	<.001

Fin1	Availability of funds and financial investments	43	-26.679	<.001
Fin2	Affordability of software and hardware upgrading, and maintenance costs	43	-9.942	<.001
HR1	Skilled human resources for adopting DT	43	-11.429	<.001
Reg1	Rules and regulations imposed by the Government	43	-17.202	<.001
Org1	Top management supportiveness	43	-7.942	<.001
Org2	Readiness of the individual business units	43	-13.516	<.001
Org3	Personnel readiness to change and adopt new technology	43	-14.401	<.001
Org4	Stakeholder engagement to adopt the technology	43	-14.206	<.001
Dat1	Assurance of data privacy and security	43	-9.498	<.001
Dat2	Availability of clear project documentation and requirements	43	-22.920	<.001
Dat3	Availability of standards and codes for the new technology	43	-7.954	<.001
Knw1	Availability of knowledge, skills and competencies to adopt the technology	43	-10.546	<.001
Knw2	Availability of practical cases of the technology	43	-37.481	<.001
Knw3	Continuity of research and development efforts to enhance the adaptability of the technology	43	-15.974	<.001
Mar1	Market demand for the technology	43	-20.347	<.001
Mar2	Readiness of the industry to manage and overcome resistance to adopting the technology	43	-24.059	<.001
Mar3	Availability of KPIs for tracking progress	43	-25.875	<.001

Based on the findings, all tested dimensions have negative T values and P values less than 0.05, indicating that the mean readiness scores are significantly below the threshold of 3.5. The p-value suggested that this result is highly statistically significant, and it suggested rejecting the alternative hypothesis and accepting the null hypothesis. Further, it is concluded that none of the prerequisites is ready for DT-FM implementation in the Sri Lankan FM industry.

5. Conclusion

This study has assessed the awareness and willingness to adopt the digital twin-enabled facilities management to revamp building O&M in Sri Lanka. The study assesses the awareness of the DT enabled FM among stakeholders, and findings revealed that 18.6% were very familiar with the concept, 39.53% of stakeholders were somewhat familiar with the concept and 23.26% of stakeholders were neutral familiar. On the other hand, 16.28% of Stakeholders were not very familiar with DT enabled FM concept. Moreover, this research assessed the willingness level to adopt the DT enabled FM among stakeholders. The findings highlighted that there was a notable lack of willingness to adopt DT-enabled FM within the industry. However, the findings of this paper emphasise the awareness and willingness of the Lankan FM industry towards the adoption of DT enabled FM concept for their O&M activities.

6. References

- Agnusdei, G. P., Elia, V., & Gnoni, M. G. (2021). Is Digital Twin Technology Supporting Safety Management? A Bibliometric and Systematic Review. *Applied Sciences*, 11(6). <https://doi.org/10.3390/app11062767>
- Almatared, M., Liu, H., Abudayyeh, O., Hakimi, O., & Sulaiman, M. (2023). Digital-Twin-Based Fire Safety Management Framework for Smart Buildings. *Buildings*, 14, 4. <https://doi.org/10.3390/buildings14010004>
- Arowoiya, V. A., Moehler, R. C., & Fang, Y. (2023). Digital twin technology for thermal comfort and energy efficiency in buildings: A state-of-the-art and future directions. In *Energy and Built Environment. KeAi Communications Co.* <https://doi.org/10.1016/j.enbenv.2023.05.004>
- Attaran, M., & Celik, B. G. (2023). Digital Twin: Benefits, use cases, challenges, and opportunities. *Decision Analytics Journal*, 6. <https://doi.org/10.1016/j.dajour.2023.100165>
- Bortolini, R., Rodrigues, R., Alavi, H., Vecchia, L. F. D., & Forcada, N. (2022). Digital Twins’ Applications for Building Energy Efficiency: A Review. *Energies*, 15(19). <https://doi.org/10.3390/en15197002>
- Brilakis, I., Pan, Y., Borrmann, A., & Mayer, H.-G. (2019). Built Environment Digital Twinning. December, 17–18.
- CDBB. (2017). Centre for Digital Built Britain completed its five-year mission and closed its doors at the end of September 2022.
- Chen, K. L., & Tsai, M. H. (2021). Conversation-based information delivery method for facility management. *Sensors*, 21(14). <https://doi.org/10.3390/s21144771>
- Clausen, A., Arendt, K., Johansen, A., Sangogboye, F. C., Kjærgaard, M. B., Veje, C. T., & Jørgensen, B. N. (2021). A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings. *Energy Informatics*, 4(2), 40. <https://doi.org/10.1186/s42162-021-00153-9>
- Cooperative Research Centre for Construction Innovation. (2007). Adopting BIM for facilities management Solutions for managing the Sydney Opera House.
- Deepu, T. S., & Ravi, V. (2021). Exploring critical success factors influencing adoption of digital twin and physical internet in electronics industry using grey-DEMATEL approach. *Digital Business*, 1(2), 100009. <https://doi.org/https://doi.org/10.1016/j.digbus.2021.100009>
- Desogus, G., Quaquero, E., Rubiu, G., Gatto, G., & Perra, C. (2021). Bim and iot sensors integration: A framework for consumption and indoor conditions data monitoring of existing buildings. *Sustainability (Switzerland)*, 13(8). <https://doi.org/10.3390/su13084496>
- Dixit, M. K., Venkatraj, V., Ostadalimakhmalbaf, M., Pariafsai, F., & Lavy, S. (2019). Integration of facility management and building information modeling (BIM): A review of key issues and challenges. *Facilities*, 37(7–8), 455–483. <https://doi.org/10.1108/F-03-2018-0043>
- Edirisinghe, R., London, K., Kalutara, P., & Aranda-Mena, G. (2017). Building information modelling for facility management: Are we there yet? *Engineering, Construction and Architectural Management*, 24, 0. <https://doi.org/10.1108/ECAM-06-2016-0139>
- Elyasi, N., Bellini, A., & Klungseth, N. J. (2023). Digital transformation in facility management: An analysis of the challenges and benefits of implementing digital twins in the use phase of a building. *IOP Conference Series: Earth and Environmental Science*, 1176(1). <https://doi.org/10.1088/1755-1315/1176/1/012001>

- Errandonea, I., Beltrán, S., & Arrizabalaga, S. (2020). Digital Twin for maintenance: A literature review. *Computers in Industry*, 123, 103316. <https://doi.org/https://doi.org/10.1016/j.compind.2020.103316>
- Eyre, J., & Freeman, C. (2018). Immersive Applications of Industrial Digital Twins. <https://www.researchgate.net/publication/328803997>
- Glaessgen, E. H., & Stargel, D. S. (2012). The digital twin paradigm for future NASA and U.S. Air force vehicles. *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April. <https://doi.org/10.2514/6.2012-1818>
- Götz, C. S., Karlsson, P., & Yitmen, I. (2022). 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>
- Groombridge, D. (2023). Gartner - Top Strategic Technology Trends 2023. 1–33. <https://www.gartner.com/en/articles/gartner-top-10-strategic-technology-trends-for-2023>
- Hong, Y., Hammad, A. W. A., Sepasgozar, S., & Akbarnezhad, A. (2019). BIM adoption model for small and medium construction organisations in Australia. *Engineering, Construction and Architectural Management*, 26(2), 154–183. <https://doi.org/10.1108/ECAM-04-2017-0064>
- Huang, G., Ng, S. T., & Li, D. (2023). Determinants of digital twin adoption in hospital operation management. *Urban Lifeline*, 1(1), 6. <https://doi.org/10.1007/s44285-023-00005-w>
- Javaid, M., Haleem, A., & Suman, R. (2023). Digital Twin applications toward Industry 4.0: A Review. In *Cognitive Robotics* (Vol. 3, pp. 71–92). KeAi Communications Co. <https://doi.org/10.1016/j.cogr.2023.04.003>
- Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmstrom, J. (2019). Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7(October), 147406–147419. <https://doi.org/10.1109/ACCESS.2019.2946515>
- Li, L., Aslam, S., Wileman, A., & Perinpanayagam, S. (2022). Digital Twin in Aerospace Industry: A Gentle Introduction. *IEEE Access*, 10, 9543–9562. <https://doi.org/10.1109/ACCESS.2021.3136458>
- Liu, Z., Lu, Y., Nath, T., Wang, Q., Tiong, R. L. K., & Peh, L. L. C. (2022). Critical success factors for BIM adoption during construction phase: a Singapore case study. *Engineering, Construction and Architectural Management*, 29(9), 3267–3287. <https://doi.org/10.1108/ECAM-12-2020-1072>
- Liu, Z., Meyendorf, N., & Mrad, N. (2018). The role of data fusion in predictive maintenance using digital twin. *AIP Conference Proceedings*, 1949. <https://doi.org/10.1063/1.5031520>
- Lu, Q., Xie, X., Parlikad, A. K., & Schooling, J. (2020). Digital Twin-Enabled Anomaly Detection for Built Asset Monitoring in Operation and Maintenance. *Automation in Construction*, 118. <https://doi.org/10.1016/j.autcon.2020.103277>
- Martin, T., & Fjeld, B. (2020). Digital Twin-Towards a joint understanding within the AEC/FM sector.
- Mohanta, A., & Das, S. (2016). BIM as Facilities Management Tool: A brief review.
- Muctadir, H. M., Manrique Negrin, D. A., Gunasekaran, R., Cleophas, L., van den Brand, M., & Haverkort, B. R. (2024). Current trends in digital twin development, maintenance, and operation: an interview study. *Software and Systems Modeling*, 23(5), 1275–1305. <https://doi.org/10.1007/s10270-024-01167-z>

- Muhlheim, M. D., Ramuhalli, P., Huning, A., Yigitoglu, A. G., Saxena, A., & Wood, R. T. (2022). Regulatory Requirements, Guidance, and Review of Digital Twins. *Transactions of the American Nuclear Society*, 127(1), 254–257. <https://doi.org/10.13182/T127-39785>
- Negri, E., Berardi, S., Fumagalli, L., & Macchi, M. (2020). MES-integrated digital twin frameworks. *Journal of Manufacturing Systems*, 56(May), 58–71. <https://doi.org/10.1016/j.jmsy.2020.05.007>
- Omrany, H., Al-Obaidi, K. M., Husain, A., & Ghaffarianhoseini, A. (2023). Digital Twins in the Construction Industry: A Comprehensive Review of Current Implementations, Enabling Technologies, and Future Directions. In *Sustainability (Switzerland)* (Vol. 15, Issue 14). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/su151410908>
- Opoku, D.-G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., & Bamdad, K. (2022). Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review. *Buildings*, 12(2), 113. <https://doi.org/10.3390/buildings12020113>
- Opoku, D. G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., & Bamdad, K. (2022). Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review. In *Buildings* (Vol. 12, Issue 2). MDPI. <https://doi.org/10.3390/buildings12020113>
- Pomè, A. P., & Signorini, M. (2023). Real time facility management: Assessing the effectiveness of Digital Twin in the Operation and Maintenance phase of building life cycle. *IOP Conference Series: Earth and Environmental Science*, 1176(1). <https://doi.org/10.1088/1755-1315/1176/1/012003>
- Shahzad, M., Shafiq, M. T., Douglas, D., & Kassem, M. (2022). Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. *Buildings*, 12(2). <https://doi.org/10.3390/buildings12020120>
- Slioa, A. E. (2022). Evaluation of Digital Twin implementations in Facility Management-A systematic review.
- Stacchio, L., Angeli, A., & Marfia, G. (2022). Empowering digital twins with eXtended reality collaborations. *Virtual Reality & Intelligent Hardware*, 4(6), 487–505. <https://doi.org/https://doi.org/10.1016/j.vrih.2022.06.004>
- van der Valk, H., Haße, H., Möller, F., Arbter, M., Henning, J. L., & Otto, B. (2020). A taxonomy of digital twins. 26th Americas Conference on Information Systems, AMCIS 2020, August.
- VanDerHorn, E., & Mahadevan, S. (2021). Digital Twin: Generalization, characterization and implementation. *Decision Support Systems*, 145, 113524. <https://doi.org/https://doi.org/10.1016/j.dss.2021.113524>
- Yalcinkaya, M., & Singh, V. (2014). Building Information Modeling (BIM) for Facilities Management – Literature Review and Future Needs. 1–10. https://doi.org/10.1007/978-3-662-45937-9_1
- Yao, J. F., Yang, Y., Wang, X. C., & Zhang, X. P. (2023). Systematic review of digital twin technology and applications. In *Visual Computing for Industry, Biomedicine, and Art* (Vol. 6, Issue 1). Springer. <https://doi.org/10.1186/s42492-023-00137-4>
- Yu, G., Wang, Y., Mao, Z., Hu, M., Sugumaran, V., & Wang, Y. K. (2021). A digital twin-based decision analysis framework for operation and maintenance of tunnels. *Tunnelling and Underground Space Technology*, 116, 104125. <https://doi.org/https://doi.org/10.1016/j.tust.2021.104125>
- Zhang, A., Yang, J., & Wang, F. (2023). Application and enabling digital twin technologies in the operation and maintenance stage of the AEC industry: A literature review. *Journal*

of Building Engineering, 80(October 2022), 107859.
<https://doi.org/10.1016/j.jobe.2023.107859>

Zhao, J., Feng, H., Chen, Q., & Garcia de Soto, B. (2022). Developing a conceptual framework for the application of digital twin technologies to revamp building operation and maintenance processes. Journal of Building Engineering, 49.
<https://doi.org/10.1016/j.jobe.2022.104028>

SAFETY RISK OF INDUSTRIAL LIQUEFIED PETROLEUM GAS INSTALLATIONS OF THE HOTEL SEGMENT IN SRI LANKA

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Abstract. The increasing use of Liquefied Petroleum Gas (LPG) in homes and businesses is attributed to its effectiveness, affordability, and eco-friendliness compared to other fuels, despite the potential fire and explosion hazards. When handling this highly flammable gas, it is crucial to implement specific control measures based on its application. Numerous incidents related to LPG are frequently reported in the industry due to issues associated with handling and technical aspects. The use of industrially liquefied petroleum gas (ILPG) in hotel kitchens has become a critical concern due to several safety incidents. This research established 88 risks causing factors under 12 main categories. Bibliometric analysis and focus group interviews were carried out to establish those factors. Further, a questionnaire survey was conducted to assess risk levels contributed by those risk factors to ILPG safety in the hotel segment in Sri Lanka. Findings show that exposed electrical parts, flammable gas contact with electrical circuits, capacity of cylinder stacking, hazardous electrical equipment's without installation, explosion-proof mechanical installations, provision of ventilation, faulty wiring, emergency procedures, compliance with the design code and availability of fire extinguishers are the most vulnerable risks related to ILPG installations in hotel segments. The findings of this research would allow safety practitioners and policymakers to provide preventive measures to enhance the safety of ILPG operations.

Keywords. Liquefied Petroleum Gas, Safety, Risk Causing Factors, Hotel Segment, Bibliometric Analysis

1. Introduction

Liquid Petroleum Gas (LPG) used as a fuel in Sri Lanka is a hydrocarbon gas that contains propane (C₃H₈) and butane (C₄H₁₀). In addition to these two primary chemical compounds, several other compounds are available for various purposes (Sarvestani et al., 2021). According to the revised Sri Lanka Standard, SLS 712:2022, the maximum allowable propane composition in LPG in Sri Lanka is 30% (SLS 712;2021). Bulk usage of LPG with cylinder manifolds for industrial applications refers to Industrial Liquid Petroleum Gas (ILPG) systems. In Sri Lanka, 37.5 kg commercial cylinders are utilized in various industrial applications, and bulk LPG storage systems are used due to high consumption needs (Basnayake & De Silva, 2024).

The country's demand for LPG in 2024 was 480,000 MT, with ILPG consumption at approximately 120,000 MT (Central Bank Annual Report, 2024). According to ILPG demand, the tile manufacturing sector is the highest consumer, followed by rubber manufacturing, glass manufacturing, hotels, and the textile industry (Rajmohan & Weerahewa, 2010). In commercial applications, LPG is widely utilized for space and process heating, running industrial ovens, food production, operating kilns and furnaces, manufacturing processes, packaging materials, and powering forklift trucks in warehouse operations (Malviya & Rushaid, 2018).

This high demand is mainly due to its greater energy content, which provides a competitive edge over other alternative fuel sources (Amuzuvi & Ashilevi, 2016). In many industries, a higher flame temperature is a crucial necessity (Gupta, 2000). Since LPG has a high heating capacity, it allows for quicker temperature attainment, significantly reducing fuel expenses for industrial applications. Propane and Butane complete combustion give a higher heat value, leaving no residue or

particulate matter, resulting in lower maintenance costs and a reduced carbon footprint (Gould & Urpelenean, 2018). ILPG also contributes to reduced emissions compared to traditional fossil fuels, supporting cleaner and more sustainable industrial operations. As a result of the above factors, the adoption of ILPG has significantly risen in recent years among commercial enterprises (Amuzuvi & Ashilevi, 2016).

LPG is a highly flammable gas that easily catches fire. A leak or unanticipated gas release occurs when the system's primary containment fails. When ILPG leaks, it evaporates and creates a substantial gas cloud that tends to accumulate in low-lying areas, such as drains, LPG storage zones, or basements. Hence, there is a huge risk of fire if a flammable source is introduced (Chakraborty et al., 2015). An explosion, fire or cold burn has become an intrinsic risk associated with the use of LPG (Bruce et al., 2015). Under these circumstances, many incidents have been reported related to ILPG (Bariha et al., 2019). They were mainly due to users' lack of knowledge, failure in design, operation, and maintenance (Yadav et al., 2017; Paliwal et al., 2014).

Numerous hotels worldwide have reported incidents involving fires, explosions, and cold burns in kitchens and storage areas (Roberts & Chan, 2000; Wu, 2007; Rasbash, 2010; Zheng & Chen, 2011; Pradhan et al., 2017). On average, approximately six incidents related to LPG fires are reported each month within the industrial and commercial sectors of Sri Lanka (Incidents Reports LGLL, 2024). In the year 2024, 18 incidents were reported from hotels (Incidents Reports LGLL, 2024). The majority of incidents pertain to asset damage, with one case of severe injury documented in this segment. In terms of fire risk, hotels often contain hazardous industrial equipment, particularly in their kitchens, as 80% of their cooking depends on ILPG. Less area availability for ILPG installations, poor knowledge on safety procedures, high replacement frequency of LPG cylinders, design & installation failures, appliance failure, defective installation, and user carelessness are identified as common root causes of many incidents in hotels (Malviya & Rashid, 2018; Basnayake & De Silva, 2024). In Korea, more than 54% of total accidents were attributed to unsafe user behaviour (Park et al., 2015; Jung et al., 2020). According to the Annual Report on Liquefied Petroleum Gas-Related Accidents (2018 version) of Japan, in 2017, 27% of accidents reported in hotel kitchens were due to issues in the ILPG distribution system. Therefore, it is evident that there are many lapses in the distribution of ILPG system safety and safety behaviours of ILPG stakeholders in the hotel sector. In Sri Lanka, there are a lot of installation-related deviations observed. Special considerations must be made to consider the function of a hotel kitchen as an industrial application in terms of safety within the hotel sector.

Many control measures have been introduced to enhance the safety of ILPG users. For instance, countries such as the USA, UK, Japan, and Korea have implemented a range of strategies, regulations, and technologies to reduce the risks of ILPG systems (WLPGA, 2020). In Sri Lanka, the regulations for ILPG usage, including SLS 1196 and SLS 712, and several international standards, such as NFPA, BS, APA, and CODAP have been used. While installers may refer to these standards as necessary, there are no compulsory requirements or regulatory bodies to ensure their enforcement.

Despite the availability of numerous risk prediction methods in other industries, identifying a suitable approach for assessing risks in ILPG installations remains a significant challenge. A comprehensive system to compile all risks associated with ILPG installations and assess the significance of their deviations has not yet been addressed by researchers.

2. Literature Survey

This topic has become an important area for many researchers, as more than 500 LPG application-related articles have been published since the year 2000, according to VOS Scopus journal publication data (Table 1).

Table 1: ILPG highlighted in research publications (VOS Scopus Journal Analysis)

No.	Year	Number of Publications
1	2000 to 2005	67
2	2005 to 2010	96
3	2011 to 2015	115
4	2015 to 2020	104
5	2021 to 2024	144
	Total	526

Risks of using ILPG have been discussed by many researchers over the past decade (Rasbash, 2010; Zheng & Chen, 2011; Bansal et al., 2012; Pradhan et al., 2017). The primary risk in an ILPG distribution system is the loss of primary containment (LOPC), which occurs when liquid spills from a pressurized container or pipeline. This can lead to rapid dispersion and evaporation of the substance (Rasbash, 2010). Fire, explosions and toxic release are considered major consequences of ILPG leaks (Kumar et al., 2024; Nyanana et al., 2024). ILPG liquid can cause cold burns upon contact with the skin or eyes, and further, inhaling LPG vapour at high concentrations may lead to fainting or death. Exposure to LPG vapour can also cause irritation of the nose and throat, headaches, nausea, vomiting, dizziness, and loss of consciousness (Nyanana et al., 2024). The primary cause of death following LPG exposure has typically been attributed to asphyxia due to hypoxia (Iacoponi et al., 2024). The fire risk of the ILPG distribution system can be divided into three segments including (1) ILPG tank that includes filling and safety systems, such as an automatic fill limiter, excess-flow valve, non-return valve, and pressure relief valve; (2) the procedure for preparing the fuel mixture (Zheng & Chen, 2011); and (3) the processes involved in fuel delivery, gas/air mixture formation, and injection control (Lam & Cruz, 2018; Zheng & Chen, 2011).

An explosion results from the rapid release of energy, as energy release is generally sudden, which creates a localized accumulation of energy. This energy is then dissipated by a variety of mechanisms, including formation of a pressure wave, projectiles, thermal radiation and acoustic energy (Kumar et al., 2024). If an explosion occurs in LPG, the energy causes the gas to expand rapidly, forcing back the surrounding gas and generating a pressure wave that rapidly propagates

outward from the blast source. Figure 1 can be used as a process mapping tool in the identification of risks of fire or explosions, such as Boiling Liquid Expanding Vapour Explosion (BLEVE), Vapour Cloud Explosion (VCE), etc. (Beheshti et al., 2018).

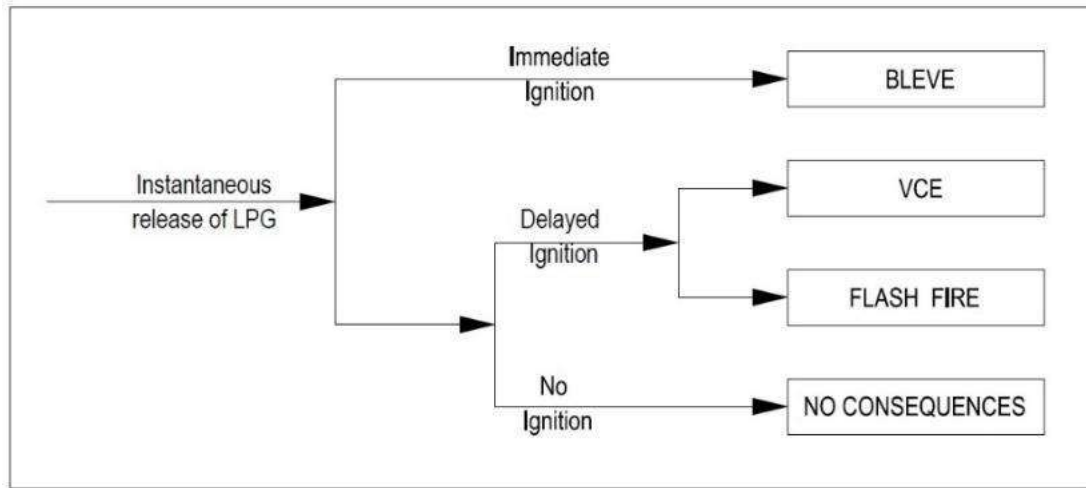


Figure 1: Consequences of LPG leaks

Source: Beheshti et al., 2018

These scenarios are generally recognized as the energy from an explosion poses a risk during the processes of energy dissipation and dispersion (Tauseef et al., 2010). Research by Roberts & Chan (2010) has revealed that 1744 major industrial accidents have occurred due to BLEVE. Indeed, some significant tragedies have been caused by these explosions, which often lead to fires and secondary incidents (Tauseef & Abbasi, 2013). While it is impossible to eliminate the risks associated with LPG installations, the level of safety largely depends on the reliability of safety devices (Kumar et al., 2024).

Lack of awareness among people regarding safety measures, fire escape plans, fire databases and increased defects of cylinders and accessories has led to a rise in ILPG related burns (Zheng & Chen, 2011; Bansal et al., 2012; Pradhan et al., 2017). Usage of recommended standard pipes, good quality accessories and gas cylinders, increasing supply to meet the demands, standard operation procedures, proper design and distancing to keep cylinders, and personnel training are discussed in the literature to prevent ILPG related burns and accidents inside the kitchens (Tauseef & Abbasi, 2013).

Literature showed hotels kitchen are more prone to accidents due to presence of cooking oil and that makes an ideal combination for fire hazards (Kumar et al., 2024; Nyanana et al., 2024). Further, low- and high-voltage electrical systems, gas installations, boilers, and even tanks containing liquid petroleum products are other sources for fire risks (Bansal et al., 2012; Pradhan et al., 2017). Additionally, the presence of larger and more complex units in crowded hotel kitchens can increase the potential for significant damage (Malviya & Rushaid, 2018). Further, large-scale pool fires have high risk consequences related to hotel segment accidents (Rasbash, 2010).

Therefore, to assess the potential fire and explosion hazards associated with the ILPG systems in hotels, it is essential to consider specific risk-causing factors. They can be mainly segmented as process related and system related risks (Bribián et al., 2009). While the process related risk is mainly due to deviations in operations procedures, maintenance issues, design issues, competency issues, process safeguarding & installation issues (Bansal et al., 2012), System-related risks are mainly due to issues in the distribution system or primarily LOPC (Bruce et al., 2015). Literature highlighted many factors, and they are summarized in Table 2.

Table 2: Most highlighted risk causing factors

Risk factor	Literature source
1. Location of the Cylinder Manifold	Selvan, 2016; Setiyo, 2016; Tauseef, 2017; Park, 2015; Qian, 2021; Sarker, 2022; Hadzihafizovic, 2024; SLS 1196; BS 6891; NFPA 54; COP1
2. Cylinder Manifold Design	Sridhar et al., 2016; Moorthy & Srinivas, 2018; Kiran & Sruthi, 2018; Shevtsov, 2018; Majerczyk, 2011; Mohsen et al., 2023; BS 6891; SLS 1196; NFPA 54; COP1
3. Cylinder Manifold Operations	Jafarzadeh et al., 2016; Menon, 2019; Shevtsov, 2018; Rissman et al., 2020; Diab et al., 2024; BS 6891; SLS 1196; NFPA 54; COP1
4. Audit, Assessment and Monitoring	Rissman et al., 2020; Hasan & Ahammed, 2021; Nyabuto et al., 2020; Dewantari et al., 2023; Thürer et al., 2023; BS 6891; SLS 1196; NFPA 54; COP1
5. Cylinder Stacking Requirement (if the area is not enough)	Rissman et al., 2020; Chatelier, 2021; Drgoňa et al., 2020; Kim et al., 2018; Kora, 2023; Lin, 2018; BS 6891; SLS 1196; NFPA 54; COP1
6. Cylinder Stack Sizes	Derhami et al., 2016; Yener & Yazgan, 2019; Molina et al., 2018; Sawicki & Sawicka, 2023; Silalahi et al., 2022; BS 6891; SLS 1196; NFPA 54; COP1
7. Ventilation to the Cylinder Manifolds	Brzezinska, 2016; Lin, 2018; Kim et al., 2018; Drgoňa et al., 2020; BS 6891; SLS 1196; NFPA 54; COP1
8. Vehicle Movements near the LPG Supply System	Chakraborty & Saha, 2024; Chawla & Chawla, 2023; Martin et al., 2023; Papadopoulos et al., 2018; Ulutaş et al., 2023; Viskup et al., 2019; BS 6891
9. Fire Protection	Jiao, 2023; Brzezinska, 2016; Shevtsov et al., 2018b; Yener & Yazgan, 2019; Kim et al., 2018; BS 6891; SLS 1196; NFPA 54; COP1
10. Maintenance of ILPG Supply System	Sridhar et al., 2016; Moorthy & Srinivas, 2018; Kiran & Sruthi, 2018; Shevtsov, 2018; Majerczyk, 2011; BS 6891; SLS 1196; NFPA 54; COP1
11. Training & Emergency Procedures	Shevtsov et al., 2018b; Malviya & Rashid, 2017; Park, 2017; BS 6891; SLS 1196; NFPA 54; COP1
12. Electrical & Pneumatic Installation	Kiran & Sruthi, 2018; Shevtsov, 2018; Majerczyk, 2011; Mohsen et al., 2023; BS 6891; SLS 1196; NFPA 54; COP1

3. Research Methodology

3.1 ESTABLISHING ILPG RISK DOMAIN

With the rapid increase in the number of academic journals, congresses, and other publications in recent years, scientific knowledge has drastically increased (Kraus et al., 2020). Therefore, it is difficult to follow the state, new developments, and evolution and to categorize the body of knowledge in a given field using traditional literature review methods (Öztürk et al., 2024). Therefore, many researchers have used bibliometric analysis, which enables the review of literature relevant to a particular research field systematically. Therefore, bibliometric analysis was carried out to search for risk causing factors related to ILPG from the impactful publications from 2000 to 2024. VOSviewer software tool was used to analyze the identified literature sources. The following steps are followed to establish the ILPG risk domain.

- Step 1

Literature review was conducted using Scopus and WLPGA articles. The title search was conducted using the search string of "LPG Safety" or "LPG Risk." The selected publications were further filtered using;

(a) Papers published between 2010 and 2024,

(b) Papers available in online databases,

(c) Papers written in English.

Based on the above filtering process, a total of 526 research papers were identified.

- Step 2

Abstracts of the identified 526 papers were reviewed manually, and those identified as relevant to the risks of LPG installation were selected to be retrieved and reviewed in full. Thus, abstracts focus on hotels, restaurants, catering facilities, event & conference facilities, where LPG cylinder manifolds are used for cooking, have been selected to identify ILPG risk causing factors in the hotel segment. However, papers focus on the use of LPG cylinder manifolds for construction, manufacturing, such as tile, rubber, etc., confectionery, chemical processing, textiles, auto gas stations, and apartment complexes have not been utilized for this research. Based on the above search results, a total of 82 papers were selected for detailed analysis.

- Step 3

Qualitative content analysis was conducted using the NVivo software tool to identify patterns and similarities of factors. This method involves a detailed and systematic examination of a body of material to uncover themes, trends, or biases (Zou et al., 2011). It is recognized as a systematic and replicable technique for condensing large volumes of text into meaningful content categories based on clear coding rules (Stemler, 2001). Eighty-two research papers were categorized based on several key aspects, including their type, data collection methods, analytical techniques, research objectives, key findings, contributions, limitations, year of

publication, and country of origin. Using NVivo, 10 main factors and 78 sub-variables were identified.

- Step 4

The identified 10 main risk factors and 78 sub-factors were presented with the aid of a questionnaire to 20 experts for confirmation to validate the literature findings.

These 20 experts were divided into two groups. The most senior-level experts with more than twenty years of experience in the LPG industry available in the field of LPG safety, based on the "LPG suppliers' consultant registration list", were selected as group one. A total of ten members were included in this group. The second group comprised operational-level field experts in the LPG industry. A total of ten members were invited to the discussion. Table 3 shows their profiles.

Table 3: Profile of experts

Expert Group and Name	Description	No. of years of experience in the field of LPG
FG1_E1	Working as a Consultant	10 years - local and 10 years - foreign
FG1_E2	Working as a Consultant	30 years - local
FG1_E3	Working as a Consultant	27 years - local
FG1_E4	Retired Consultant	35 years - local
FG1_E5	Working as a Consultant	30 years - local
FG1_E6	Working as a Consultant	31 years - local
FG1_E7	Working as a Consultant	20 years - local
FG1_E8	Working as a Consultant	10 years - local
FG1_E9	Retired Consultant	35 years - local
FG1_E10	Working as a Consultant	30 years - local
FG2_E11	Working as an Engineer	11 years - local
FG2_E12	Working as a Safety Manager	8 years - local
FG2_E13	Working as a Project Engineer	18 years - local
FG2_E14	Working as an HSE Manager	22 years - local
FG2_E15	Working as a Safety Engineer	30 years - local
FG2_E16	Working as a Process Engineer	24 years - local
FG2_E17	Working as a Consultant	13 years - local

FG2_E18	Working as a Project Manager	10 years - local
FG2_E19	Working as a Technical Manager	10 years - local
FG2_E20	Working as an Engineer	20 years - local

During this task, two new factors were added to the list of main risk-causing factors, increasing the initial 10 factors to 12. Therefore, to identify the sub factors for the newly added two main risk causing factors, another round of literature survey was conducted by referring to the keywords of the factors. A total of 5 new sub factors were identified under each new factor, based on 8 journal papers published after 2010. These were validated through the same experts in the focus group.

3.2 ASSESS THE RISKS

3.2.1 Data Collection

A questionnaire survey was conducted to obtain data to assess the impact and probability of those established risk factors on ILPG safety in the hotel segment in Sri Lanka. Data were collected from the industry practitioners with the aid of qualitative terms as "Low, Medium, High". Accordingly, respondents were asked to rank the 88 risk factors according to the above scale provided.

Consultants, Site Managers, Engineers, Safety Professionals, LPG accessory suppliers and ILPG installation contractors were selected based on the database maintained by LPG suppliers. A total of 400 questionnaires were emailed, of which 198 respondents fully completed the whole survey. Another 100 emails were sent to LPG suppliers, where their staff also contributed to completing the questionnaire survey. A total of 198 were received, with a 49% response rate.

3.2.2. Risk Quantification

Risk ratings obtained for (impact) and (2) probability using qualitative terms of "low", "moderate and "high" were converted to quantitative terms using fuzzylogy. The conversion process is discussed in the following steps.

- Step 1

In order to derive the potential risk levels using those two variables (i.e. impact and probability), the Mandani-style if-and-then fuzzy rules used by Han (2005) and Dikmen et al. (2007) were applied. Since these rules are more intuitive and easier to understand, they are well-suited to expert system applications where the rules are created from human expert knowledge, which is more acceptable and widespread (Kaur and Kaur,2012; Hishammuddin 2008), and hence used for this study.

- Step 2

Trapezoidal fuzzy membership function is used to diffuzified linguistic values into quantitative numbers (i.e. crisp values) as applied by Chen (1997) and further by Yener in 2007. Figure 2 illustrates a typical trapezoidal fuzzy membership function.

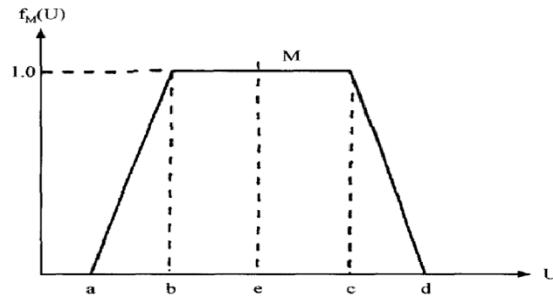


Figure 2: A typical trapezoidal fuzzy membership function

4. Results and Discussion

4.1 ILPG RISK DOMAIN FOR HOTEL SEGMENT

ILPG risks identified through literature and focus group interviews were used to establish the ILPG risk domain for the hotel segment in Sri Lanka, which consists of 12 main risk causing factors and 85 sub risk causing factors (Table 4).

Table 4: ILPG Risk Domain

Main Risk Causing Factors	Sub Risk Causing Factors
1. Location of the cylinder manifold	1.1 Base/floor conditions, 1.2 LPG storage area, 1.3 Escape and access routes, 1.4 LPG cylinder storage separation distance, 1.5 The zone boundaries, 1.6 Construction of robust fences, 1.7 Escape doors, 1.8 Separation distance to boundary, 1.9 Fire extinguishers placements, 1.10 Access Controls, 1.11 Adjuscent drains pits, 1.12 Weather Protection, 1.13 LPG storage area identification
2. Cylinder manifold design	2.1 Equipment Selection, 2.2 Design Code, 2.3 Basement Dimensions, 2.4 Safety Distances, 2.5 Cylinder markings, 2.6 Safety Devices Installations, 2.7 Number of cylinders in the manifold
3. Cylinder manifold operations	3.1 Availability of operation procedures at site, 3.2 Emergency procedures/ Call list display, 3.3 Warning signs and emergency action plan, 3.4 The failure to adhere to internal policies, 3.5 Risks arising from catastrophic events, 3.6 Health and safety guidelines, 3.7 ESD Functionality, Skill Operators
4. Audit assessment and monitoring	4.1 Conducting Health & Safety internal audits, 4.2 Conducting Health & Safety external audits, 4.3 Conducting specific risk related audits, 4.4 Equipment testing and inspection audits, 4.5 Workplace exposure monitoring, 4.6 Fire and LPG leak detection systems, 4.7 Legal compliance audit, 4.8 Management review audits, 4.9 Risk assessments

5. Cylinder stacking requirement (if the area is not enough)	5.1 Cylinder stacking storage, 5.2 Segregation of liquid and vapor withdrawal cylinders, 5.3 Filled and empty cylinder separation
6. Cylinder stack sizes	6.1 Capacity of Stacking, 6.2 Gangways between non- palletized stacks
7. Ventilation to the cylinder manifolds	7.1 Availability of ventilation, 7.2 Placement of ventilation openings, 7.3 Entrance, exit doors and windows gates and fences, 7.4 Ventilation openings availability from at least one side of the wall, 7.5 Storage ventilation protection, 7.6 Full cylinder stand-by storage ventilation, 7.7 Empty cylinder storage ventilation
8. Vehicle movements near the LPG supply system	8.1 Accessibility of delivery vehicles to site, 8.2 Maintenance of vehicles related to LPG supply system, 8.3 Internal traffic control, 8.4 Vehicle drivers
9. Fire protection	9.1 Fire approvals, 9.2 Fire extinguishers, 9.3 Fire brigade access to site, 9.4 Fire hydrants, 9.5 Other available fire extinguishing mechanisms, 9.6 Fire risk assessment, 9.7 Fire drills
10. Maintenance of ILPG supply system	10.1 Written schemes of examinations, 10.2 Maintenance scope, 10.3 Maintenance scheduling e.g. Rosters, 10.4 Maintenance records, 10.5 Cylinder testing, 10.6 Proactive Maintenance Plan
11. Training & Emergency Procedures	11.1 Operational trainings, 11.2 Conduct emergency training practical, 11.3 Conduct emergency drills, Conducting first aid trainings, 11.4 Staff members are aware of how to report emergencies, 11.5 Emergency procedures, 11.6 Gas leak detection system, 11.7 Use of necessary PPE, 11.8 Fire exits are clearly shown with directions, 11.9 Assembly point in case of emergency, 11.10 Emergency response plan, 11.11 Potential incident reporting
12. Electrical & Pneumatic installation	12.1 Hazardous electrical equipment with improper installation, 12.2 Electrical equipment's contact with metal surfaces, 12.3 Fires due to faulty wiring, 12.4 Ignition of fires or explosions due to electrical contact with potentially flammable, 12.5 Exposed electrical parts, 12.6 Inadequate wiring, Explosion proof mechanical installations, Pneumatic Installation inspection and maintenance

4.2 RISK ASSESSMENT USING FUZZYLOGIC

As per the Mandani-style if-and-then fuzzy rules, the potential levels for each risk causing factor were assessed (Table 5).

Table 5: Potential Risk Levels of Risk Risk-Causing Factors

Rule	If then Rule for Risk Situations	Potential Risk
1	If expected probability for an incident is low and the expected impact of the incident is also low	VERY LOW

2	If expected probability for an incident is low and the expected impact of the incident is medium	LOW
3	If expected probability for an incident is low and the expected impact of the incident is high	MEDIUM
4	If expected probability for an incident is medium and the expected impact of the incident is low	LOW
5	If expected probability for an incident is medium and the expected impact of the incident is medium	MEDIUM
6	If expected probability for an incident is medium and the expected impact of the incident is high	HIGH
7	If expected probability for an incident is high and the expected impact of the incident is low	MEDIUM
8	If expected probability for an incident is high and the expected impact of the incident is medium	HIGH
9	If expected probability for an incident is high and the expected impact of the incident is high	VERY HIGH

Trapezoidal fuzzy membership function was applied to difuzzified "very low", "low", "medium", "high", and "very high" to crisp values. The corresponding crisp values are shown in Table 6.

Table 6: Diffuzified Values

Linguistic Terms	Crisp Values
Very low (VL)	0.075
Low (L)	0.275
Medium (M)	0.5
High (H)	0.725
Very high (VH)	0.925

- Step 3

Based on the questionnaire results, ILPG risks are assessed using derived crisp values, risk rating matrix (Figure 3) was developed with five risk categories (Table 6). Results shows Exposed electrical parts, flammable gas contact with electrical circuits, capacity of cylinder stacking, hazardous electrical equipment's without installation, explosion-proof mechanical installations, provision of ventilation, faulty wiring, emergency procedures, compliance with the design code and availability of fire extinguishers identified as critical risk causing factors ILPG risk in hotels in Sri Lanka and relate to the "Very High" category. Figure 3 shows the respective risk category of each risk causing factor. As a summary, out of 88 risk factors, 9 factors have very low vulnerability, 23 factors have low vulnerability, 34 factors have

medium vulnerability, 13 factors have high vulnerability, and 9 factors are very highly vulnerable.

Expected probability	HIGH	MEDIUM 1.8,11.11,11.12,11.13,3.1 3.2,3.4,3.5,3.6,4.1,4.4,9.3	HIGH 1.10,2.1,2.5,2.6, 3.8,4.6	VERY HIGH 12.1,12.3,12.4, 12.5,12.6,11.5,6.1, 2.2,9.2
	MEDIUM	LOW 1.1,1.2,1.3,1.4,1.5,1.6 1.9,2.3,2.4,2.7,3.3,4.2	MEDIUM 4.9,5.3,5.5,6.2,7.2, 7.4,7.5,7.6,9.1,9.2	HIGH 5.1, 5.2, 7.1, 9.5, 11.6, 11.7, 11.8
	LOW	VERY LOW 6.2,8.3,6.1,4.5,1.13 8.1,3.6,4.7,11.3	LOW 4.3,4.5,4.7,4.8,7.3, 8.3,8.4,8.5,10.4	MEDIUM 9.4,10.1,10.2,10.3,10.5, 11.1,11.3,11.4,11.5,11.9
		LOW	MEDIUM	HIGH
Expected impact				

Figure 3: Risk rating matrix

5. Conclusion

A thorough investigation into the safety of industrial liquefied petroleum gas (ILPG) was carried out. Following a literature review and focus group discussions, a risk domain for ILPG was established, comprising 12 primary risk factors and 88 sub factors. The risks associated with these factors were quantified using fuzzy logic. A questionnaire survey with a sample of industry LPG practitioners was conducted to obtain data. The results indicated that critical risk factors for LPG installations in the hotels segment of Sri Lanka include exposed electrical components, flammable gas interaction with electrical circuits, cylinder stacking capacity, improperly installed hazardous electrical equipment, explosion-proof mechanical systems, adequate ventilation, faulty wiring, emergency procedures, adherence to design codes, and the availability of fire extinguishers are the most vulnerable risks, while Gangways between non- palletized stacks, Internal traffic control, Capacity of stacking, Work place exposure monitoring, LPG storage area identification, Accessibility of delivery vehicles to site, Health and safety guidelines, Legal compliance audit and Conducting first aid trainings are least vulnerable risks.

This research addresses the complexities associated with ILPG installations by pinpointing prevalent risks. The findings of this research could be effectively used

for taking proactive measures to minimize ILPG accidents in the hotel segment of Sri Lanka.

6. References

- Amuzuvi, C. K., & Ashilevi, P. K. (2016). Making the use and storage of liquefied petroleum gas safe by using electronic gas leakage detectors – Opportunities and threats. *GHANA JOURNAL OF TECHNOLOGY*, 1(1), 12–20. <http://www2.umat.edu.gh/qjt/index.php/qjt/article/download/2/4>
- Bansal, M., Saini, R., & Khatod, D. (2012). Development of cooking sector in rural areas in India—A review. *Renewable and Sustainable Energy Reviews*, 17, 44–53. <https://doi.org/10.1016/j.rser.2012.09.014>
- Basnayake, J., & De Silva, N. (2024). Development of Liquefied Petroleum Gas (LPG) Safety Risk Prediction Model for the hotel sector in Sri Lanka. *International Journal of Safety and Security Engineering*, 14(4), 1049–1060. <https://doi.org/10.18280/ijssse.140404>
- Beheshti, M. H., Dehghan, S. F., Hajizadeh, R., MohammadJafari, S., & Koohpaei, A. (2018b). Modelling the consequences of explosion, fire and gas leakage in domestic cylinders containing LPG. *Annals of Medical and Health Sciences Research*. <https://www.amhsr.org/articles/modelling-the-consequences-of-explosion-fire-and-gas-leakage-in-domestic-cylinders-containing-lpg.pdf>
- Bribián, I. Z., Usón, A. A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, 44(12), 2510–2520. <https://doi.org/10.1016/j.buildenv.2009.05.001>
- Bruce N., Pope D., Rehfuess E, Balakrishnan K., Adair-Rohani H., Dora C. (2015), WHO indoor air quality guidelines on household fuel combustion: Strategy implications of new evidence on interventions and exposure risk functions, *Atmospheric Environment*, Vol. 106, pp. 451-457.
- Carlos F. Gould, J. U. (2018). LPG as a clean cooking fuel: Adoption, use, and impact in rural India. *Energy Policy*, 395-408. doi:doi.org/10.1016/j.enpol.2018.07.042.
- Chakraborty, A., Roy, S., & Banerjee, R. (2015). An experimental based ANN approach in mapping performance-emission characteristics of a diesel engine operating in dual-fuel mode with LPG. *Journal of Natural Gas Science and Engineering*, 28, 15–30. <https://doi.org/10.1016/j.jngse.2015.11.024>
- Chakraborty, S., & Saha, A. K. (2024). SELECTION OF FORKLIFT UNIT FOR TRANSPORT HANDLING USING INTEGRATED MCDM UNDER NEUTROSOPHIC ENVIRONMENT. *Facta Universitatis Series Mechanical Engineering*, 235. <https://doi.org/10.22190/fume220620039c>
- Chatelier, J. Y. (2021). "Creating a rule framework for the green revolution in shipping industry" internal & territorial waters. *Ciencia Y Tecnología De Buques*, 15(29), 71–88. <https://doi.org/10.25043/19098642.222>
- Chawla, S., & Chawla, H. (2023). A comparative study on monitoring of LPG gas cylinders to prevent hazards. *LPG Cylinders and Associated Equipment*, 1479–1484. <https://doi.org/10.1109/icacite57410.2023.10182432>
- COP1 UK. (2017). Bulk LPG Storage at Fixed Installations, Design, Installation and Operation of Vessels Located Above Ground. CODE OF PRACTICE 1 - PART 1.
- D. J. Rasbash(2010), Review of Explosion and Fire Hazard of Liquefied Petroleum Gas, *Fire Safety Journal* 2, (2010/11) 223 – 236, doi: Review of Explosion and Fire Hazard of Liquefied Petroleum Gas
- Derhami, S., Smith, J. S., & Gue, K. R. (2016). Optimising space utilisation in block stacking warehouses. *International Journal of Production Research*, 55(21), 6436–6452. <https://doi.org/10.1080/00207543.2016.1154216>

- Dewantari, N. M., Ferdiansyah, M., Herlina, L., Mariawati, A. S., & Umyati, A. (2023). Risk analysis and safety measures: JSA, HIRA, and FTA in LPG distribution. *Journal Industrial Serviss*, 9(2), 247. <https://doi.org/10.36055/jiss.v9i2.21847>
- Diab, A., Hassan, A., Awad, A., Zaher, S., Botaly, Y., Sherif, N., & Bassyouni, M. (2024). Simulation and hazard operability analysis of liquefied petroleum gas plant: A case study. *International Journal of Industry and Sustainable Development*, 5(1), 44–78. <https://doi.org/10.21608/ijisd.2024.257658.1044>
- Drgoňa, J., Arroyo, J., Figueroa, I. C., Blum, D., Arendt, K., Kim, D., Ollé, E. P., Oravec, J., Wetter, M., Vrabie, D. L., & Helsen, L. (2020). All you need to know about model predictive control for buildings. *Annual Reviews in Control*, 50, 190–232. <https://doi.org/10.1016/j.arcontrol.2020.09.001>
- Guidelines for Good Safety Practices in LPG Industry. World Liquefied Petroleum Gas Association WLPGA 2018.
- Guidelines for Good Safety Practices in LPG Industry. World Liquefied Petroleum Gas Association (WLPGA, UNEP 2020)
- Gupta, A. (2000). Flame characteristics with high temperature air combustion. 38th Aerospace Sciences Meeting and Exhibit. <https://doi.org/10.2514/6.2000-593>
- Hadzihafizovic, D. (2024). LPG Cylinders and Associated Equipment.
- Hasan, M. Z., & Ahammed, R. (2021). Application of Industry 4.0 in LPG condition monitoring and emergency systems using IoT approach. *World Journal of Engineering*, 18(6), 971–984. <https://doi.org/10.1108/wje-06-2020-0218>
- Hishammuddin, A. (2008). Fuzzy methodologies for automated university. Ph.D. Thesis. University of Nottingham.
- Iacononi, N., Del Duca, F., Marcacci, I., Occhipinti, C., Napoletano, G., Spadazzi, F., La Russa, R., & Maiese, A. (2024). Butane-related deaths in post-mortem investigations: A systematic review. *Legal Medicine*, 69, 102442. <https://doi.org/10.1016/j.legalmed.2024.102442>
- Incidents Reports and KPI report, Litro Gas Lanka Limited, 2024. www.litrogas.com
- Irem Dikmen, M. T. (2007). Using fuzzy risk assessment to rate cost overrun risk in international construction projects. *International Journal of Project Management*, 494–505. doi:<https://doi.org/10.1016/j.ijproman.2006.12.002>.
- Jafarzadeh, S., Paltrinieri, N., Utne, I. B., & Ellingsen, H. (2016). LNG-fuelled fishing vessels: A systems engineering approach. *Transportation Research Part D Transport and Environment*, 50, 202–222. <https://doi.org/10.1016/j.trd.2016.10.032>
- Jiao, Y. C. (2023). Simulation of scenario characteristics of LPG tank explosion accident and its contribution to emergency planning: A case study. *Journal of Loss Prevention in the Process Industries*,. doi: <https://doi.org/10.1016/j.jlp.2023.105066>
- Jung, S., Woo, J., & Kang, C. (2020). Analysis of severe industrial accidents caused by hazardous chemicals in South Korea from January 2008 to June 2018. *Safety Science*, 124, 104580. <https://doi.org/10.1016/j.ssci.2019.104580>
- Kim, J., Doh, D., & Choi, B. C. (2018). Evaluation of the ventilation safety requirements for the fuel gas supply system room of a gas-fueled vessel: Simulated leaks of methane and propane. *Journal of Mechanical Science and Technology*, 32(11), 5521–5532. <https://doi.org/10.1007/s12206-018-1050-7>
- Kiran, C. S., & Sruthi, J. (2018). Design and Finite Element Analysis of Domestic LPG Cylinder using ANSYS Workbench. *CVR Journal of Science & Technology*, 14(01), 97–101. <https://doi.org/10.32377/cvrjst1419>
- Kora, A. J. (2023). A domestic pressure cooker mediated, facile autoclaving method for the synthesis of silver nanoparticles. *MethodsX*, 11, 102438. <https://doi.org/10.1016/j.mex.2023.102438>

- Kraus, S., Breier, M., & Dasí-Rodríguez, S. (2020). The art of crafting a systematic literature review in entrepreneurship research. *International Entrepreneurship and Management Journal*, 16(3), 1023–1042. <https://doi.org/10.1007/s11365-020-00635-4>
- Kumar, M., Yadav, H., & Roy, A. K. (2024b). Assessment of impact loads on structures due to LPG gas leakage and explosion—a numerical modelling approach. *Asian Journal of Civil Engineering*, 25(6), 4949–4971. <https://doi.org/10.1007/s42107-024-01091-z>
- Lam, C., & Cruz, A. (2018). Risk analysis for consumer-level utility gas and liquefied petroleum gas incidents using probabilistic network modeling: A case study of gas incidents in Japan. *Reliability Engineering & System Safety*, 185, 198–212. <https://doi.org/10.1016/j.res.2018.12.008>
- Lin, F. (2018). Construction network ventilation system for underground LPG storage cavern. *Civil Engineering Journal*, 4(7), 1521. <https://doi.org/10.28991/cej-0309192>
- Martin, N., Broumi, S., Sudha, S., & Priya, R. (2023). Neutrosophic MARCOS in decision making on smart manufacturing system. *Neutrosophic Systems With Applications*, 4, 12–32. <https://doi.org/10.61356/j.nswa.2023.14>
- Menon, N. S. (2019). Loss prevention in hydrocarbon facilities. *Journal of Oil Gas and Petrochemical Sciences*, 2(1), 26–28. <https://doi.org/10.30881/jogps.00021>
- Mohsen, M. J., Al-Dawody, M. F., Jamshed, W., Din, S. M. E., Abdalla, N. S. E., Abd-Elmonem, A., Iqbal, A., & Shah, H. H. (2023). Experimental and numerical study of using of LPG on characteristics of dual fuel diesel engine under variable compression ratio. *Arabian Journal of Chemistry*, 16(8), 104899. <https://doi.org/10.1016/j.arabjc.2023.104899>
- Molina, E., Horvath, L., & White, M. S. (2018). Investigation of pallet stacking pattern on unit load bridging. *Packaging Technology and Science*, 31(10), 653–663. <https://doi.org/10.1002/pts.2406>
- Moorthy, C. V. K. N. S. N., & Srinivas, V. (2018). Discretization analysis of a composite GFRP cylinder. *International Journal of Engineering & Technology*, 7(4.5), 277. <https://doi.org/10.14419/ijet.v7i4.5.20088>
- NFPA54/58. (2024). Liquefied Petroleum Gas Code
- Nilambar Bariha, I. M. (2016). Fire and explosion hazard analysis during surface transport of liquefied petroleum gas (LPG): A case study of LPG truck tanker accident in Kannur, Kerala, India,. *Journal of Loss Prevention in the Process Industries*, 449–460. [doi:doi.org/10.1016/j.jlp.2016.01.020](https://doi.org/10.1016/j.jlp.2016.01.020)
- Nyabuto, J. K., Mburu, C., & Gichuhi, M. (2020). Evaluation of occupational safety and health practices by LPG cylinder retailers in Kiambu County, Kenya. *International Journal of Scientific and Research Publications*, 10(7), 635–644. <https://doi.org/10.29322/ijsrp.10.07.2020.p10368>
- Nyanana, A., Rwanyuma, L., Chiwanga, F., Mbwambo, J., Pallangyo, C., Tarimo, U., Spangler, S. A., & Thompson, L. M. (2024b). Cooking-related burn injuries at Muhimbili National hospital and knowledge about safe use of liquefied petroleum gas in Dar Es Salaam, Tanzania: A cross-sectional study. *Burns Open*, 8(3), 211–216. <https://doi.org/10.1016/j.burnso.2024.05.002>
- Öztürk, O., Kocaman, R., & Kanbach, D. K. (2024). How to design bibliometric research: an overview and a framework proposal. *Review of Managerial Science*, 18(11), 3333–3361. <https://doi.org/10.1007/s11846-024-00738-0>
- Pak, S., Jung, S., Roh, C., & Kang, C. (2019). Case Studies for Dangerous Dust Explosions in South Korea during Recent Years. *Sustainability*, 11(18), 4888. <https://doi.org/10.3390/su11184888>
- Paliwal, G., Agrawal, K., Srivastava, R. K., & Sharma, S. (2014b). Domestic liquefied petroleum gas: Are we using a kitchen bomb? *Burns*, 40(6), 1219–1224. <https://doi.org/10.1016/j.burns.2013.12.023>
- Papadopoulos, G., Keramydas, C., Ntziachristos, L., Lo, T., Ng, K., Wong, H. A., & Wong, K. K. (2018). Emission factors for a taxi fleet operating on liquefied petroleum gas (LPG)

- as a function of speed and road slope. *Frontiers in Mechanical Engineering*, 4. <https://doi.org/10.3389/fmech.2018.00019>
- Park, M., Elsafty, N., & Zhu, Z. (2015). Hardhat-Wearing detection for enhancing On-Site safety of construction workers. *Journal of Construction Engineering and Management*, 141(9). [https://doi.org/10.1061/\(asce\)co.1943-7862.0000974](https://doi.org/10.1061/(asce)co.1943-7862.0000974)
- Pradhan, P., Mishra, P. C., & Samantaray, B. B. (2017). Performance and emission analysis of a novel porous radiant burner for domestic cooking application. *Heat Transfer Engineering*, 39(9), 784–793. <https://doi.org/10.1080/01457632.2017.1341231>
- Qian, X., Zhang, R., Zhang, Q., Yuan, M., & Zhao, Y. (2021). Cause analysis of the Large-Scale LPG explosion accident based on key investigation technology: a case study. *ACS Omega*, 6(31), 20644–20656. <https://doi.org/10.1021/acsomega.1c02837>
- Rajmohan, K., & Weerahewa, J. (2010). Household energy consumption patterns in Sri Lanka. *Sri Lankan Journal of Agricultural Economics*, 9(0), 55. <https://doi.org/10.4038/sjae.v9i0.1833>
- Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S. A., Roy, J., Fennell, P., Cremmins, B., Blank, T. K., Hone, D., Williams, E. D., De La Rue Du Can, S., . . . Helseth, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy*, 266, 114848. <https://doi.org/10.1016/j.apenergy.2020.114848>
- Roberts, D., & Chan, D. H. (2000). Fires in hotel rooms and scenario predictions. *International Journal of Contemporary Hospitality Management*, 12(1), 37–45. <https://doi.org/10.1108/09596110010305028>
- Rupesh Kumar Malviya Muhamed Rushaid(2018), Consequence Analysis of LPG Storage Tank, *Materials Today: Proceedings* 5 (2018) 4359–4367, doi: 10.1016_j.matpr.2017.12.003
- Sarker, M. S. (2022). Optimization of Maintenance Management Framework in LPG Cylinder Manufacturing. *Gazipur*. doi:http://103.82.172.44:8080/xmlui/handle/123456789/1829
- Sarvestani, K. A. (2021). LPG Storage Tank Accidents: Initiating Events, Causes, Scenarios, and Consequences. *Journal of Failure Analysis and Loss Prevention*, 1305–1314. doi:doi.org/10.1007/s11668-021-01174-y
- Sawicki, P., & Sawicka, H. (2023). Design optimization of stacked pallet load units. *Applied Sciences*, 13(4), 2153. <https://doi.org/10.3390/app13042153>
- Selvan, R. (2016). Study of hazard identification and consequence assessment of flammable gas facilities and development of methodology to find failure data. Retrieved from <http://hdl.handle.net/123456789/2610>
- Setiyo, M. W. (2016). Performance of gasoline/LPG BI-fuel engine of manifold absolute pressure sensor (MAPS) variations feedback. *ARNP Journal of Engineering and Applied Sciences*, 11(7), 4707–4712. Retrieved from <https://repository.petra.ac.id/17333/>
- Shevtsov, S. A., Kargashilov, D. V., & Shutkin, A. N. (2018). Fire and explosion safe technology of storage and regasification of liquefied petroleum gas. *Chemical and Petroleum Engineering*, 54(1–2), 38–40. <https://doi.org/10.1007/s10556-018-0435-x>
- Silalahi, D. F., Gunawan, D., Wahyuni, E., Dipayana, G. F., Hardhi, M., Winofa, N. C., Ramadhan, R. A., & Hidayat, T. (2022). Indonesia Post-Pandemic Outlook: Strategy towards Net-Zero Emissions by 2060 from the Renewables and Carbon-Neutral Energy Perspectives. In Penerbit BRIN eBooks. <https://doi.org/10.55981/brin.562>
- SLS 712 ; SLS1196 Part 2. (n.d.). Specification for Liquefied Petroleum Gas 2021, Bulk LPG Installation 2000. Sri Lanka Standard Institution.
- SLS 712. (2021). Specification for Liquefied Petroleum Gas. Sri Lanka Standards Institution.

- Sridhar, R., Shanmugasundar, G., & Srithar, A. (2016). A Geometrical Modular Design for Handling of LPG Cylinders using Nested Kinematic Robotic Gripper. *Indian Journal of Science and Technology*, 9(48). <https://doi.org/10.17485/ijst/2016/v9i48/108474>
- Stemler, S. (2001). An Introduction to Content Analysis. ERIC Digest. ERIC Clearinghouse on Assessment and Evaluation College Park MD. <http://files.eric.ed.gov/fulltext/ED458218.pdf>
- Tauseef, S. M. (2017). The risk of domino effect associated with the storage of liquefied petroleum gas (LPG) and the safety codes for accident prevention. *International Journal of Engineering, Science and Mathematics*, 6(7), 456-482. Retrieved from <http://www.ijesm.co.in>
- Tauseef, S. M., Abbasi, T., & Abbasi, S. A. (2010). Risks of fire and explosion associated with the increasing use of liquefied petroleum gas. *Journal of Failure Analysis and Prevention*, 10(4), 322-333. <https://doi.org/10.1007/s11668-010-9360-9>
- Tauseef, S., Premalatha, M., Abbasi, T., & Abbasi, S. (2013). Methane capture from livestock manure. *Journal of Environmental Management*, 117, 187-207. <https://doi.org/10.1016/j.jenvman.2012.12.022>
- Thürer, Y., Blanc, F., Ottimofiore, G., Morales, A., Amaral, M., Hernandez, G., Karttunen, M., Baxter, M., Van Langen, V., Pietikäinen, A., Trnka, D., Davidson, P., Botta, E., Saffirio, C.,
- Daglio, M., Varazzani, C., Hubble, C., Blazey, A., Lindberg, C., . . . Callewaert, S. (2023). Better regulation for the green transition. In *Public Governance Policy Papers*. <https://doi.org/10.1787/c91a04bc-en>
- Ulutaş, A., Topal, A., Karabasevic, D., & Balo, F. (2023). Selection of a Forklift for a Cargo Company with Fuzzy BWM and Fuzzy MCRAT Methods. *Axioms*, 12(5), 467. <https://doi.org/10.3390/axioms12050467>
- Viskup, R., Wolf, C., Baumgartner, W., Viskup, E., Kumar, N., Sonthalia, A., Pali, H., Sarıkoç, S., Monemian, E., Cairns, A., Kulkarni, A., Deshmukh, D., Simões, A., Farinha, J., Fonseca, I., & Reşitoğlu, İ. (2019). Diesel and gasoline engines. In *IntechOpen eBooks*. <https://doi.org/10.5772/intechopen.75259>
- Wu, H. (2007). A critical study on the fire safety for big hotels in Hong Kong. <https://theses.lib.polyu.edu.hk/bitstream/200/965/1/b20940488.pdf>
- Yadav V., Shukla A., Bandra S., Kumar V., Ansari U, Khanna S. (2017), A Review On IOT Based Hazardous Gas Leakage Detection & Controlling System Using Microcontroller & GSM Module, *Journal of VLSI Design and Signal Processing*, Vol. 3,
- Yener, F., & Yazgan, H. R. (2019). Optimal warehouse design: Literature review and case study application. *Computers & Industrial Engineering*, 129, 1-13. <https://doi.org/10.1016/j.cie.2019.01.006>
- Zheng B., & Chen G. (2011). Storage tank fire accidents. *Process Safety Progress*, 30(3), 291-293. doi:10.1002/prs.10458
- Zou, P X W, Sunindijo, R Y and Dainty, A (2011) Review of construction safety research methods: Integrating theory and practice In: Egbu, C. and Lou, E.C.W. (Eds.) *Procs 27th Annual ARCOM Conference*, 5-7 September 2011, Bristol, UK, Association of Researchers in Construction Management, 953-962.

UTILISING AUTOMATION SOLUTIONS TO MINIMISE OCCUPATIONAL SAFETY AND HEALTH ISSUES IN PORTS

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Abstract. This research explores the potential of utilising automation solutions to minimise Occupational Safety and Health (OSH) issues in port operations. Ports are inherently hazardous environments, with workers exposed to physical strain, machinery-related accidents, hazardous materials, and adverse weather conditions, leading to injuries, illnesses, and fatalities. The integration of automation technologies is proposed as a key strategy to mitigate these risks by replacing high-risk manual tasks with robotic systems and automated processes. This study examines existing literature on the role of automation in improving workplace safety, focusing on its application in port operations. By analysing the challenges and barriers to automation adoption, including financial constraints, infrastructural limitations, and resistance to technological change, this research aims to propose a framework for successful automation implementation to minimise OSH issues. The findings suggest that automation has the potential to significantly enhance OSH standards in ports, reducing accidents and health-related issues while improving operational efficiency. The study concludes by offering strategic recommendations to overcome barriers and integrate automation for a safer, more efficient port environment.

Keywords. Automation, Occupational Safety and Health (OSH), Port Operation, Barriers, Strategies

1. Introduction

The Port operations are a major concern due to the inherent hazards faced by workers. These include physical strain from heavy lifting, the operation of intricate machinery, handling potentially hazardous materials, exposure to adverse weather conditions, and falls from height (Alias et al., 2022). Poor working conditions, inadequate training, and unsafe equipment contribute to an increased likelihood of accidents and health implications (Usman, 2020). International Labor Organization (n.d.) emphasizes the importance of enhancing Occupational Safety and Health (OSH) regulations across various industries, including port operations. One of the key challenges facing the shipping and ports industry is OSH. The industry is facing an increasing number of accidents and injuries, and there is a need to improve safety standards. The industry is also facing a shortage of skilled workers, making it difficult to implement safety measures (Tseng & Pilcher, 2017). Fire and explosions are a major threat in ports as they store a large amount of flammable materials and use heavy machinery. Workers in the port are prone to assaults by criminals or accidents from equipment or vehicles (Alias et al., 2022). Work stress, often attributed to long hours of work, shift work, and high workloads, are source of numerous health issues such as anxiety, depression, and cardiovascular diseases (Usman, 2020).

Automation technology adoption in ports requires a complete approach that balances human aspects, regulatory frameworks, and technological improvements (De Alwis & Nam, 2024). This entails not only the installation of automated systems but also the creation of a competent workforce capable of running and maintaining such technology. However, there are many challenges in the way of complete automation, ranging from infrastructure and financial limitations to cultural resistance to technological advancement, particularly noticeable in developing

nations (Buzinkay, 2022). This research aims to present a comprehensive examination of the ways in which automation might be utilised to minimise OSH in port, while considering the various advantages and tackling the associated obstacles and improving OSH levels of standards. By addressing the research gap and proposing framework that integrates automation, this research aims to contribute to the advancement of occupational health and safety in ports, creating a safer and more conducive environment for all port personnel.

2. Background Literature

2.1 PORT OPERATION

Port operations comprise a variety of tasks, such as cargo handling, quality control, simulation, and logistical procedures (Higgins & Hall, 2000). Ungureanu et al., (2023) highlights the necessity of implementing a robust quality management framework in port operations, with a specific focus on stevedoring activities. To guarantee the seamless and effective operation of ports, it is crucial to adopt a complete strategy that includes careful planning, coordinated implementation, and efficient resource allocation (Brooks et al., 2017). This complex coordination entails a sequence of clearly defined protocols that smoothly combine the several elements of port operations, encompassing ship pre-arrival, arrival, berthing, cargo handling, and departure (Dalaklis, 2017)

2.2 OCCUPATIONAL HEALTH AND SAFETY (OHS) IN PORTS

In addition to the physical features of port operations, there is a strong focus on ensuring OSH and security. The port implements rigorous procedures to prevent accidents, theft, and unauthorised access, protecting its assets and staff. An effective port safety management system is built upon regular safety drills, thorough risk assessments, and strong security measures (Dalaklis, 2017).

OSH is very important in port facilities because it has a direct effect on the health and safety of port workers and the speed with which ports run their businesses. Physical, chemical, and environmental risks are just some of the dangers that port workers face, which is why strong safety measures and health management strategies are needed (Wang et al. 2017). Evaluations of OSH practices, like the ones done in Damietta Port, North Egypt, show how important it is to keep doing evaluations to improve safety routines and make sure workers are happy with the ones that are already in place. Fixing problems and strengthening the OSH structure are important for making the workplace safer and more productive (Beheary et al., 2020). Alias et al., (2022) also talk about how important it is to know what makes safety professionals think differently about health and safety risks in ports

2.3 IMPACT OF AUTOMATION ON PORT OPERATION

The implementation of automation technologies has played a crucial role in the progression of OSH protocols within the context of port operations. Through the identification of Occupational Health, Safety and Security (OHSS) Standards by Antão et al. (2016), having assessed and analysed the port practices and legislations, it is evident that automation has positive impacts on OSH in the port areas. Furthermore, such changes incorporated in automation and information technology, according to Yang (2014), have enhanced the sanitary treatment

procedures by offering increased clearance, and supported the development of the port, but with a strict OSH compliance.

Automation tool integration has been vital in the improvement of OSH measures and risk management strategies in different workplaces. Park & Kang (2024), have given an example of the application of automation solutions creates a less hazardous working environment for human beings by collecting and analysing meticulous data related to workers.

Nof, S. Y. (2009) states automation as the utilisation of technology, machinery, or systems to perform tasks or operations autonomously or semi-autonomously, with minimal human intervention. It encompasses the creation and deployment of autonomous machines, tools, or devices capable of executing complex sequences of decisions and actions in response to predefined programs and external stimuli, typically powered by their own energy source (Rodrigue & Notteboom, 2021). Additionally, automation extends to the broader implementation of automated processes, including the use of software, robotics, sensors, and control systems, to streamline workflows, enhance efficiency, reduce errors, and improve consistency across various industries and applications (Vega-Muñoz et al., 2021).

Although ports have adopted automation more slowly than comparable sectors, notably mining and warehousing, the pace is now starting to accelerate. Automated ports are safer than conventional ones. The number of human-related disruptions falls, and performance becomes more predictable (De Alwis & Nam, 2024). Yet the up-front capital expenditures are quite high, and the operational challenges a shortage of capabilities, poor data, siloed operations, and difficulty handling exceptions are very significant (Marielle, n.d.). A McKinsey survey indicates that while operating expenses decline, so does productivity, and the returns on invested capital are currently lower than the industry norm. Nonetheless, successful automated ports show that careful planning and management can surmount these difficulties, operating expenses could fall by 25% to 55% and productivity could rise by 10% to 35% (McKinsey & Company, 2024). In the long run, these investments will lead the way toward a new paradigm called Port 4.0, the shift from asset operator to service orchestrator, part of a larger transition to Industry 4.0, or digitally enabled efficiency gains throughout the world economy (De Alwis & Nam, 2024). Port 4.0 will generate more value for port operators, suppliers, and customers alike, but that value is not proportionally distributed across ports and their ecosystems. Innovative business models and forms of collaboration will be required to realise this vision (Heikkilä et al., 2022). Automation is important to ports for many reasons such as it can improve product quality, making operations safer, making the best use of resources, and reducing damage to the environment (Kai-Chieh & Paul, 2011). In Jämsä-Jounela (2007) stated how important automation is in highly industrialized nations. He said that automation not only speeds up mass production but also helps people learn how to make a wide range of products, which makes plants more available and improves process safety. This is especially clear in businesses like petrochemicals, chemicals, and power generation and in ports where process automation is in high demand. This is part of a larger trend in organisations to use automation to save money and time.

3. Methodology

This study employs a comprehensive non-systematic literature review to examine how automation solutions can minimise occupational health and safety (OSH) issues in port operations. The research is guided by the question: "How can automation solutions be used to minimise OSH issues in port operations?" To address this question, the study synthesizes existing literature on OSH in ports, automation in industrial settings, and the impact of technological advancements on workplace safety.

A non-systematic literature review is widely used to explore and summarise existing studies without adhering to a rigid methodological framework (Enferm, 2007). This approach allows for a broad examination of theoretical and conceptual perspectives, helping to identify knowledge gaps and key insights in the field.

Through the review, this study develops a conceptual framework that outlines how automation can be leveraged to address OSH concerns in port environments. The framework is built upon key themes and findings from the literature, providing a structured understanding of the relationship between automation and workplace safety. By synthesizing relevant research, the study contributes to the ongoing discourse on enhancing OSH standards through technological innovations in port operations.

4. Findings

4.1. OSH ISSUES IN DIFFERENT STAGES OF PORT OPERATIONS

The working environment in seaports presents numerous OSH challenges across different operational stages, including chemical exposures, physical hazards, ergonomic risks, biological threats, and psychosocial stressors, all of which impact worker well-being and productivity.

4.1.1 Pre-arrival stage

During the pre-arrival stage, workers are exposed to chemical hazards from fuel, cleaning agents, and cargo-related volatile compounds, increasing the risk of respiratory illnesses, neurological disorders, and skin conditions (Wang et al, 2017). Additionally, psychosocial hazards such as stress and fatigue arise due to irregular work schedules and prolonged shifts, while high noise levels from preparation activities contribute to hearing loss and exhaustion (Hooydonk, 2013). According to Wang et al.(2017), before implementing occupational health policies, port firms must determine the number of risks that occupational health might pose, including chemical, physical, and psychological factors.

4.1.2 Arrival stage

As vessels arrive, the risks associated with the port environment become more pronounced. Slippery surfaces, congested workspaces, and the movement of heavy machinery increase the likelihood of slips, trips, and falls, leading to serious injuries (Andriani et al., 2019). Musculoskeletal Disorders (MSDs) are also prevalent, as workers frequently engage in repetitive lifting and the handling of heavy loads, causing back pain, fatigue, and chronic injuries (Febriyanto & Suprayitno, 2020). Moreover, exposure to hazardous chemicals from cargo materials poses further respiratory and dermatological risks (Wang et al, 2017).

4.1.3 Berthing stage

During the berthing stage, high noise levels generated by machinery and docking operations lead to hearing loss and stress-related fatigue among port workers (Walters, Wadsworth, & Bhattacharya, 2020). Additionally, biological hazards such as ship waste and animal-related cargo introduce risks of infectious diseases, mold exposure, and airborne pathogens, while the handling of heavy equipment further increases the potential for crush injuries and other accidents (Febriyanto & Suprayitno, 2020).

4.1.4 Cargo handling stage

The cargo handling stage presents one of the most hazardous working environments within the port. Poor posture, repetitive lifting, and exposure to vibration contribute significantly to ergonomic issues, leading to chronic musculoskeletal disorders and worker fatigue (Andriani et al., 2019). At the same time, handling flammable and toxic chemicals within cargo poses serious health threats, including respiratory distress and skin complications (Wang et al, 2017). Workers are also at risk of biological hazards when dealing with contaminated shipments, such as food, livestock, or medical waste, which may expose them to infectious diseases and allergens (Febriyanto & Suprayitno, 2020).

4.1.5 Departure stage

As the vessel departs, psychosocial hazards continue to impact workers due to fixed working hours, long shifts, and high-pressure deadlines, which contribute to increased stress, anxiety, and mental fatigue (Hooydonk, 2013). Physical risks also remain a concern as workers navigate between vessels and docks, increasing the likelihood of falls, trips, or being struck by moving objects (Andriani et al., 2019). Additionally, prolonged exposure to high decibel levels from ship engines, cranes, and forklifts poses a long-term threat to hearing health (Walters et al., 2020).

Each stage of port operations presents unique occupational safety challenges that demand strategic interventions to mitigate risks and protect workers. Addressing these hazards through automation, improved safety policies, and ergonomic interventions can enhance worker protection, operational efficiency, and compliance with safety regulations, ultimately fostering a safer and more sustainable working environment in seaports.

4.2. AUTOMATION SOLUTIONS THAT IMPROVE OSH

Automation has played a major role in raising OSH standards in the field of port operations. One important way to reduce industrial injuries is by implementing automated systems for professional risk management and forecasting. The fact that these systems apply a multifactor approach to assess dangers present at certain workplaces is explained by Klimova et al. (2018), paving the way for a more proactive and predictive approach to OSH. This technological advancement considers several factors that can benefit the enhancement of workplace safety like the credential of the employees and their psychophysiological condition (Klimova et al., 2018). Table 1 shows the Automation solutions that can be used to improve the OSH in ports.

Table 1: Automation tools that improve occupational safety and Health

Automation Tool	Description	References
Digital Twin Technology	Creates a digital representation of physical assets to collect and analyse workplace data.	(Park et al., 2023)
Handheld Devices for Health and Safety	Devices used for inspections, reducing manual data collection and paperwork.	(Shibi, 2006)
Automated Risk Assessment Systems	Uses complex algorithms for multifactor analysis to assess and forecast occupational risks.	(Klimova et al.,2018)
Information Technology in OSH Management	Software and computerization tools for managing specific OSH threats.	(Sorokin et al., 2019)
Automated Scheduling Systems	Specialized software solutions designed to manage appointments, bookings, or tasks without the need for manual input, enhancing efficiency and compliance.	(Howard et al.,2020)
Automated Notification Systems	Communication platforms designed to quickly disseminate critical information to many people during emergencies, enhancing workplace safety.	(Crises Control, 2024)
Automated Pilotage Systems	Advanced systems that assist in the navigation and manoeuvring of vessels, reducing human error and enhancing maritime safety.	(Fehse, 2003)
Automated Cranes	Cranes equipped with automation technology to improve efficiency and safety in material handling operations.	(Bucur, 2019)
Automated Docking Systems	Systems that automate the docking process of vessels, enhancing precision and safety in maritime operations.	(Miyauchi et al., 2021)
Automated Berthing Systems	Technology that automates the berthing process of ships, improving efficiency and reducing the risk of accidents.	(Zhang et al., 2023)
Remote Monitoring	The use of technology to monitor workplace environments and equipment from a distance, ensuring safety and compliance.	(Patel et al., 2022)
Automated Cargo Handling Systems	Integrated technologies that automate the loading, unloading, and management of cargo, enhancing efficiency and reducing manual labour in logistics operations.	(Japan Ministry of Land, Infrastructure, Transport and Tourism, 2024)

Predictive Maintenance	Utilizes AI and machine learning to predict equipment failures before they occur, allowing for proactive maintenance and reducing downtime.	(Vanderlande, 2024)
Automated Unberthing Systems	Advanced systems designed to automate the process of unberthing ships, improving safety and operational efficiency in maritime ports.	(Antão et al., 2016)
Drones for Safety Checks	Deployment of unmanned aerial vehicles to conduct inspections in hazardous or hard-to-reach areas, enhancing safety and efficiency in maintenance operations.	(Skydio, 2024)

4.3. APPLICATION OF AUTOMATION SOLUTIONS TO ENHANCE OSH IN PORTS

The integration of automation technologies in port operations significantly improves OSH by reducing human exposure to hazardous environments, minimizing operational risks, and enhancing overall efficiency. Ports are evolving towards Port 4.0, incorporating digitalisation and automation to optimise operations and improve worker safety (Orive et al., 2020). Various stages of port operations, including berthing and unberthing, cargo handling, storage and inventory management, workforce safety, and emergency response, benefit significantly from these advancements.

4.3.1 Berthing

The berthing of vessels involves risks such as collisions, human errors, and structural damage. Automated Berthing Systems improve docking precision through sensor-based guidance and AI-driven alignment, reducing manual intervention and accident risks (Zhang et al., 2023). Additionally, Automated Pilotage Systems, utilising autonomous navigation technology, facilitate safe vessel movement in congested waters, minimising navigational errors (Miyauchi et al., 2021). These technologies enhance situational awareness and reduce reliance on human piloting, mitigating safety hazards in maritime operations.

4.3.2 Cargo Handling

Cargo handling remains one of the most hazardous activities in ports, involving heavy lifting, repetitive tasks, and large machinery operation. Automated cranes eliminate manual lifting requirements, significantly reducing fall-related injuries and equipment-related accidents (Bucur, 2019). Automated Cargo Handling Systems, integrating robotic arms, conveyor belts, and AI-powered sorting technologies, optimise loading and unloading processes, improving both safety and operational efficiency (Japan Ministry of Land, Infrastructure, Transport and Tourism, 2024). These systems also reduce workers' exposure to hazardous cargo materials, improving workplace safety compliance (Antão et al., 2016).

4.3.3 Storage and Inventory Management

Port storage facilities present various hazards, including structural failures, hazardous material exposure, and equipment malfunctions. Digital Twin Technology

provides a real-time digital representation of storage areas, allowing proactive risk identification and operational optimization (Park et al., 2023). Predictive Maintenance, powered by AI-driven analytics and IoT sensors, enables continuous equipment monitoring, preventing unexpected failures that could cause workplace injuries (Vanderlande, 2024). Additionally, Remote Monitoring technologies allow supervisors to oversee high-risk areas remotely, reducing direct exposure to hazardous conditions (Patel et al., 2022).

4.3.4 Workforce Safety and Operational Efficiency

Maintaining workforce safety requires advanced monitoring, communication, and compliance solutions. Handheld Devices for Health and Safety facilitate real-time hazard detection, incident reporting, and compliance tracking, allowing immediate intervention (Shibi, 2006). Automated Notification Systems provide instant alerts in case of chemical spills, equipment malfunctions, or gas leaks, ensuring timely responses to potential hazards (Crises Control, 2024). Furthermore, Information Technology in OSH Management improves incident reporting, regulatory compliance, and safety tracking, fostering a safer working environment (Sorokin et al., 2019).

4.3.5 Emergency Response and Risk Management

Effective emergency response strategies are essential for preventing workplace hazards and ensuring worker safety. Automated Risk Assessment Systems use AI-based predictive models to assess potential threats and proactively mitigate safety risks (Klimova et al., 2018). Drones for safety checks improve emergency response by conducting aerial inspections of hazardous areas, such as cranes, storage tanks, and confined spaces, where manual inspections pose safety risks (Skydio, 2024). These automation tools enhance risk detection and incident management, ensuring ports comply with international OSH standards (Antão et al., 2016).

4.4. BARRIERS IN IMPLEMENTING AUTOMATION SOLUTIONS IN PORTS

One of the primary challenges in adopting automation is the limitation of existing IT infrastructure. Many organisations lack the digital readiness and maturity required for integrating Robotic Process Automation (RPA) and other advanced technologies (Flechsig et al., 2021). Additionally, selecting and integrating the right hardware and software pose significant difficulties. Compatibility issues between old and new systems can hinder seamless automation implementation Flechsig et al.,(2021). Moreover, automation often involves complex programming and maintenance requirements, making it difficult for organisations to develop and sustain automated processes (Cordy, 2003). The high initial investment required for automation technologies presents a major financial challenge. Upgrading infrastructure, acquiring new equipment, and implementing training programs demand substantial resources that many organisations struggle to afford (Wijayatunga et al., 2006). Limited financial resources, particularly in developing economies, further slowdown automation adoption. Organisations often prioritize immediate operational costs over long-term automation benefits, making it difficult to justify large-scale investments in automation solutions (Silva & Wimalaratne, 2012).

Regulatory and policy constraints create additional obstacles in automation adoption. Unclear or inconsistent government policies can deter businesses from

investing in automation due to the uncertainty surrounding compliance requirements (Wijayatunga et al., 2006). Additionally, concerns about the environmental impact of automation, such as increased energy consumption and electronic waste, raise questions about sustainability. Organisations must balance technological advancements with sustainable practices to ensure long-term benefits. Resistance to change is a significant challenge in automation implementation. Employees and labour unions often fear job displacement due to automation, leading to reluctance in adopting new technologies (Singh & Namekar, 2020). A lack of a skilled workforce further exacerbates the issue, as organisations struggle to find employees who are adequately trained to operate and maintain automated systems (Pereira & Jayasena, 2006). Additionally, cultural and organisational challenges play a crucial role in automation resistance. Many companies lack a culture of innovation, and management hesitancy towards change further slows automation adoption (Trujillo & Holt, 2020).

Table 2: Barriers of implementing automation solutions in ports

No	Barrier	References
B1	Lack of digital readiness and maturity for integrating RPA and advanced technologies	Flehsig et al., (2021)
B2	Compatibility issues between legacy and new systems	Flehsig et al., (2021)
B3	Complex programming and maintenance requirements	Cordy (2003)
B4	High initial investment in automation technologies	Wijayatunga et al. (2006)
B5	Cost of infrastructure upgrades, new equipment, and training programs	Wijayatunga et al. (2006)
B6	Prioritization of short-term operational costs over long-term automation benefits	Silva & Wimalaratne (2012)
B7	Unclear or inconsistent government regulations	Wijayatunga et al. (2006)
B8	Resistance to change due to fear of job displacement	Singh & Namekar (2020)
B9	Lack of skilled workforce to operate and maintain automated systems	Pereira & Jayasena (2006)
B10	Absence of innovation culture and management hesitancy toward change	Trujillo & Holt (2020)

4.5. STRATEGIES TO OVERCOME THE IDENTIFIED BARRIERS

To address technical barriers, organisations must prioritise upgrading their IT infrastructure to accommodate automation technologies. Standardized hardware and software solutions should be adopted to improve system compatibility and ensure smooth integration (U.S. Government Accountability Office, 2024). Additionally, targeted training programmes should be implemented to equip employees with the necessary skills for maintaining and managing automated

systems, reducing dependence on external technical support (Cordy, 2003). To overcome financial constraints, organisations should explore cost-effective automation solutions tailored to their specific industry needs. Government financial incentives, such as subsidies and tax reductions, can provide businesses with the necessary support to invest in automation technologies (Wijayatunga et al., 2006). Additionally, public-private partnerships can help share the financial burden and accelerate automation adoption (Silva & Wimalaratne, 2012). Businesses should also develop long-term investment strategies that balance short-term costs with long-term efficiency and productivity gains.

Regulatory frameworks should be revised to provide businesses with clear and consistent policies on automation adoption (Wijayatunga et al., 2006). Organizations must invest in environmentally sustainable automation technologies that minimize energy consumption and reduce waste. The integration of energy-efficient automation systems can address environmental concerns while improving operational efficiency. Furthermore, long-term policy planning should ensure that businesses have the confidence to invest in automation without facing regulatory uncertainties. To reduce resistance to automation, organizations should implement workforce engagement programs that involve employees in the automation transition process. Providing reskilling and upskilling opportunities will help employees adapt to new roles rather than fear job losses (Pereira & Jayasena, 2006). Additionally, leadership support is essential in fostering a culture of innovation and ensuring smooth technological transitions (Trujillo & Holt, 2020). Pilot projects can also be introduced to demonstrate the benefits of automation before committing to full-scale implementation, helping employees and stakeholders understand its value (Pereira & Jayasena, 2006).

Table 3: Strategies to overcome identified barriers

Barrier ID	Strategy to Overcome the Barrier	References
B1	Upgrade IT infrastructure to support automation technologies	U.S. Government Accountability Office (2024)
B2	Adopt standardized hardware and software for better compatibility	U.S. Government Accountability Office (2024)
B3	Provide targeted training to build internal capacity for maintaining and managing automated systems	Cordy (2003)
B4	Explore cost-effective automation solutions tailored to industry needs	Wijayatunga et al. (2006)
B5	Seek government incentives such as subsidies and tax reductions to ease financial burdens	Wijayatunga et al. (2006)
	Promote public-private partnerships to share automation investment costs	Silva & Wimalaratne (2012)
B6	Develop long-term investment strategies balancing short-term costs and long-term productivity gains	Silva & Wimalaratne (2012)

B7	Revise regulatory frameworks to ensure clear, consistent automation policies	Wijayatunga et al. (2006)
	Align long-term policy planning with sustainability goals to build investor confidence	Wijayatunga et al. (2006)
B8	Invest in energy-efficient and environmentally sustainable automation technologies	Wijayatunga et al. (2006)
	Align long-term policy planning with sustainability goals to build investor confidence	Wijayatunga et al. (2006)
B9	Implement employee engagement programs during automation transitions to reduce fear of job displacement	Pereira & Jayasena (2006)
B9	Offer reskilling and upskilling opportunities to help employees adapt to new roles	Pereira & Jayasena (2006)
B10	Ensure leadership support to foster innovation culture and support smooth technology transitions	Trujillo & Holt (2020)
	Use pilot projects to showcase automation benefits and build trust among employees and stakeholders	Pereira & Jayasena (2006)

4.6. CONCEPTUAL FRAMEWORK

This framework is developed based on insights from existing literature. In this conceptual framework, overall OSH issues will be identified through surfacing sub-operation procedures of the main operations of the port. After the potential hazards are identified, possible solutions that automation can offer will be drafted to address each OSH issue. Thereafter a workflow will be created where automation solutions to avoid these potential hazards and to move with the operation swiftly. The following figure OSH issues in ports, automation-driven solutions, barriers to implement those solutions and strategies to overcome identified barriers to enhance safety and efficiency in port operations

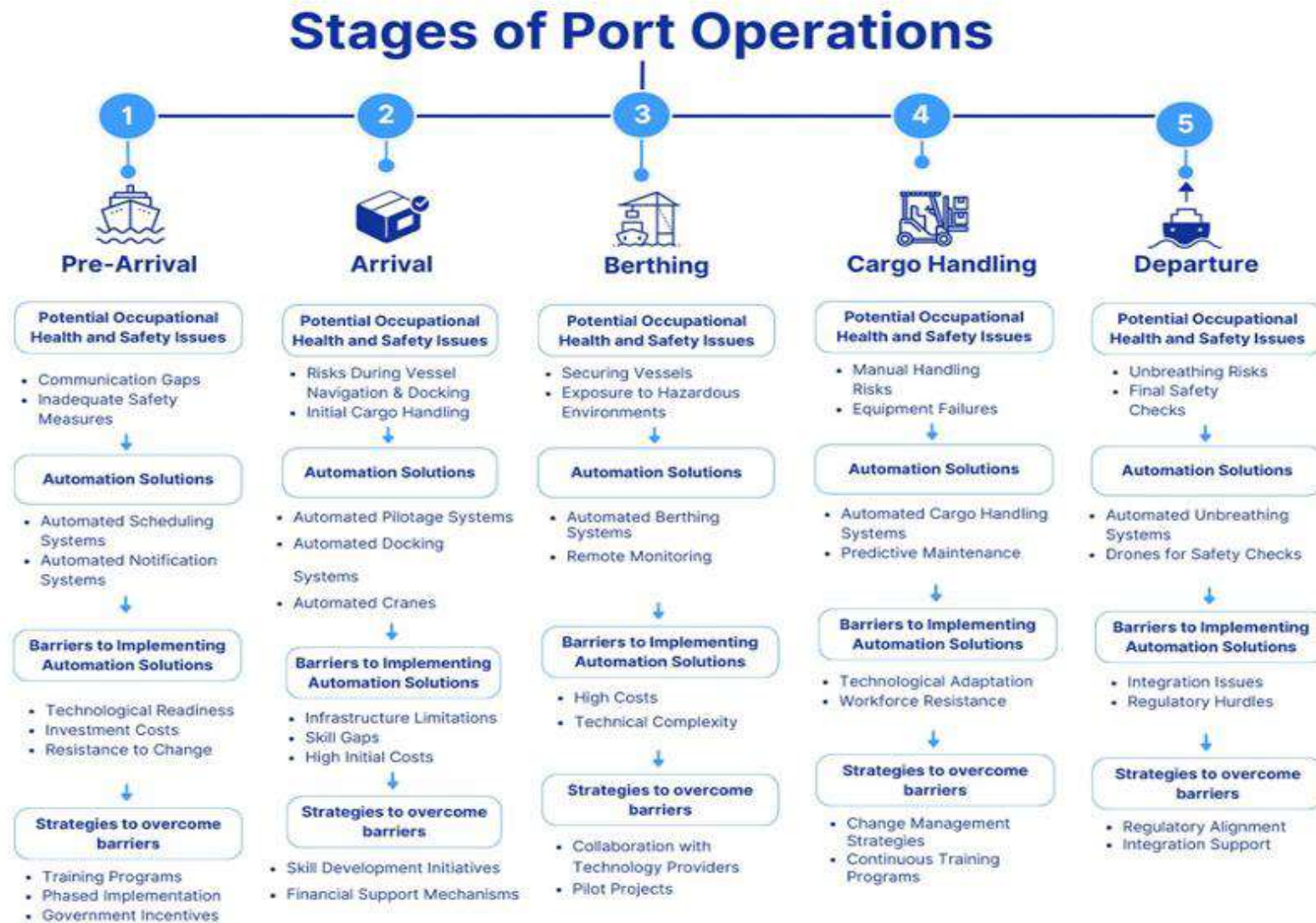


Figure 1: Conceptual Framework for OSH Issues and Automation Solutions in Port Operations

5. Conclusion

In conclusion, the integration of automation solutions in port operations holds significant potential to address numerous OSH challenges that workers face. Automation can reduce the risks associated with manual handling, machinery operation, hazardous material exposure, and workplace accidents by assigning high-risk tasks to robots and automated systems. This shift not only improves safety but also reduces work-related stress and long-term health implications, fostering a healthier work environment. However, the successful implementation of automation in ports requires overcoming several barriers, including financial constraints, infrastructural limitations, and resistance to technological change. Addressing these challenges demands a comprehensive approach that incorporates technological advancements, skill development, and effective regulatory frameworks. By leveraging automation, ports can mitigate the frequency of accidents, improve operational efficiency, and create a safer working environment for all personnel. Furthermore, the development of a competent workforce to manage and maintain these automated systems is essential to ensure smooth integration and long-term sustainability. This study develops a conceptual framework to illustrate how automation solutions can minimize OSH risks in port operations. The framework is significant as it provides a structured approach to understanding the role of automation in reducing workplace hazards, enhancing safety standards, and improving operational efficiency. It serves as a guiding tool for port authorities, policymakers, and industry stakeholders, helping them navigate the integration of automation technologies while addressing key challenges such as financial constraints, infrastructural readiness, and workforce adaptation. By developing this framework, the study highlights the importance of a strategic, well-planned transition to automation, ensuring that safety improvements align with technological advancements. This contribution is particularly valuable for decision-makers seeking to enhance OSH practices in port environments, ultimately fostering a safer and more sustainable future for the industry.

6. References

- Alias, A. N., Yaakub, N., Baharuddin, M. R., & Noor, M. A. M. (2022). Port terminal safety: A conceptual paper on factors that affects occupational stress risk assessment in container terminal. *International Journal of Health Sciences*, 6(August), 47078–47088. <https://doi.org/10.53730/ijhs.v6ns7.13097>
- Andriani, Y., Nugraha, A., & Darmawan, A. (2019). Analysis of occupational health and safety (OHS) risk management in cargo handling at seaports. *International Journal of Maritime Studies*, 24(2), 99–110.
- Andriani, D. P., Novianti, V. D., Adnandy, R., & A'yunin, Q. (2019, June 1). Quantitative risk modelling of occupational safety in green-port. *IOP Conference Series: Materials Science and Engineering*, 546(5), 052007. <https://doi.org/10.1088/1757-899x/546/5/052007>
- Antão, P., Calderón, M., Puig, M., Michail, A., Wooldridge, C., & Darbra, R. M. (2016). Identification of Occupational Health, Safety, Security (OHSS) and Environmental Performance Indicators in port areas. *Safety Science*, 85, 266–275. <https://doi.org/10.1016/j.ssci.2015.12.031>
- Beheary, M. S., Abdelaal, A., & Matar, S. M. (2020). Occupational Health and Safety Practices Assessment in Damietta Port, North Egypt. *Asian Journal of Advanced Research and Reports*, 8(4), 17–27. <https://doi.org/10.9734/ajarr/2020/v8i430204>

- Brooks, M. R., Cullinane, K. P. B., & Pallis, A. A. (2017). Revisiting port governance and port reform: A multi-country examination. *Research in Transportation Business & Management*, 22, 1–10. <https://doi.org/10.1016/J.RTBM.2017.02.005>
- Bucur, V. (2019). Automated cranes in modern port operations. In *Automation and Control in Transportation and Communication* (pp. 123–145). Springer. https://doi.org/10.1007/978-3-030-23543-6_5
- Buzinkay, M. (2022). Known Port Automation Challenges. In *Identec Solutions*. <https://www.identecsolutions.com/news/known-port-automation-challenges>
- Cordy, J. R. (2003). Comprehending legacy systems: A survey of approaches. *Proceedings of the 10th International Workshop on Program Comprehension*, 35–44.
- Crises Control. (2024). Automated notification systems for workplace safety. Retrieved from <https://www.crises-control.com>
- Dalaklis, D. (2017). Safety and Security in Shipping Operations BT - Shipping Operations Management (I. D. Visvikis & P. M. Panayides (eds.); pp. 197–213). Springer International Publishing. https://doi.org/10.1007/978-3-319-62365-8_9
- De Alwis, N., & Nam, H.-S. (2024). A way towards port automation: challenges and implications. *WMU Journal of Maritime Affairs*. <https://doi.org/10.1007/s13437-024-00350-9>
- Enferm, A. paul. (2007). Systematic literature review X narrative review. 2(20).
- Febriyanto, K., & Suprayitno, S. (2020, January 8). IMPLEMENTATION OF OCCUPATIONAL SAFETY AND HEALTH FOR USING SEA TRANSPORTATION (CASE STUDY AT TENGKAYU II PORT OF TARAKAN CITY). *Jurnal Ilmu Kesehatan*, 7(2), 97–102. <https://doi.org/10.30650/jik.v7i2.1282>
- Fehse, W. (2003). Automated and autonomous docking of spacecraft. *Cambridge Aerospace Series*. <https://doi.org/10.1017/CBO9780511535887>
- Flechsig, M., Anslinger, K., & Lasch, R. (2021). Overcoming barriers to automation in logistics: A decision-making framework. *Logistics Research*, 14, 15. <https://doi.org/10.1007/s12159-021-00223-6>
- Heikkilä, M., Saarni, J., & Saurama, A. (2022). Innovation in Smart Ports: Future Directions of Digitalization in Container Ports. *Journal of Marine Science and Engineering*, 10(12). <https://doi.org/10.3390/jmse10121925>
- Higgins, T., & Hall, R. (2000). *Port Operations : a Review of Practices*.
- Hooydonk, E. (2013). Port labour in the EU: Labour market, qualifications & training. *European Transport Research Review*, 5, 145–162.
- Howard, R., Gao, X., & Sankey, A. (2020). Automated scheduling systems in construction project management. *Automation in Construction*, 119, 103331. <https://doi.org/10.1016/j.autcon.2020.103331>
- International Labour Organization. (n.d.). Code of practice on safety and health in ports. Retrieved from <https://www.imo.org/en/OurWork/Facilitation/Pages/ILOCode-Default.aspx>
- Jämsä-Jounela, S. L. (2007). Future trends in process automation. *Annual Reviews in Control*, 31(2), 211–220. <https://doi.org/10.1016/j.arcontrol.2007.08.003>
- Japan Ministry of Land, Infrastructure, Transport and Tourism. (2024). Automated cargo handling systems in Japanese ports. Retrieved from <https://www.mlit.go.jp/english/>
- Kai-Chieh, H. U., & Paul, T. W. (2011). Developing a new technique for evaluating service quality of container ports. *Current Issues in Shipping, Ports and Logistics*, April, 337.
- Klimova, O., Semeykin, A., & Nosatova, M. (2018). Automated systems for professional risk management and forecasting in industrial enterprises. *MATEC Web of Conferences*, 224, 05020. <https://doi.org/10.1051/mateconf/201822405020>

- MARIELLE, D. A. R. (n.d.). THE IMPACT OF AUTOMATION ON CONTAINER PORT TERMINALS Abstr act. 2020879005.
- McKinsey & Company. (2024). The future of port automation. Retrieved from <https://www.mckinsey.com/industries/logistics/our-insights/the-future-of-automated-ports>
- Miyauchi, T., Koseki, T., & Sato, T. (2021). Development of an automated docking system for small vessels. *Journal of Marine Science and Technology*, 26(4), 1012-1023. <https://doi.org/10.1007/s00773-021-00785-0>
- Nof, S. Y. (2009). *Springer handbook of automation*. Springer Science & Business Media. <https://doi.org/10.1007/978-3-540-78831-7>
- Orive, A., Iturralde, E., & Zubillaga, F. (2020). Port 4.0: The evolution of the port industry in the digital age. *Journal of Physics: Conference Series*, 1432(1), 012093. <https://doi.org/10.1088/1742-6596/1432/1/012093>
- Park, J., & Kang, D. (2024). Artificial Intelligence and Smart Technologies in Safety Management: A Comprehensive Analysis Across Multiple Industries. *Applied Sciences (Switzerland)*, 14(24), 1–22. <https://doi.org/10.3390/app142411934>
- Park, J., Lee, D., Jiménez, J., Lee, S., & Kim, J. (2023). Human-Focused Digital Twin Applications for Occupational Safety and Health in Workplaces: A Brief Survey and Research Directions. *Applied Sciences*. <https://doi.org/10.3390/app13074598>.
- Patel, S., Shah, M., & Patel, N. (2022). Remote monitoring system for industrial automation using IoT. *Materials Today: Proceedings*, 51, 175-179. <https://doi.org/10.1016/j.matpr.2022.02.012>
- Pereira, R., & Jayasena, S. (2006). Workforce readiness for automation in developing economies. *International Journal of Industrial Engineering*, 13(3), 127-145.
- Rodrigue, J. P., & Notteboom, T. (2021). Automation in Container Port Systems and Management. *TR News*, 334(January), 20–25.
- Shibi, I. (2006). Handheld devices for health and safety inspections in construction sites. *Journal of Information Technology in Construction (ITcon)*, 11, 409-420.
- Silva, R., & Wimalaratne, C. (2012). Financial constraints in automation adoption: The case of port operations in Sri Lanka. *Journal of Maritime Economics & Logistics*, 14(2), 95-112.
- Singh, S., & Namekar, S. (2020). A REVIEW ON AUTOMATION OF INDUSTRIES. , 04, 298-300. <https://doi.org/10.33564/ijeast.2020.v04i12.051>.
- Skydio. (2024). Drones for safety checks in industrial environments. Retrieved from <https://www.skydio.com/>
- Sorokin, A., Kolesnik, S., & Smirnov, A. (2019). Information technology in occupational safety and health management systems. *Procedia Computer Science*, 150, 951-956. <https://doi.org/10.1016/j.procs.2019.02.002>
- Tseng, P. H., & Pilcher, N. (2017). Maintaining and researching port safety: a case study of the port of Kaohsiung. *European Transport Research Review*, 9(3). <https://doi.org/10.1007/s12544-017-0250-z>
- Trujillo, D., & Holt, T. (2020). Overcoming organizational resistance to automation. *Journal of Business Research*, 120, 151-162. <https://doi.org/10.1016/j.jbusres.2020.01.001>
- Ungureanu, A. M., Doicin, C. V., Stanca, C., & Titu, A. M. (2023). The Role of an Integrated Quality Management System in Improving Performance in the Port Organization. *Proceedings of the International Conference on Business Excellence*, 17(1), 1286–1296. <https://doi.org/10.2478/picbe-2023-0115>
- U.S. Government Accountability Office. (2024). Automation in transportation and logistics: Challenges and opportunities. Retrieved from <https://www.gao.gov/>

- Usman, F. A. (2020). Occupational safety and health in the maritime industry : a case study of Nigerian Ports Authority (NPA). World Maritime University The.
- Vanderlande. (2024). Predictive maintenance solutions for automated logistics systems. Retrieved from <https://www.vanderlande.com/>
- Vega-Muñoz, A., Salazar-Sepulveda, G., Espinosa-Cristia, J. F., & Sanhueza-Vergara, J. (2021). How to measure environmental performance in ports. Sustainability (Switzerland), 13(7), 1–18. <https://doi.org/10.3390/su13074035>
- Walters, D., Wadsworth, E., & Bhattacharya, S. (2020, January). What about the workers? — Experiences of arrangements for safety and health in global container terminals. Safety Science, 121, 474–484. <https://doi.org/10.1016/j.ssci.2019.09.017>
- Wang, Y., Shou-Yi, Z., Liu, Y., & Li, Y. (2016). Occupational hazards to health of port workers. International Journal of Occupational Safety and Ergonomics, 23(4), 584–588. <https://doi.org/10.1080/10803548.2016.1199501>
- Wang, Y., Zhan, S., Liu, Y., & Li, Y. (2017). Occupational hazards to health of port workers. International Journal of Occupational Safety and Ergonomics, 23, 584 - 588. <https://doi.org/10.1080/10803548.2016.1199501>.
- Wijayatunga, P. D. C., Siriwardena, K., Fernando, W., Shrestha, R., & Attalage, R. (2006). Strategies to overcome barriers for cleaner generation technologies in small developing power systems: Sri Lanka case study. Energy Conversion and Management, 47(7-8), 1179-1191.
- Yang, C. S. (2019, November). Maritime shipping digitalization: Blockchain-based technology applications, future improvements, and intention to use. Transportation Research Part E: Logistics and Transportation Review, 131, 108–117. <https://doi.org/10.1016/j.tre.2019.09.020>
- Zhang, Y., Wang, J., & Li, X. (2023). Development of an automated berthing system for large vessels. Ocean Engineering, 258, 111789. <https://doi.org/10.1016/j.oceaneng.2023.111789>

BIRD NESTING AND DROPPINGS IN HIGH-RISE BUILDINGS: A LITERATURE REVIEW

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Abstract. Bird nesting and droppings create substantial barriers to the operations and maintenance of high-rise buildings in urban areas, consequently creating numerous issues for buildings and their stakeholders. Therefore, it is crucial to properly investigate this significant problem and provide robust solutions. As an initial step, a comprehensive literature review on the research domain was conducted to explore the concerns of bird nesting and droppings in high-rise buildings, employing content analysis as the analysis method. Findings revealed that numerous factors affect bird nesting and droppings, which can cause impacts on building elements, health and safety of building stakeholders, aesthetic aspects of the building, and financial status of the business carried out in the building. According to the findings, the strategies that are currently practised to manage these issues include integrated pest management, habitat modification, physical and bio-acoustic deterrents, chemical repellents and technological solutions. The findings of this comprehensive literature review establish a strong foundation to enhance the field of facilities management in urban high-rise structures by providing essential knowledge on this long-standing issue. In addition, this study creates a basis for future research to identify more effective prevention methods and improved facility planning, design, and management practices.

Keywords. Bird Nesting; Bird Droppings; High-Rise Urban Structures; Bird-Related Issues

1. Introduction

The rapid growth of cities through urbanisation has sparked an extensive trend of high-rise construction throughout urban areas. These built structures provide essential housing and commercial spaces, especially in densely populated metropolitan regions. The increasing number of high-rise developments has led to unintended consequences, including greater interactions between birds and buildings (Gelder, 2003). The adaptation of urban habitats by birds such as pigeons, crows, and house sparrows has made high-rise buildings suitable for perching, roosting, and nesting (Fitzwater, 1988). These nesting habits and bird droppings in high-rise buildings create numerous operational challenges and issues for urban facilities and residents. In particular, they lead to unanticipated building maintenance problems and negatively impact both visual appeal and public health conditions (Janus & Lesinski, 2018).

Despite the growing challenges posed by bird nesting and droppings, limited research has been conducted on this issue in the context of high-rise buildings. Specifically, there is a lack of scientific evidence that comprehensively reviews the extent of the problem and its consequences. To address this research gap, this study aims to critically review the available literature on the impact of bird nesting and droppings, highlight several bird-attracting factors, and evaluate existing control strategies. Furthermore, the objectives are to identify key factors that attract birds to high-rise buildings, analyse the main impacts of bird nesting and droppings on high-rise structures, and investigate current bird management strategies. The uniqueness of this work is that it provides a holistic review of a significant real-world problem that high-rise buildings face and its state-of-the-art up to date. With the limitation of focusing entirely on high-rise building settings in

urban areas, this paper is organised to provide background on the problem, outline the methodology, present the literature findings, and conclude with key insights.

2. Methodology

To achieve the aim, a qualitative method was adopted for conducting this literature review. Papers related to bird droppings and nesting in building stock were identified through searches performed in academic databases such as ScienceDirect and Scopus. Only 21 relevant studies published over the past forty years (from 1985 to 2025) were recognised. Furthermore, a manual content analysis was used to synthesize the selected literature, as it was considered ideal for this paper's context due to its ability to provide rich qualitative insights from a limited and manageable number of papers, while also enhancing the depth, nuance, and flexibility of the review (Torelli et al., 2020)

The design of the review was structured into four main sections to ensure a comprehensive and coherent analysis. First, an overview of the issue of bird nesting and droppings in high-rise buildings was presented in order to establish the context and highlight the significance of the problem. Second, the review examined the key factors contributing to issue's occurrence and persistence, based on insights drawn from the selected literature. Third, a detailed synthesis of the identified impacts was conducted, with particular attention given to their implications within the facilities management context. Finally, the review explored various strategies currently used to mitigate and eliminate bird-related challenges in high-rise building environments.

3. Literature Findings

3.1. INTRODUCTION TO BIRD NESTING AND DROPPINGS IN HIGH-RISE BUILDINGS

Various bird species, such as pigeons, house sparrows, and crows, often choose high-rise buildings in cities as their preferred nesting locations. These structures offer secure roosting areas, protection from predators, and direct access to food resources, making them highly attractive for both roosting and nesting (Kodmany, 2018). As Spennemann & Watson (2018) explain, urban areas provide stable and reliable conditions for birds to nest, leading to large bird populations due to the city's resilience to seasonal changes and limited accessibility for predators. Moreover, bird nests and droppings found in high-rise buildings cause several serious problems, affecting both the structure and appearance of buildings, while also generating financial burdens and health risks (Clark et al., 2020). Consequently, this contributes to the deterioration of structural elements, reduces the building's lifespan, lowers occupant satisfaction with the built environment, and significantly increases costs for maintenance management. Therefore, high-rise environments essentially require effective management strategies due to the existing issues caused by bird populations. Therefore, high-rise environments require effective management strategies to address the challenges posed by bird populations. Although stakeholders involved in the operational phase, such as facilities management staff, building owners, and occupants experience the impact of bird nesting and droppings, it is not sufficient to implement control measures only during the operation and maintenance stages. These concerns should also be

addressed during the planning and design phases of buildings (Janus & Lesiński, 2018).

3.2 FACTORS AFFECTING BIRD NESTING AND DROPPINGS IN HIGH-RISE BUILDINGS

As per the literature findings, various elements that affect bird nesting and droppings in high-rise buildings comprise building architecture, environmental elements, food availability, human actions, and the absence of predators. Figure 1 depicts the main factors that affect bird nesting and droppings in high-rise buildings, and those factors are collected from several literature. The understanding of these factors serves as a necessity for creating successful management approaches to minimise bird-related problems in cities (Gelder, 2003).

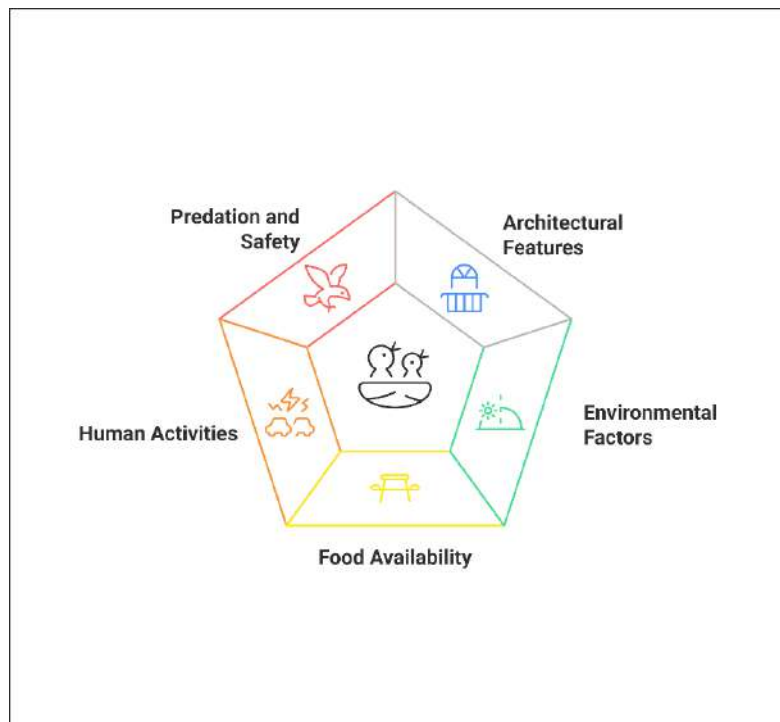


Figure 1: Factors affecting bird attraction

3.2.1 Architectural Features

High-rise building structures together with their architectural elements, create ideal conditions for bird nesting and perching possibilities. Ledges along with balconies, rooftop structures and ventilation openings resemble natural rock formations which attract birds to roost (Spennemann & Watson, 2018). The locations preferred by birds serve as protective shelter from adverse weather conditions and human disturbances (Balasubramaniam et al., 2021). Buildings with rough-textured surfaces enable birds to maintain a better grip, which enhances their chances of establishing nests (Sun et al., 2020). Modern glass facades prevent bird perching, yet they produce accumulated droppings, which impact building appearances (Clark et al., 2020). The nesting behaviour of birds becomes possible through gaps or cracks, which appear in poorly maintained structures (Janus & Lesinski, 2018).

3.2.2 Environmental Factors

Climate conditions together with wind patterns and artificial lighting sources, affect how birds choose their nesting areas (Lowry et al., 2013). The tropical climate of Sri Lanka sustains consistent bird activity across all seasons because of steady temperatures and plentiful food resources, according to Spennemann and Watson (2018). Birds choose their nesting locations based on weather protection, whereby recessed balconies and shaded rooftops serve as suitable shelters (Clark et al., 2020). Urban artificial lighting systems play an additional role in these environments. The presence of bright building lighting interferes with birds' regular roosting behaviour, causing them to seek rest on lit structures (Sun et al., 2020). According to Kodmany (2018), birds select nesting positions around high-rise buildings based on wind conditions because they prefer areas with reduced airflow.

3.2.3 Food Availability

The availability of a constant food supply in urban areas creates ideal conditions that draw numerous birds (Lowry et al., 2013). High-rise buildings attract more birds because of improper waste management practices and open garbage bins together with intentional feeding activities (Janus & Lesinski, 2018). The availability of food scraps creates ideal conditions for both pigeons and crows which enables them to establish permanent nest sites (Spennemann & Watson, 2018). Buildings with outdoor dining spaces, rooftop cafes, and exposed trash disposal areas unintentionally draw birds seeking food, according to Clark et al. (2020). The regular food supply in these areas motivates birds to settle near human areas which leads to increased droppings throughout the area (Balasubramaniam et al., 2021).

3.2.4 Human Activities

Human actions through behaviour create specific patterns for bird nesting activity within high-rise buildings. The process of construction enables birds to build their nests because scaffolding and unfinished structures function as suitable nesting locations (Spennemann & Watson, 2018). Bird populations settle into existing areas which they initially occupied after construction ends (Clark et al., 2020). The practice of public bird feeding helps birds establish themselves in urban environments. Bird populations within urban areas grow because both pigeons and crows find an abundance of food at human feeding locations (Balasubramaniam et al., 2021). Green spaces, rooftop gardens, and courtyards found in buildings provide birds with both food resources and materials for building nests which boosts their chances of settlement (Sun et al., 2020). Birds select locations with minimal human activity for nesting which includes mechanical rooms together with underutilized balconies and rooftop installations since these spaces create minimal disturbance (Kodmany, 2018).

3.2.5 Predation and Safety

The absence of natural predators in high-rise environments constitutes one major factor that allows birds to succeed. The natural landscape of birds exposes them to hawks, snakes and other predators yet urban areas create a more secure space for nesting (Spennemann & Watson, 2018). Bird populations grow without restraint because predation is absent which results in higher nesting densities (Clark et al., 2020). Group roosting behaviour that pigeons exhibit helps them survive better

through decreased exposure to dangers (Balasubramaniam et al., 2021). The grouping behaviour leads to excessive accumulation of droppings at locations which create extensive maintenance difficulties for high-rise buildings (Kodmany, 2018).

3.3 ISSUES ARISING DUE TO BIRD NESTING AND DROPPINGS IN HIGH-RISE BUILDINGS

The nesting behaviour of birds thrives within urban high-rise buildings, which creates multiple structural, health and safety problems, financial expenses, and visual disturbances. Droppings and nesting materials that accumulate create problems for building structures and represent health risks for residents as well as maintenance workers and facility managers (Gelder, 2003). Bird activities within high-rise buildings present multiple complex problems that need a thorough evaluation to determine their effects on the future maintenance of buildings and urban infrastructure. Figure 2 displays the main issues that arise due to birds in the buildings.

3.3.1 Issues for Building Elements (Structural Damage)

Bird nesting and droppings inflict substantial harm to high-rise structures by damaging concrete and metal materials as well as glass elements and roofing surfaces. Nesting material creates blockages that interrupt drainage systems and ventilation pathways, causing operational problems that cost money to fix. Uric acid in bird droppings, together with the physical accumulation of nests and debris in important building locations causes these structural problems (Spennemann & Watson, 2018).

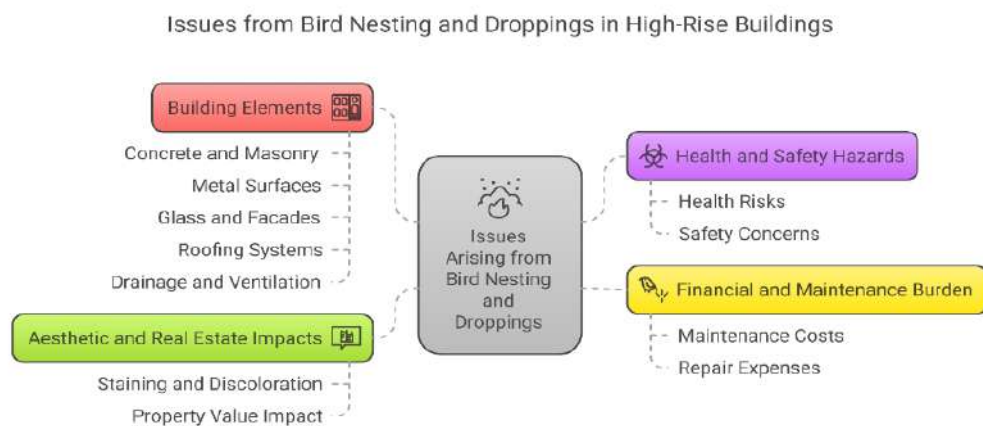


Figure 2: Major issues arise due to birds

3.3.2 Impact on Concrete and Masonry (Corrosion and Cracking Due to Uric Acid)

Bird droppings inflict significant damage on concrete and masonry surfaces because these materials have a porous composition. The uric acid in bird droppings maintains a pH level between 3 and 4 to create conditions that degrade concrete by breaking down calcium carbonate in the material (Clark et al., 2020). Prolonged exposure to bird droppings results in a degradation of concrete material strength,

which creates erosion of surfaces and deep cracks that let moisture reach the inner layers.

The entrance of moisture leads to concrete degradation that expands the material and creates fractures, which ultimately results in spalling (Sun et al., 2020). The rate of deterioration reaches its highest point in coastal cities because the combination of high humidity worsens the chemical interaction between building materials (Forr et al., 2022). Studies reveal that when bird droppings remain uncleaned, they decrease concrete durability by 40%, which requires increased maintenance work and resurfacing (Kodmany, 2018).

3.3.3 Impact on Metal Surfaces (Rusting and Degradation of Window Frames, Railings)

Metal surfaces face severe threats from bird droppings because their acidic nature speeds up oxidation processes and corrosion effects. The chemical interactions between uric acid and aluminium steel and iron components used in windows, beams, and balcony railings result in material degradation and rust formation (Spennemann & Watson, 2018). The duration that droppings stay on metal surfaces, along with moisture exposure from rain and humidity, intensifies this problem. The chemical reaction produces deep holes in the metal structure known as pitting corrosion, which severely weakens material durability (Forr et al., 2022). Unprotected metal surfaces develop corrosion at a rate five times faster than normal when exposed to bird droppings, according to Janus and Lesinski (2018). High maintenance expenses for cleaning operations exist due to the need for frequent cleaning to prevent long-term damage from corrosion on high-rise buildings. Facility managers must replace corroded metal fixtures because the damage exceeds repairability, which leads to additional expenses (Clark et al., 2020).

3.3.4 Impact on Glass and Facades (Staining and Discoloration)

Modern high-rise buildings commonly use glass facades, which experience high susceptibility to permanent staining and etching caused by bird droppings. Glass rejects the absorption of uric acid, yet extended contact leads to permanent discoloration through surface etching which results in glass becoming hazy and permanently clouded (Sun et al., 2020). Building exteriors that use glass facades face significant aesthetic damage, which harms the property value and market appeal of commercial and luxury residential properties. The accumulation of droppings on windows creates visibility reduction through blocked natural light, which requires regular professional cleaning services (Kodmany, 2018). According to Spennemann & Watson (2018), urban high-rises with glass exteriors need regular maintenance cycles of 2-3 weeks when bird droppings affect their surfaces, thus escalating building maintenance costs. Acidic etching creates surface weaknesses in glass, which will eventually lead to cracking (Clark et al., 2020).

3.3.5. Impact on Roofing Systems (Erosion and Leakage Caused by Acidic Runoff)

Bird droppings have a severe impact on roofing systems because they are exposed to environmental conditions. Uric acid in droppings creates acidic runoff after combining with rainwater, which progressively destroys roofing materials, including asphalt shingles, tiles, and membranes (Balasubramaniam et al., 2021). Flat roofs

covered in stagnant water provide perfect conditions where droppings can gather to speed up material breakdown processes (Clark et al., 2020). The acidic material that flows from roofing surfaces weakens the structure until water enters through leaks and mould forms inside (Clark & Shah, 2019). Building owners must replace roofs prematurely because the maintenance costs rise together with reduced lifespan, which stems from severe building damage (Sun et al., 2020). When birds occupy rooftops, they create drainage system blockages that block water runoff, which leads to structural damage through water accumulation (Kodmany, 2018).

3.3.5 Blockage of Drainage and Ventilation Systems (Obstruction by Nests and Droppings)

The presence of bird nests and their droppings accumulation creates blockages which disrupt fundamental building systems such as drainage systems and ventilation and air conditioning units. The placement of nesting materials across rooftop gutters along with downspouts causes rainwater accumulation that produces leaks and leads to interior flooding (Spennemann & Watson, 2018).

HVAC systems and exhaust fans along with chimneys face vulnerability from bird nesting which produces airflow limitations and overheating effects and leads to mechanical breakdowns (Janus & Lesinski, 2018). When ventilation is blocked it produces inferior indoor air quality while increasing power costs and raising fire risks because components become overheated (Clark & Shah, 2019). The study by Sun et al. (2020) identified that intake vents experienced clogging due to bird nesting materials in 60% of HVAC malfunctions that occurred in buildings prone to bird activity. System functionality requires regular inspection followed by nest removal to stop permanent damage from occurring.

3.3.6 Health and Safety Issues

The presence of bird droppings represents a significant health risk to communities because these droppings contain dangerous pathogens and zoonotic diseases. Studies have found more than sixty diseases that can be transmitted through bird droppings with histoplasmosis, cryptococcosis, and psittacosis among them (Stafford III, 2004). People who contact with infected surfaces face serious health risks alongside residents and personnel who maintain the building and those who visit the facility. The most significant health risk takes place because dried bird droppings spread spores through the air. The disturbance of these spores releases them into the air, leading to respiratory illnesses like others have reported (Balasubramaniam et al., 2021). Buildings that have ventilation systems infected with bird excrement face high risks because airborne spores spread to indoor zones where occupants become exposed to health dangers (Spennemann & Watson, 2018). The presence of bird droppings on walkways, staircases, and balconies poses both health hazards and dangerous slip risks that raise injury probabilities (Schmidt et al., 2005). Research shows that urban environments experience a substantial number of slip-and-fall accidents because of bird droppings (Clark et al., 2020).

Facility managers operating in high-rise buildings face legal risks from fall accidents triggered by slippery surfaces, thus making bird management issues more difficult. The presence of bird nests in electrical and mechanical installations creates significant fire risks. Birds construct their nests within air conditioning units,

electrical boxes, and ventilation ducts, which enable overheated nesting materials to ignite into electrical fires (Sun et al., 2020). Urgent bird management solutions must be developed for high-rise buildings because of these recently reported incidents.

3.3.7 Financial and Maintenance Impact

Bird nesting, along with their droppings, creates significant financial burdens by increasing maintenance expenses and reducing building market value. Specialized procedures, including high-pressure washing, chemical treatments, and manual scrubbing, become necessary to remove bird droppings and nests (Janus & Lesinski, 2018). The occurrence of cleaning cycles is more frequent in buildings with substantial bird populations, which drives up operational expenses together with labour costs (Clark et al., 2020).

According to research on urban property management, buildings that experience bird droppings require exterior maintenance costs that increase by as much as 30% compared to unaffected properties (Spennemann & Watson, 2018). The additional expense required for cleaning combined with repainting and material substitution, creates substantial financial challenges for property owners and management companies. Bird-caused property damage forces property owners to pay elevated insurance premiums on top of their cleaning expenses. Structural repairs on buildings with bird-related damage earn insurance agencies a higher classification as risky properties, which drives policy rates for such repairs higher (Sun et al., 2020). Bird-related expenses create sustained economic problems for buildings that lack proper bird management methods in high-rise structures.

3.3.8 Aesthetic and Real Estate Impact

High-rise buildings depend heavily on their visual appearance to determine both their property value and their market potential. Bird droppings cause permanent stains on facades as well as balconies and windows, which diminishes building reputation and leads to tenant dissatisfaction (Kodmany, 2018). The visual appearance of commercial properties and luxury residential buildings depends on exterior cleanliness because it determines market desirability for buyers and tenants (Clark et al., 2020).

The appearance of buildings deteriorates when aesthetics degrade, which leads to decreased property values. Bird-related damage that can be observed by potential renters or buyers frequently leads to reduced property demand and income reductions through negative perceptions about building maintenance quality (Spennemann & Watson, 2018). The unpleasant odour from accumulated birds due to droppings causes discomfort among building occupants and forms negative impressions about building cleanliness (Balasubramaniam et al., 2021). The maintenance of high-rise building aesthetics, together with commercial value, requires immediate proactive bird control strategies.

3.4 STRATEGIES TO MITIGATE AND ELIMINATE BIRD-RELATED ISSUES

Multiple strategies, including physical barriers together with chemical substances and bio-acoustic devices, as well as habitat adjustments and technological developments, aim to reduce bird impacts in high-rise buildings. Figure 3 depicts several strategies that are used to mitigate and eliminate bird-related issues. The

implementation of these strategies produces different levels of effectiveness alongside variable sustainability and cost characteristics, thus demanding specific urban solutions.

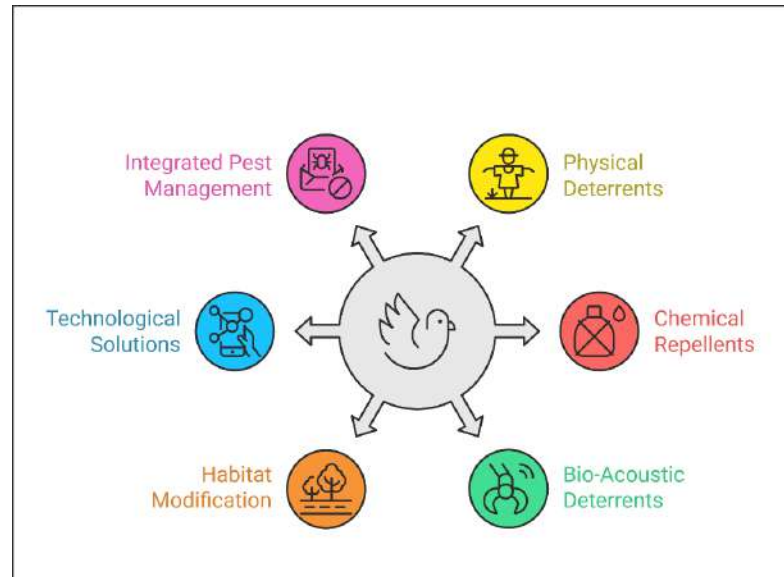


Figure 3: Bird controlling strategies

3.4.1 Physical Deterrents

The implementation of bird spikes and netting stands as the primary barrier approach for stopping birds from using building ledges and balconies as roosting sites (Clarke, 2004). Also, large open areas receive effective protection from netting, and bird spikes effectively stop birds from accessing narrow ledges (Williams et al., 2015). The effectiveness of these solutions decreases when installation goes wrong or when they experience prolonged exposure to weather elements (Dwyer & Mannan, 2007).

3.4.2 Chemical Repellents

Building surfaces receive regular applications of gel-based and scent-based deterrents, which make them unattractive for perching activities (Bishop et al., 2003). Methyl Anthranilate functions as a widely used chemical repellent because its grape-scented composition creates an unpleasant experience for birds through both taste and smell (Clark & Shah, 2019). Rain and environmental exposure diminish chemical repellents, so they need regular reapplication, thus increasing the long-term maintenance expenses (Clark et al., 2020).

3.4.2 Bio-Acoustic Deterrents

Bio-acoustic systems transmit prerecorded predator alarm sounds and distress signals that function as bird deterrents for buildings (Bishop et al., 2003). The technology allows users to program the systems for different types of birds (Seamans et al., 2013). The effectiveness of these devices becomes limited in the long run since birds develop a tolerance to repeated sounds, which demands periodic changes in frequency patterns for continued deterrence (Clarke, 2004).

3.4.4 Habitat Modification

The field of urban planning, together with architecture, has started to redesign buildings in ways that eliminate potential nesting sites (United States Department of Agriculture [USDA] & Tennessee Valley Authority [TVA], 2014). The combination of sloped surfaces with smooth building exteriors and the removal of small ledges stops birds from establishing their nests (Janus & Lesiński, 2018). Secure waste management systems combined with food waste reduction practices eliminate food sources in urban spaces, which make urban buildings less attractive to birds (De Araujo et al., 2018).

3.4.5 Technological Solutions

The combination of laser-based bird deterrents with automated monitoring systems and AI-driven control methods offers effective non-invasive solutions for addressing bird-related issues (Blackwell et al., 2002). The movement of laser-detected light beams functions as a threat signal for birds, which drives them to stay away from treated areas (Taylor et al., 2018). Automated bird monitoring tools combine motion detectors with video surveillance to sense bird movements, which trigger appropriate deterrent responses (Bishop et al., 2003). AI-based solutions have been developed to study bird behaviour patterns through analysis, which enables dynamic adjustments to deterrent strategies for improved bird control (Balasubramaniam et al., 2021).

3.4.6 Integrated Pest Management (IPM)

The integrated pest management approach develops extensive bird control plans through a combination of physical barriers and chemical and behavioural intervention methods (Clark et al., 2020). The method operates for sustainable long-term outcomes through modifications of bird control strategies, which depend on environmental conditions and bird activities (Baldwin et al., 2017).

Hence, the review of literature could provided valuable insights into the bird nesting and droppings, with a focus on three key areas of concern, and the findings are summarized in Figure 4

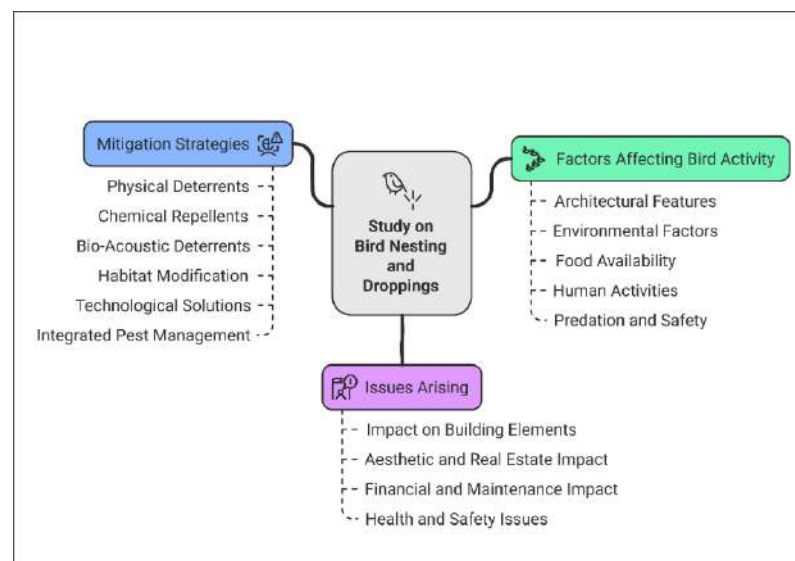


Figure 4: Summary of literature findings on bird nesting and droppings in high-rise buildings

4. Conclusion

The issues caused by bird nesting and droppings in high-rise buildings emphasise the urgent need for effective strategies to ensure the sustainability of built environments of high-rise buildings (Klug et al., 2023). Figure 4 provides a summary of the main literature findings on bird nesting and droppings in high-rise buildings and creates a compilation of other research. This research demonstrates how bird nesting, combined with their droppings creates significant challenges for high-rise buildings in urban areas. Accordingly, as the study reveals, the bird population at high-rise building structures are increasing because buildings provide suitable habitats and plenty of food sources and lack predator presence. Furthermore, uncontrolled bird activity produces structural harm, financial loss and health dangers as its major effects. The acidic nature of bird excrement speeds up building material breakdown along with concrete, metal and glass surfaces and blocked drainage pipes and ventilation systems creating water damage and HVAC malfunction. The presence of bird droppings creates multiple serious health threats which endanger the health of those living in high-rise buildings along with their maintenance workers. Additionally, the identified controlling strategies imply that the physical barriers combined with chemical repellents and bio-acoustic deterrents fail to establish enduring sustainable solutions for bird control. Thus, the integration of bird management strategies with emerging technological approaches would improve the productivity of the solutions (Harris et al., 2018). Policymakers should design appropriate regulations and building codes on bird management at the design stage. The practitioners of the industry should also embrace the use of integrated bird deterrent systems that incorporate physical, chemical, and smart technologies. The academics are encouraged to further study bio-acoustic adaptation, material innovations and AI-powered surveillance.

Beyond the identified control measures, this research underscores the requirement of a robust framework to effectively and efficiently address this issue. Hence, future studies can develop upon this research to develop such a framework. The outcome of this work will be immensely advantageous to facilities/maintenance managers, helping ensure the well-being of the building structure, reducing maintenance costs, and improving stakeholder satisfaction and safety within tall buildings.

5. References

- Al-Kodmany, K. (2018). Sustainability and the 21st-century vertical city: A review of design approaches of tall buildings. In *Buildings* (Vol. 8, Issue 8). MDPI AG. <https://doi.org/10.3390/buildings8080102>
- Balasubramaniam, K. N., Bliss-Moreau, E., Beisner, B. A., Marty, P. R., Kaburu, S. S. K., & McCowan, B. (2021). Addressing the challenges of research on human-wildlife interactions using the concept of Coupled Natural & Human Systems. In *Biological Conservation* (Vol. 257). Elsevier Ltd. <https://doi.org/10.1016/j.biocon.2021.109095>
- Baldwin, R., Wilcox, S., & Barnett, J. (2017). Integrated pest management strategies for urban bird control. *Pest Management Science*, 73(2), 245–253. <https://doi.org/10.1002/ps.4532>
- Bishop, J., McKay, H., Parrott, D., & Allan, J. (2003). Review of international research literature regarding the effectiveness of auditory bird scaring techniques and potential alternatives.

- Blackwell, B. F., Bernhardt, G. E., & Dolbeer, R. A. (2002). Lasers as nonlethal avian repellents. *Journal of Wildlife Management*, 66(1), 250. <https://doi.org/10.2307/3802891>
- Clark, D. E., & Shah, R. (2019). Evaluating the effectiveness of chemical repellents for urban bird management. *Environmental Management*, 53(4), 667–674. <https://doi.org/10.1007/s00267-019-1212-4>
- Clark, L., Eisemann, J., Godwin, J., Horak, K. E., Oh, K., O'Hare, J., Piaggio, A., Pepin, K., & Ruell, E. (2020). Invasive Species Control and Resolution of Wildlife Damage Conflicts: A Framework for Chemical and Genetically Based Management Methods (pp. 193–222). https://doi.org/10.1007/978-3-030-53183-6_9
- Clarke, T. L. (2004). An autonomous bird deterrent system. ResearchGate. https://www.researchgate.net/publication/279478907_An_autonomous_bird_deterrent_system
- De Araujo, G. M., Peres, C. A., Baccaro, F. B., & Guerta, R. S. (2018). Urban waste disposal explains the distribution of Black Vultures (*Coragyps atratus*) in an Amazonian metropolis: management implications for birdstrikes and urban planning. *PeerJ*, 6, e5491. <https://doi.org/10.7717/peerj.5491>
- Dwyer, J. F., & William Mannan, R. (2007). PREVENTING RAPTOR ELECTROCUTIONS IN AN URBAN ENVIRONMENT. *Journal of Raptor Research*, 41(4), 259–267. doi:10.3356/0892-
- Fitzwater, W. D. (1988). SOLUTIONS TO URBAN BIRD PROBLEMS. <https://www.semanticscholar.org/paper/SOLUTIONS-TO-URBAN-BIRD-PROBLEMS-Fitzwater/71e36762eeeb7463b79216611b57d5a036fee235#related-papers>
- Forr, F., Mysliu, E., Nordlien, J. H., & Erbe, A. (2022). The effect of bird droppings on the corrosion of steel and aluminum used in offshore applications. *Materials and Corrosion*, 74(3), 464–481. <https://doi.org/10.1002/maco.202213533>
- Gelder, J. (2003). BIRDS AND BUILDINGS. Source: *Environment Design Guide*, 56, 1–10. <https://doi.org/10.2307/26148829>
- Harris, E., De Crom, E. P., Fouche, J., & Wilson, A. (2018). Comparative study on the short-term effects of audio and visual raptor presence on a pigeon population, with a view towards pest control. *International Journal of Pest Management*, 66(1), 31–39. <https://doi.org/10.1080/09670874.2018.1542185>
- Janus, K., & Lesinski, G. (2018). Birds and bats using buildings as a place of breeding or shelter. *Annals of Warsaw University of Life Sciences - SGGW - Animal Science*, 57(1), 19–29. <https://doi.org/10.22630/aas.2018.57.1.2>
- W, P. G., Terrell, P. S., & Crabb, A. . C. (2000). A national review of the status of trapping for bird control. *Proceedings - Vertebrate Pest Conference*, 19. <https://doi.org/10.5070/v419110061>
- Klug, P. E., Shiels, A. B., Kluever, B. M., Anderson, C. J., Hess, S. C., Ruell, E. W., Bukoski, W. P., & Siers, S. R. (2023). A review of nonlethal and lethal control tools for managing the damage of invasive birds to human assets and economic activities. In *Management of Biological Invasions* (Vol. 14, Issue 1, pp. 1–44). Regional Euro-Asian Biological Invasions Centre. <https://doi.org/10.3391/mbi.2023.14.1.01>
- Lowry, H., Lill, A., & Wong, B. B. M. (2013). Behavioural responses of wildlife to urban environments. *Biological Reviews*, 88(3), 537–549. <https://doi.org/10.1111/brv.12012>
- Schmidt, R. H., Erickson, D. J., Wainness, H., & Paul, S. (2005). Sanitary Design and Construction of Food Processing and Handling Facilities 1. <http://edis.ifas.ufl.edu>
- Seamans, T. W., Martin, J. A., & Belant, J. L. (2013). Tactile and Auditory Repellents to Reduce Wildlife Hazards to Aircraft. https://digitalcommons.unl.edu/icwdm_usdanwrc
- Spennemann, D. H. R., & Watson, M. J. (2018). Experimental Studies on the Impact of Bird Excreta on Architectural Metals. Source: *APT Bulletin: The Journal of Preservation Technology*, 49(1), 19–28. <https://doi.org/10.2307/26452201>

- Stafford III, K. C. (2004). Tick Management Handbook A integrated guide for homeowners, pest control operators, and public health officials for the prevention of tick-associated disease The Centers for Disease Control and Prevention The Connecticut Agricultural Experiment Station. www.semguay.com
- Sun, L., Chen, J., Li, Q., & Huang, D. (2020). Dramatic uneven urbanization of large cities throughout the world in recent decades. *Nature Communications*, 11(1). <https://doi.org/10.1038/s41467-020-19158-1>
- Taylor, J., Harrison, K., & Green, P. (2018). Laser technology for humane bird deterrence in urban environments. *Journal of Wildlife Management*, 82(6), 1234–1242. <https://doi.org/10.1111/jwmg.12412>
- Torelli, R., Balluchi, F., & Furlotti, K. (2020). The materiality assessment and stakeholder engagement: A content analysis of sustainability reports. *Corporate Social Responsibility and Environmental Management*, 27(2), 470–484. <https://doi.org/10.1002/CSR.1813>
- United States Department of Agriculture Animal and Plant Health Inspection Service Wildlife Services, in cooperation with Tennessee Valley Authority. (2014). Environmental assessment: Managing damage caused by birds in the state of Tennessee. https://www.aphis.usda.gov/wildlife_damage
- Williams, G. M., Whittaker, R. H., & Nelson, L. (2015). Perching prevention techniques in urban architecture. *Urban Ecology Reports*, 24(2), 77–83. <https://urbanecologyjournals.com/prevention-techniques>

ADAPTATION OF AUTOMATED DEMAND RESPONSE (ADR) TECHNOLOGY TO REDUCE PEAK ENERGY DEMAND IN SRI LANKAN COMMERCIAL BUILDINGS

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Abstract. Automated Demand Response (ADR) technology could potentially be used to lower peak energy use in commercial buildings in Sri Lanka. By assessing the feasibility, benefits, and challenges of ADR in the local context, the study aims to fill the implementation gap. Using a mixed-method approach, surveys and expert interviews with stakeholders, utility providers, regulatory bodies, and energy market experts were used to acquire quantitative and qualitative data. The results show that Sri Lanka's commercial buildings increase operational expenses and increase grid instability by contributing significantly to peak energy consumption. By allowing dynamic energy consumption changes during peak hours, ADR technology offers an acceptable approach that enhances grid stability and lowers energy costs. The study found several barriers to the ADR, such as the high initial setup costs, the lack of standardized protocols, incentives, and supportive legislation. Despite these barriers, the study emphasizes how ADR might improve sustainability and energy efficiency in Sri Lanka's commercial sector. The surveys showed a mixed state of current readiness for ADR adaptation, while expert interviews offered deeper insights into the feasibility of ADR adaptation. Stakeholders are generally aware of and interested in ADR technology; however, there are still significant gaps in technical capability, financing, and regulatory support. The study concludes with a three-year roadmap for implementing ADR, highlighting the significance of regulatory support, stakeholder involvement, and tech-infrastructure investment.

Keywords. Demand Response, Demand Side Management, Automated Demand Response, Feasibility, Readiness

1. Introduction

In recent years, global energy consumption has been on the rise, which is driven by factors like urbanization, industrialization, technological progress, a growing population, expanding economies, and the widespread adoption of energy-intensive technologies in daily life (Avtar et al., 2019). This global phenomenon is mirrored in Sri Lanka, where urbanization and economic growth have resulted in a simultaneous increase in energy demand, particularly in the commercial sector (Morimoto & Hope, 2004). When it comes to the Sri Lankan context, the load profile of Sri Lanka's electricity system has a high peak in the evening and a poor load factor as a result. (Study report on electrical demand curve and system peak reduction, 2017. According to the Generation summary (2023) load curve, there are two peaks as a day peak and a night peak. The day peak occurs at 16.00 while the night peak occurs at 19.15, with respective values of 1984.9MW and 2324.5MW. To handle peak loads, utility companies were encouraged to look for load management programs (Cappers et al., 2010).

At the forefront of modern energy management technologies, Automated Demand Response (ADR) provides a methodical and automated approach to demand response in commercial buildings. The foundation of ADR is the concept of facilitating communication and control to regulate power usage dynamically between utilities and end customers (Abate et al., 2013). The basic idea is that signals are exchanged, usually in the form of price or dependability data, to initiate

automated changes in energy consumption and this demand response system gives end users the freedom to adjust to shifting grid conditions while improving grid efficiency and stability (Institute of Electrical and Electronics Engineers, 2014). An Automated Demand Response (ADR) solution that enables the utility to quickly and efficiently manage its customers to enhance the DR capability for wider implementation is presented in (Daisuke et al., 2016). ADR uses technology advancements and automated mechanisms to automatically reduce energy use during times of high demand, doing so without the need for human intervention (Piette et al., 2004).

Globally, power systems are increasingly challenged by growing peak electricity demand, aging infrastructure, and the integration of intermittent renewable energy sources. As a result, Automated Demand Response (ADR) has emerged as a crucial tool for demand-side management, offering a dynamic and intelligent approach to energy reduction during peak periods (Wang et al., 2022; IEA, 2021). ADR systems utilize communication and control technologies to automatically adjust building loads in response to grid signals, providing grid flexibility and reducing operational costs.

While developed countries have seen widespread deployment of ADR technologies, their adaptation in developing nations like Sri Lanka remains limited. According to Fernando (2018), the concept of demand response is still in its early stages in Sri Lanka, highlighting the need for strategic exploration and implementation. Recent analyses by the Public Utilities Commission of Sri Lanka (PUCSL, 2022) emphasize that DR programs, especially when automated, could significantly defer infrastructure investments and optimize grid stability.

However, Sri Lanka's commercial sector, a major contributor to national peak demand, has yet to adopt ADR technologies in a scalable and systematic manner. This research therefore seeks to fill that gap by examining the current readiness, feasibility, and adaptation potential of ADR technologies in Sri Lankan commercial buildings. The study aims to provide actionable insights for utilities, policymakers, and building managers, thereby contributing to the modernization of the country's energy management systems in alignment with global best practices. In order to achieve the research aim, following research objectives were formulated.

- Review the state of demand response programs and their impact on peak energy demand and concept of Automated Demand Response
- Assess the current level of readiness for Automated Demand Response (ADR) adaptation in Sri Lanka
- Develop a roadmap to adapt ADR in next three years in Sri Lanka.

2. Literature Review

This section presents the key literature findings related to two major areas: (i) Current energy market and state of demand response programs and their impact on peak energy demand, and (ii) The concept of ADR and barriers for ADR technology.

2.1 DEMAND SIDE MANAGEMENT AND DEMAND RESPONSE PROGRAMS

Demand response (DR) can be defined as the act whereby consumers who are the end users of electricity modify their consumption levels based on the changes in

the price of power at different times. As stated in the literature analysis by Albadi et al., (2008), it is the process of convincing consumers to shift their consumption of electricity to the periods when there is more availability of electricity or there is less consumption by others in order to balance the load on power systems, which is mainly done through prices or incentive/penalty schemes. (Emi Bertoli, 2023). Based on this definition, the idea is to make DR attractive to consumers, in order to manage their power usage preferences in a way that will benefit not only themselves but also the power grid (Güner et al., 2020).

For many reasons, commercial buildings have a significant potential to engage in DR projects. Commercial buildings account for a large portion of the electricity load in most countries (i) buildings account for more than half of the total electricity load (ii) commercial buildings have many predictable loads operating on repeating schedules, making them good candidates for distributed renewable energy (DR); (iii) many commercial buildings have centralized control, which lowers the cost of integrating them in DR programs (Jradi & Veje, 2017).

2.2 EFFECT OF DR APPROACHES ON PEAK ENERGY DEMAND

Supply-side management (SSM) and demand-side management (DSM) are both techniques used in power system management to reduce peak loads, improve network-loading capacity, and mitigate contingencies (Jabir et al., 2018). According to, United Nations Industrial Development Organization, (2007), the study states that supply-side management seeks to improve the operational effectiveness of electricity generation, transmission, and distribution, guaranteeing effective energy production at the lowest possible cost, meeting electricity demand without unnecessary infrastructure investments, and minimizing environmental impacts through the effective use of power system assets.

Programs for demand response (DR) are acknowledged as a crucial subset of demand-side management (DSM) as a whole (Meyabadi & Deihimi, 2017). Demand response is a strategy that aims to optimize electricity usage by intentionally engaging end users to adjust their consumption patterns in response to changing market conditions or grid dynamics (Palensky & Dietrich, 2011).

The study conducted by, Logenthiran et al., (2012), stated that, DSM benefits consumers as well as energy providers as it enables consumers to actively participate in reshaping their load profiles through informed decision-making to achieve optimal energy consumption which leads to reduced peak load demand and, as a result, contributes to the stability of the power system network as a whole.

Optimization of utility system performance is largely dependent on load management, which is an essential component of demand-side management (Gellings, 1985). Currently, utility operations are focused on achieving specific load shape objectives through various types of demand response initiatives that fall into six main categories: flexible load shape, strategic load growth, peak clipping, valley filling, load shifting, and strategic conservation (Logenthiran et al., 2012).

Peak clipping is the process of lowering utility loads during periods of peak demand, whereas valley filling is the process of constructing off-peak loads. Their common objective is to close the gap between peak and valley load levels (Esther & Kumar, 2016) Load shifting is transferring the load from periods of peak demand to periods

of off-peak demand while maintaining constant overall energy consumption. This makes it one of the DSM's most successful load control techniques (Javor & Janjic, 2016). The goal of strategic conservation is to lower both peak demand and overall energy consumption by modifying the load-shape at the customer premises. Strategic load growth refers to an increase in electricity sales based on competitive fuel pricing (Sharda et al., 2021). The foundation of flexible load shape is those adaptable clients who are prepared to accept changes in service quality in return for monetary incentives (Javor & Janjic, 2016).

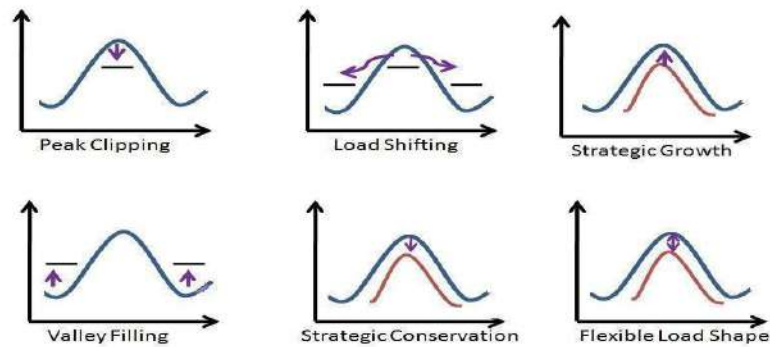


Figure 1: Demand Management

2.3 REVIEW OF ADR TECHNOLOGY

ADR (Automated Demand Response) technology encompasses a range of systems and protocols designed to automate the process of adjusting electricity usage in response to grid signals. Among these technologies, OpenADR (Open Automated Demand Response) stands out as a widely adopted open standard that facilitates seamless communication between utilities and energy management systems.

In its simplest form Open ADR is an open communication standard, which acts as a tool for energy providers, and end users by allowing efficient DR signal exchange. Hoekstra et al., (2016) have postulated that OpenADR provides the facilities to allow this communication to take place efficiently via a standard language that operates over existing Internet Protocol based networks. The OpenADR has been applied in the context of peak load control for quite some time now, but its application has recently been ramped up for the rapid DR programs and auxiliary services. Notably, this change underscores the increasing need to balance variable energy production from renewable sources, emphasizing OpenADR's flexibility and applicability in modern energy environments (Hoekstra et al., 2016)

When OpenADR is incorporated into smart grids, automated demand response (ADR) is created as a result of the systematic transmission of signals. ADR is emphasized by the OpenADR Alliance as fully automated power supply signaling that enables automatic connectivity to end-user control systems (OpenADR Alliance, 2014). This entails a dynamic and predetermined series of steps to successfully balance energy load availability and demand. As stated in the U.S. Department of Energy (2007), ADR is a critical energy management approach, particularly given that an ongoing increase in energy use is placing pressure on available generation capacity.

2.4 BARRIERS FOR ADR TECHNOLOGY

Table 1: Barriers for ADR adaptation

Barriers	Cited From
Integration with existing building management system	(Page et al., 2011)
Lack of standardized protocols	(Heffner, 2009)
Limited incentives	(Electric Power Research Institute, 2011)
High initial setup and installation cost	(California Edison, 2020)
Lack of supportive policies	(Wikler, 2021)
Low awareness	(Bruceri et al., 2017)
Limited knowledge and expertise	(Electric Power Research Institute, 2011)

3. Methodology

The methodical, theoretical examination of the approaches used in a field of study is known as research methodology (Steffe et al., 2012). Consequently, a mixed method was adopted in this research. Experts for interviews and surveys were selected based on the snowball technique. Eight expert interviews were conducted, with the energy industry experts working on utility companies, the sustainable energy authority, and the public utility commission in Sri Lanka, and the questionnaire survey was circulated among 30 people who are involved with the energy market and have knowledge about the Sri Lankan energy sector. Snowball sampling is not a probability technique, and it is a random method. Manual content analysis is used to analyze the data retrieved from expert interviews. To summarize the responses' central tendency, the mean value was calculated when analyzing the questionnaire survey data. The mean value, also called the average, gives a number that sums up the typical answer. The calculation involves adding up each response and dividing the result by the total number of responses, and analyzing the 5-point Likert scale results, for which the SPSS software was used. A comprehensive literature review was conducted on the state of demand response programs and their impact on peak energy demand and the concept of Automated Demand Response concept achieving objective 1. A survey was conducted to assess the current level of readiness for Automated Demand Response (ADR) adaptation in Sri Lanka, achieving objective 2. Findings of the survey and interviews were used to develop the roadmap to adapt ADR in the next three years in Sri Lanka, achieving objective 3.

4. Results

4.1 THE CURRENT LEVEL OF READINESS FOR AUTOMATED DEMAND RESPONSE (ADR) ADAPTATION

The current state of readiness for ADR adaptation is examined in this analysis in five major areas: financial, market, regulatory, technological, and knowledge, expertise, and competency readiness. Each component was evaluated by a survey in which 30 participants from the energy market rated their level of readiness using

a Likert scale. The analysis was conducted using the mean of the total responses, and SPSS software was used for these results interpretation.

Readiness levels are categorized based on the mean values from the survey. To summarize the responses' central tendency, the mean value was calculated when analyzing the questionnaire survey data. Given the relatively balanced Likert-type scale used in the survey. Following a structural clarification.

Level 1 0-1 Not ready at all (No or minimal funding, technology and infrastructure, awareness, government and policy support)

Level 2 1-2 Slightly ready (Basic funding, technology and infrastructure, awareness, government and policy support)

Level 3 2-3 Moderately ready (Considerable funding, technology and infrastructure, awareness, government and policy support)

Level 4 3-4 Almost ready (Significant funding, technology and infrastructure, awareness, government and policy support)

Level 5 4-5 Fully ready (Well-developed technology and infrastructure, awareness, adequate funding, as well as government and policy support)

Table 2: Current level of readiness for ADR

Readiness Category	Question	Mean Value	Readiness Level
Technological Readiness	Availability of advanced metering infrastructure	4.31	Level 4
	Availability of network Infrastructure (Wi-fi, Zigbee, cellular)	4.86	Level 5
	Availability of Control devices (Smart thermostats, lighting controls)	3.83	Level 4
	Availability of communication protocols (OpenADR, BACnet)	3.69	Level 4
	Availability of Cybersecurity Measures	3.07	Level 3
	Availability of Demand Response Automation Servers (DRAS)	2.00	Level 2
	Availability of energy management system (EMS, BMS)	4.97	Level 5
Overall Technological Readiness		3.81	Level 4
Financial Readiness	Government funding for smart grid pilot projects	3.79	Level 4
	Has identified as prioritized investment	2.28	Level 3
	Budget allocation for Smart grid concept including ADR technology development and implementation	1.79	Level 2
Overall financial Readiness		2.63	Level 3
Knowledge, Skills, and Competency Readiness	Availability of knowledge, skills, and competencies to adopt the technology	4.38	Level 4
	Research and development efforts to enhance the adaptability of the technology	4.00	Level 4
	Availability of practical cases of the technology	2.24	Level 3
Overall knowledge, skills, and competency Readiness		3.54	Level 4
Market Readiness	Market demand for the Technology	2.34	Level 3

	Sufficient market incentives for participants	3.17	Level 3
Overall market Readiness		2.75	Level 3
Regulatory Readiness	According to your knowledge, rate the regulatory readiness in Sri Lanka for adopting ADR technology	1.93	Level 2
Overall Regulatory Readiness		1.93	Level 2

As illustrated in above table, seven different elements were used to assess the technological readiness for Automated Demand Response (ADR) adaption. The total mean score of 3.81 indicates that while certain factors indicate higher degrees of preparedness, the level of readiness is close to "Almost ready" level. The assessment of financial readiness for the adoption of Automated Demand Response (ADR) was conducted by considering three particular areas, the average score of 2.63 indicates that financial preparedness is somewhere between "Slightly ready" and "Moderately ready." The evaluation of the readiness level for the adoption of Automated Demand Response (ADR) was conducted by assessing the knowledge, expertise, and competencies using four particular areas, the average score of 3.54 indicates a "Moderately high" readiness. The assessment of the market's readiness for the adoption of Automated Demand Response (ADR) has been carried out through the use of two specific questions. A being slightly level to tendency towards a moderate degree of regulatory readiness is indicated by the average score of 2.75. The mean score for this question is 1.93, indicating that the regulatory readiness for ADR technology in Sri Lanka is quite low. This score, which is in the middle of "Not ready at all" and "Slightly ready," indicates significant gaps in the current regulatory frameworks. The low score indicates that the laws that exist are currently insufficient to encourage the effective adoption and use of ADR technology.

4.2 STRATEGIES INTRODUCED BY EXPERTS TO OVERCOME THE BARRIERS IDENTIFIED IN LITERATURE FINDINGS

The expert interviews were used to analyze the barriers to ADR adaptation that were found in the literature. A summary of the barriers found in the literature is provided in Table 2.1 along with the experts' code who have shared their thoughts on the subject matter.

Table 3: Strategies to overcome the Identified Barriers

Barrier	Strategies	Sources
Integration with existing building management system	Collaborate with BMS and ADR technology providers to build combined solutions.	R1
	Conduct a complete assessment of the current BMS to determine its capabilities, protocols, and limits before ADR adaptation	R2, R4
Lack of standardized protocols	Always promote Open protocols rather than closed protocols to avoid proprietary issues	R7, R5
High initial setup and installation cost	Public and private partnership collaboration to share the cost	R5, R4
	Take loan through government involvement	R3

	Impose tax free regulations on import goods for ADR implementation	R6, R8
	Trying to use local materials for implementation	R2
Limited incentives	Introduce financial incentives scheme for participants	R3, R7
	Introduce non-financial incentives like tax reduction on purchase, for participants	R4
Lack of supportive legislation	Convince government to provide separate legislation for PUCSL	R5, R6
	Include ADR into local building cords	R3, R5
Limited knowledge and expertise	Bring expert knowledge from foreign countries	R3, R4, R8
	Conduct seminars and workshops and special training sessions for the workers who work in energy market	R1, R6
Low awareness	Conduct awareness programs for consumers to make them aware about	R3, R7

4.3 DEVELOPMENT OF THE ROADMAP

The five levels used to determine readiness for ADR (Automated Demand Response) adoption in Sri Lanka were developed based on the findings derived from the survey conducted as part of this study. Participants were asked to rate the level of readiness to adopt ADR technology on a 5-point Likert scale, ranging from 1 (Not ready at all) to 5 (Fully ready). The definitions for each level—Not Ready at All, Slightly Ready, Moderately Ready, Almost Ready, and Fully Ready—were constructed to reflect increasing stages of preparedness in adopting ADR systems. Following the collection of responses, the mean values of readiness criteria were calculated, and the results were categorized into five levels based on the overall mean score distribution: 0–1 for Level 1, 1–2 for Level 2, 2–3 for Level 3, 3–4 for Level 4, and 4–5 for Level 5. This data-driven framework provided a structured basis for the development of the ADR adoption roadmap, offering a clear and quantifiable approach to assess and visualize the country's preparedness from 2025 to 2028.

The roadmap below presents the graphical representation of ADR adaptation within the next three years (from 2025 to 2028). After obtaining the survey results, the calculation of mean value for all the readiness criteria, categorized based on the overall mean value. Categorization is as follow,

0 – 1 Level 01

1 – 2 Level 02

2 – 3 Level 03

3 – 4 Level 04

4 – 5 Level 05

Current level of readiness for ADR in Sri Lanka can be summarized as follows and it was obtained through the mean value of each category.

Financial – level 03

Technological – level 04

Knowledge and skills – level 04

Market – level 03

Regulatory – level 02

Lastly, this roadmap was developed using strategies found through expert interviews. Identified strategies were categorized into long-term and short-term strategies and arrowheads implies the year that the strategy needs to be put into action. Additionally red dotted arrowhead indicates the strategies that need to be prioritized.

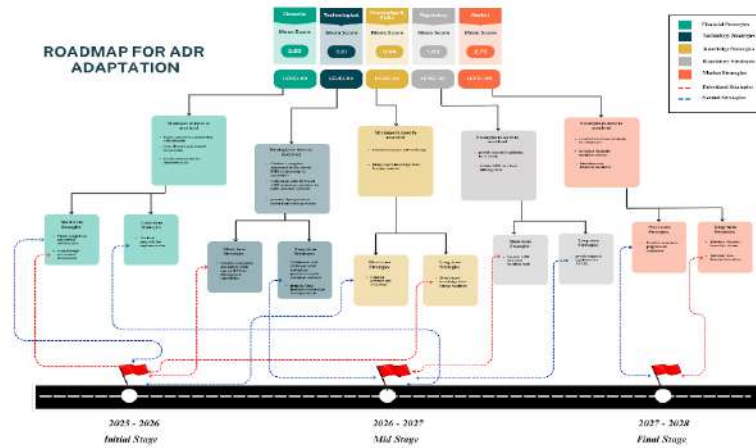


Figure 2: Roadmap for ADR Adaptation

5. Discussion

According to the literature review, Sri Lanka experiences a major imbalance in electricity supply and demand due to infrastructure, economic, and regulatory challenges (Sri Lanka Energy Balance Report, 2007). These data were discussed with experts, who discovered that seasonality and peak hours impose a strain on the system. Drought seasons pose special challenges to energy management, lowering hydropower generation. Furthermore, population increase, urbanization, and economic expansion are likely to increase the gap. Thus, interviewees emphasize the importance of diversifying the energy mix and enhancing infrastructure are critical to addressing this issue. The sources discovered that peak shaving and load shifting in demand side management (DSM) lower the peak demand and calm energy systems (Idrissi et al. , 2022). Experts found that DSM programs decrease the peak demand and grid burden by adopting long-term behavioral modifications and energy efficiency. DSM was a cheaper solution to the conventional construction of physical infrastructure for supporting energy efficiency and sustainability.

The analysis shows that Sri Lanka is almost "Moderately Ready," with a total mean score of 3.81, in terms of technological readiness for Automated Demand Response (ADR) adoption. High degrees of readiness can be seen in important sectors like energy management systems, control devices, and network infrastructure. To guarantee total readiness, however, enhancements to cybersecurity protocols and the accessibility of Demand Response Automation Servers (DRAS) are required. The potential of the current infrastructure is encouraging, but in order for ADR technology to be successfully adopted and implemented, the above key areas must be addressed. Median 2.63, the analysis shows a low level of financial readiness to adopt Automated Demand Response (ADR), which ranges between "slightly ready" and "moderately ready." Though some government funding is available for smart

grid pilot projects, it is not enough to support widespread adoption. The funding allocated for ADR and smart grid projects is relatively minimal, and these initiatives receive priority. Obtaining more funding, giving ADR and smart grid initiatives priority, and allocating sufficient funds for their development and implementation are all necessary to increase financial readiness. With an average score of 3.54, the analysis shows that Sri Lanka is somewhat prepared to adopt automated demand response (ADR) technology. Utility providers have a strong foundation in knowledge, abilities, and skills because of significant R&D investments. The lack of practical instances indicates a disconnect between theoretical knowledge and actual application. In order to achieve the maximum potential of ADR technology, it is essential to close this gap by expanding the range of real applications and making use of current knowledge and research and development efforts. With an average score of 2.75, the analysis shows that Sri Lanka is somewhat ready for the deployment of Automated Demand Response (ADR) technology. The relatively low level of market demand for ADR at the moment suggests that potential customers are not entirely aware of its advantages. Even while there are some market incentives, they are insufficient to promote broad involvement. Raising awareness and education about the benefits of ADR is crucial for improving market readiness, as is creating attractive incentive schemes. Resolving these problems will increase demand and facilitate the effective implementation of ADR technology. The results of the study show that Sri Lanka has a very low level of regulatory preparedness (mean score of 1.93) for Automated Demand Response (ADR). This score, which is in the middle of "Not ready at all" and "Slightly Ready," presents attention to important inadequacies in the laws as they are right now. The adoption and application of ADR technology cannot be effectively supported by the laws currently in existence. The creation of comprehensive laws and regulations that support and promote the use of ADR technology is crucial for enhancing regulatory readiness.

6. Conclusion

This study on "Adaptation of Automated Demand Response (ADR) Technology to Reduce Peak Energy Demand in Sri Lankan Commercial Buildings" achieved its objectives through the use of literature reviews, expert interviews, and survey analysis. The study investigated the existing condition and impact of demand response programmers, provided a thorough explanation of ADR, and emphasized the need for demand side management in Sri Lanka. According to feasibility assessments, while ADR is technically possible with infrastructure enhancements, market preparedness needs to be improved. In addition, adaptation is environmentally feasible due to the positive impacts on environment and with awareness programs along with financial incentives; this would be behaviorally feasible too. The readiness level was evaluated using technological, financial, market, knowledge competency, and regulatory factors, showing areas for improvement. Finally, a strategic roadmap was created to guide the adoption of ADR technology over the next three years, providing a clear way to improve energy management. Many commercial buildings in Sri Lanka experience higher electrical energy and cost during the peak demand hours and implementation of ADR helps to optimize energy usage and helps to reduction of electrical cost. Furthermore, ultimately ADR implementation supports Sri Lanka's sustainable goals by lowering

peak demand and use of energy sources. Future research can focus on extend the adaptation of ADR technology to domestic sector, study on integration of ADR technology with on-site renewable energy sources, and development of regulatory framework that support ADR implementation, addressing legal, policy and market barriers to further enhancement of ADR adoption and effectiveness.

7. References

- Abate, A., Kim, J. J., Kiliccote, S., & Yin, R. (2013). Automated Demand Response Technologies and Demonstration in New York City using OpenADR.
- Albadi, M. H., & El-Saadany, E. F. (2008). A summary of demand response in electricity markets. In *Electric Power Systems Research* (Vol. 78, Issue 11, pp. 1989–1996). <https://doi.org/10.1016/j.epsr.2008.04.002>
- Avtar, R., Sahu, N., Aggarwal, R., Chakraborty, T., Kharrazi, A., Yunus, A. P., ... Kurniawan, T. A. (2019). Exploring renewable energy resources using remote sensing and GIS—A review. *Resources*, 8(3), 149. <https://doi.org/10.3390/resources8030149>
- Bruceri, M., Alxugaray, M., & Pearson, D. (2017). Automated demand response in Title 24, Part 6: Stakeholder outreach assessment. Pacific Gas and Electric Company. https://title24stakeholders.com/wp-content/uploads/2017/09/T24-2019-CASE-Report-Demand-Response-Cleanup_Final_September-2017.pdf
- California Edison. (2021). 2020 demand response program executive summary. https://www.calmac.org/publications/SCE0455.01_PY2020_SCE_DR_Program_Executive_Summary_Public.pdf
- Cappers, P., Goldman, C., & Kathan, D. (2010). Demand response in U.S. electricity markets: Empirical evidence. *Energy*, 35(4), 1526–1535. <https://doi.org/10.1016/j.energy.2009.06.029>
- Electric Power Research Institute. (2014). Demand response-ready end-use technologies. <https://restservice.epri.com/publicdownload/000000003002006785/0/Product>
- Bertoli, E. (2023, July 11). Demand response. International Energy Agency. <https://www.iea.org/energy-system/energy-efficiency-and-demand/demand-response>
- Esther, B. P., & Kumar, K. S. (2016). A survey on residential Demand Side Management architecture, approaches, optimization models and methods. In *Renewable and Sustainable Energy Reviews* (Vol. 59, pp. 342–351). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2015.12.282>
- Fernando, M. D. V., & Rodrigo, A. S. (2018). Dispatch analysis of variable renewable energy penetration in Sri Lanka with HVDC grid interconnection with India. In *2018 International Conference on Electrical Engineering (EECon)* (pp. 1–6). IEEE. <https://doi.org/10.1109/EECon.2018.8541015>
- Gellings, C. W. (1985). The concept of demand-side management for electric utilities. In T. Almeida & A. H. Rosenfeld (Eds.), *Demand-side management and electricity end-use efficiency* (pp. 99–112). Springer. https://doi.org/10.1007/978-94-009-1403-2_5
- Güner, S., Erenoğlu, A. K., Şengör, İ., Erdiñç, O., & Catalão, J. P. S. (2020). Effects of on-site PV generation and residential demand response on distribution system reliability. *Applied Sciences* (Switzerland), 10(20), 1–13. <https://doi.org/10.3390/app10207062>
- Hoekstra, A., Singh, H., & Voskuilen, P. (2016). Using OpenADR with OCPP Combining these two open protocols can turn electric vehicles from threats to the electricity grid into demand-response assets. <http://products.openadr.org/>

- Heffner, G. (2009, February 1). Demand response valuation frameworks paper. Lawrence Berkeley National Laboratory. <https://escholarship.org/uc/item/401781d4>
- Iioka, D., Watanabe, S., & Yokoyama, R. (2016). Optimal operation scheduling of home energy management system using battery storage system. *International Journal of Energy Sector Management*, 10(1), 137–154. <https://doi.org/10.1108/IJESM-07-2015-0004>
- Institute of Electrical and Electronics Engineers. (2014). 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm 2014). IEEE. <https://ieeexplore.ieee.org/document/7380737>
- Jabir, H. J., Teh, J., Ishak, D., & Abunima, H. (2018). Impacts of demand-side management on electrical power systems: A review. *Energies*, 11(5), 1050. <https://doi.org/10.3390/en11051050>
- Javor, D., & Janjić, A. (2016). Application of demand side management techniques in successive optimization procedures. *Communications in Dependability and Quality Management: An International Journal*, 19(4)
- Jradi, M., & Veje, C. T. (2017). Demand response in commercial buildings with an assessable impact on occupant comfort. In 2017 IEEE International Conference on Smart Grid Communications (SmartGridComm) (pp. 410–415). IEEE. <https://doi.org/10.1109/SmartGridComm.2017.8340713>
- Logenthiran, T., Srinivasan, D., & Shun, T. Z. (2012). Demand side management in smart grid using heuristic optimization. *IEEE Transactions on Smart Grid*, 3(3), 1244–1252. <https://doi.org/10.1109/TSG.2012.2195686>
- Meyabadi, A. F., & Deihimi, M. H. (2017). A review of demand-side management: Reconsidering theoretical framework. *Renewable and Sustainable Energy Reviews*, 80, 367–379. <https://doi.org/10.1016/j.rser.2017.05.207>
- Morimoto, R., & Hope, C. (2004). The impact of electricity supply on economic growth in Sri Lanka. *Energy Economics*, 26(1), 77–85. [https://doi.org/10.1016/S0140-9883\(03\)00034-3](https://doi.org/10.1016/S0140-9883(03)00034-3)
- Palensky, P., & Dietrich, D. (2011). Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE Transactions on Industrial Informatics*, 7(3), 381–388. <https://doi.org/10.1109/TII.2011.2158841>
- Page, J., Kiliccote, S., Piette, M. A., & Parrish, K. (2011). Automated demand response technology demonstration project for small and medium commercial buildings. Lawrence Berkeley National Laboratory. <https://www.osti.gov/biblio/1045929>
- Piette, M. A., Ghatikar, G., Kiliccote, S., Palensky, P., Mcparland, C., Koch, E., & Hennage, D. (2009). Open Automated Demand Response Communications Specification (Version 1.0). <http://openadr.lbl.gov/>
- Public Utilities Commission of Sri Lanka. (2017). Study report on electricity demand curve and system peak reduction. <https://www.pucsl.gov.lk/wp-content/uploads/2017/10/STUDY-REPORT-ON-ELECTRICITY-DEMAND-CURVE-AND-SYSTEM-PEAK-REDUCTION.pdf>
- Public Utilities Commission of Sri Lanka. (2022). Techno-economic feasibility study on demand response opportunities in Sri Lanka. <https://www.pucsl.gov.lk>
- Sharda, S., Singh, M., & Sharma, K. (2021). Demand side management through load shifting in IoT-based HEMS: Overview, challenges, and opportunities. *Sustainable Cities and Society*, 65, 102517. <https://doi.org/10.1016/j.scs.2020.102517>

- Steffe, L. P., Thompson, P. W., & von Glasersfeld, E. (2012). Teaching experiment methodology underlying principles and essential elements. In *Handbook of research design in mathematics and science education* (pp. 267-306). Routledge.
- United Nations Industrial Development Organization. (2007). Introduction and user manual: Sustainable energy regulation and policymaking for Africa. UN CC:Learn. <https://www.unccllearn.org/resources/library/introduction-and-user-manual-sustainable-energy-regulation-and-policymaking-for-africa/>
- U.S. Department of Energy. (2009). Smart grid system report. <https://energy.gov/sites/prod/files/2009%20Smart%20Grid%20System%20Report.pdf>
- Wang, X., Zhang, R., & Li, F. (2022). Recent advances and challenges of demand response in smart grids: A review. *Renewable and Sustainable Energy Reviews*, 158, 112121. <https://doi.org/10.1016/j.rser.2022.112121>
- Wikler, G. (2021). Flexible demand resources need new rules. California Efficiency + Demand Management Council. https://cedmc.org/wp-content/uploads/2021/10/2021-CEDMC-Flexible-Demand-Resource-Brief_8-10-21.pdf.

ADOPTING CONCEPT OF BIOPHILIC DESIGN TO ENHANCE HEALTHY INDOOR: AN EXPERIMENT ON MOSS-BASE FOR TROPICAL BUILDING

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Abstract. The modern world is increasingly focused on sustainability, promoting the concept of a greener Earth. This forms the foundation for Industry 6.0, which aims to harness emerging technologies in harmony with nature, supporting sustainability principles where technology complements rather than dominates the environment. Within this framework, there is growing interest in exploring Nature-Based Solutions (NbS) for buildings, aiming to enhance indoor performance. The concept of integrating nature with the built environment is referred to as Biophilic Design (BD). It encompasses a variety of strategies, among which the incorporation of plants is prominent as a widely adopted practice in industry. Numerous indoor plants, such as Spider Plant, Peace Lily, Areca Palm, Rubber Plant, Aloe Vera, Pothos (commonly known as Money Plant), and non-vascular plants, such as bryophyte species, are widely used in BD. This study specifically investigates the efficacy of integrating moss plants (a type of bryophyte species), which are abundant in tropical countries like Sri Lanka, due to their ability to improve indoor air quality (IAQ). An experimental research method was employed to assess the effectiveness of moss plants in enhancing the IAQ. The experiment conducted under a controlled environment proved that Moss plants effectively reduced particulate matter (PM₁₀) and removed formaldehyde. These findings establish a foundation for future research to develop this concept into a commercially practical product, using moss as a readily available resource in Sri Lanka.

Keywords. Moss (Bryophyte), IAQ, Biophilic Design, Indoor Air Quality, Healthy Indoor, Tropical Environment

1. Introduction

Rapid urbanization and climate challenges underline the importance of sustainable architectural practices that enhance human well-being and environmental health. Nature-Based Solutions (NbS) provide a framework to address issues like climate change and urban heat through ecosystem integration (Cohen-Shacham et al., 2016). Biophilic design (BD), which aligns with key NbS strategies, incorporates natural elements into built environments to improve aesthetics, mental health, and IAQ, particularly in tropical environment (Kellert, 2008; Zhong et al., 2022). Moss, a non-vascular plant abundant in tropical regions like Sri Lanka, offers a low-maintenance, cost-effective BD solution due to its ability to reduce particulate matter (PM) and volatile organic compounds (VOCs) while regulating humidity (Gong et al., 2019; Perini et al., 2020). This study evaluates the efficacy of moss as a BD element in enhancing IAQ in a controlled tropical indoor setting, Sri Lanka, measuring PM_{2.5}, PM₁₀, formaldehyde, CO₂, temperature, and humidity. By comparing moss-integrated and control setups, the research aims to confirm moss as a sustainable BD element, contributing to healthier indoor spaces and aligning with Industry 5.0's vision of technology-nature harmony (Sadick & Kamardeen, 2024).

2. Literature Review

The escalating challenges of urbanisation and climate change have underscored the need for sustainable architectural practices that enhance human well-being while mitigating environmental impact (Haider & Kapur, 2024). Addressing this, Nature - based Solutions (NbS) have been identified as a potential solution (Kabisch et al., 2017) since it is a collection of environmentally friendly techniques and actions that aim to protect, sustainably manage, or restore ecosystem to address the urbanisation challenges, such as climate change, biodiversity loss, and urban heat, while promoting human well-being and environmental benefits (Cohen-Shacham et al., 2016). Under this circumstances, Biophilic Design (BD) has emerged as a pivotal approach aligning with NbS techniques, rooted in the innate human connection to nature, aiming to integrate natural elements into built environments to create harmony, aesthetics, and functionality (Beatley, 2011; Saha et al., 2024; Seddon et al., 2020). According to Kellert (2008) and Zhong et al. (2022), BD emphasizes the integration of natural light, vegetation, natural elements and shapes, and organic materials to foster a connection between humanity and the natural world, reflecting an intrinsic human desire for such engagement. Among the various BD applications in a building, incorporating plants or vegetation is one of the most common and widely embraced practice in the built environment worldwide (Beatley, 2016). Incorporating plants and vegetation yields multiple benefits, such as enhanced mental well-being, increased productivity, and improved thermal comfort (Klaniecki et al., 2018; Lan & Liu, 2023). Moreover Kellert (2008) and Zhong et al. (2022) emphasized, the plant application stands out as a cornerstone for establishing a naturalistic indoor environment that also enhances indoor air quality (IAQ).

Numerous indoor plants have been scientifically approved to improve air quality and promote healthier living environments. These plants offer multiple benefits, including the removal of pollutants, increased humidity, and enhanced aesthetic appeal (Dela Cruz et al., 2014). Among them, non-vascular plants, such as moss, liverworts, and hornworts, are more flexible in designing a naturalistic indoors while improving the IAQ (Paoli et al., 2023). Even though mosses, liverworts, and hornworts are all non-vascular plants belonging to the Bryophyte division, liverworts and hornworts need more dampness or waterlogged habitats, and specific wet environmental requirements, making them less practical and highly sensible to the indoor environment (Capozzi et al., 2023; Kumar & Kumar, 2023). In contrast, mosses exhibit remarkable adaptability to low light and high humidity levels which has led to commonly found indoors (Capozzi et al., 2023). Therefore, mosses can be derived from other Bryophyte species as an ideal plant for indoor tropical environments due to their unique adaptability and environmental benefits (Raymond et al., 2017). Mosses are non-woody plants, that typically grow only a few centimetres in height and primarily rely on their leaves to absorb water and nutrients (Chaffey, 2014). Like other plants, mosses perform photosynthesis, converting carbon dioxide and sunlight into energy to produce their own nutrients (Wang et al., 2018; Zhang et al., 2021). Their densely packed root system and leaves support to absorb water and more nutrients from the atmosphere (Gutiérrez et al., 2023). Therefore, moss has gained attention, particularly in tropical contexts, due to its unique ecological and practical advantages (Kato-Noguchi et al., 2010;

Negi & Chaturvedi, 2016; Vieira et al., 2014). Moss can thrive on various substrates with minimal maintenance, and fewer resource requirements, making it a cost-effective alternative to traditional greenery that often incurs high installation and upkeep costs (Perini et al., 2020; Sadick & Kamardeen, 2024). Furthermore, moss's ability to grow epiphytically on building surfaces offers creative design flexibility, such as moss walls (Heffernan, 2019; Wang & Cheng, 2020).

In Sri Lanka, moss can be commonly seen in indoors, covering pots and bonsai plants, as an aesthetic and rustic design element. Examples of these practical applications are presented in Figure 1.



Figure 1: Indoor Covering Pots

Those indoor moss applications are currently prevalent among interior designers to enhance a naturalistic, rustic aesthetic look in places such as in commercial spaces residential interiors etc. (Cruz et al., 2023; Quiet Earth Moss, 2021). Inspired by these practices, it is suggested that, instead of implementing traditional green walls, moss-based panels or designs, such as MosSkin system evaluated in Italy (Perini et al., 2020), may be a more possible integration for BD. This approach offers advantages not only in terms of initial implementation costs but also from a maintenance perspective.

To grow mosses indoors under tropical conditions, regulation of temperature, humidity, lighting, and irrigation is essential, as supported by multiple studies. Mosses can grow at temperatures of 15-30 °C (Varela et al., 2021; Yin et al., 2023; Zechmeister et al., 2023). Zechmeister et al. (2023), stated that for the better growth of moss, humidity should be optimally and daily ranges between 50% and 90%, ensuring hydration while preventing fungal growth. Lighting is another crucial parameter for the growth of moss. Zechmeister et al. (2023) recommended light intensities between 2000 and 6000 lux, aligning with Wang et al. (2018), who achieve growth at 3175 lux, using artificial white light. Irrigation methods for the moss vary across the studies, but all emphasize the importance of maintaining consistent moisture levels without waterlogging. Udawatta et al. (2018) conducted a study on outdoor moss cultivation in Moratuwa, Sri Lanka (a tropical country), successfully growing moss under an average temperature of 27 °C, 75 % of humidity with 12 hours of photoperiod (the period in a day an organism is exposed to light) at 1100 lux under a twice a day water supply. Therefore, the above

literature supports that careful regulation of temperature from 15°C to 30°C, humidity from 60% to 90%, lighting 2000 – 6000 lux, and irrigation requirement is essential to achieve an optimal growth.

In addition to its aesthetic appearance mosses are identified as a significant contributor for enhancing health indoors in many research studies. For instance, studies by Gong et al. (2019) and Gutiérrez et al. (2023) demonstrate the ability of moss to purify indoor air by filtering particulate matter (PM) and volatile organic compounds (VOCs). Experimental results indicate a reduction in PM levels from 1,000 $\mu\text{g}/\text{m}^3$ to below 200 $\mu\text{g}/\text{m}^3$ within hours while regulating the humidity, mitigating noise through its porous structure, and providing thermal insulation, thereby enhancing occupant comfort and safety (Lee & Kim, 2021; Van Renterghem, 2018; Bakatovich & Gaspar, 2019).

When testing particulate matter, the Environmental Protection Agency (2023) in the USA has identified the particle diameter of 2.5 and 10 micrometers (i.e., $\text{PM}_{2.5}$ and PM_{10}) are critical metrics for assessing indoor air quality (IAQ) due to their significant health impacts and prevalence in indoor environments. $\text{PM}_{2.5}$, capable of penetrating deep into the lungs and bloodstream, is linked to respiratory and cardiovascular diseases, while PM_{10} irritates the upper respiratory tract, worsening conditions like asthma (WHO, 2021).

VOC is a border category of chemicals that evaporate easily and contained carbon (Gao et al., 2024). Formaldehyde is a specific organic compound which falls under the umbrella of VOCs. (Skipper et al., 2024). In this study formaldehyde levels are measured as they may cause eye, nose, throat irritation, respiratory issues, and potential cancer risk (Salthammer et al., 2010). CO_2 is monitored as its high levels result in drowsiness and reduced cognitive function particularly when high level of CO_2 prevails in a less ventilated indoor space (Satish et al., 2012). Additionally, humidity and temperature levels are assessed to check their reaction with the moss plant, enabling the reduction of heat in indoor spaces, especially in tropical contexts where high humidity and warmth prevail.

This study explores the integration of moss as a BD element in tropical indoor environments, aiming to evaluate its applicability and effectiveness, as a sustainable solution for improving health, by impacting indoor quality in tropical buildings.

2. Methodology

3.1 EXPERIMENTAL DESIGN

To reach the aim of the study, the experiment was designed to evaluate the impact of moss integration on IAQ under controlled tropical environmental conditions.

Therefore, the experiment was conducted in a controlled indoor environment in a 50 cm × 50 cm × 50 cm sealed glass chamber kept at the University of Moratuwa, Sri Lanka, replicating a tropical indoor environment with a temperature of $27 \pm 2^\circ\text{C}$ and relative humidity of $75 \pm 5\%$. Two setups were investigated:

(1) **Experimental condition** featuring a moss to assess IAQ

(2) **Control condition** without moss to serve as a baseline for comparison.

IAQ was assessed using particulate matter (PM_{2.5} and PM₁₀), formaldehyde (HCHO), carbon dioxide (CO₂), temperature (°C), and relative humidity (%). Figure 2 and Figure 3 illustrate configurations of these setups, along with the pollutant generators for carbon dioxide (CO₂), volatile organic compounds (VOCs), and particulate matter (PM). The moss species selected for this experiment was cushion moss, a type commonly found in Sri Lanka.

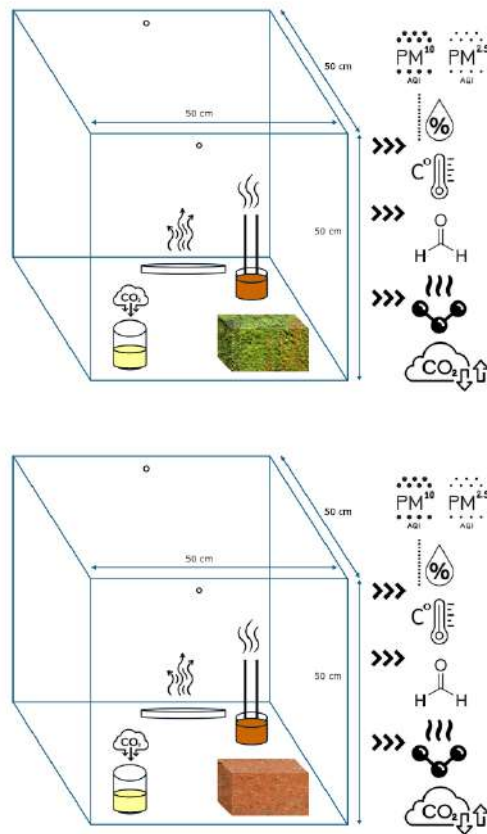


Figure 2: Experimental Condition

As shown in Figure 2, a porous brick block of 10 cm × 20 cm × 5 cm (width × height × depth) was used as the substrate, which was covered with the cushion moss species developed from a pulp prepared using local materials, such as washed moss, aloe vera gel, and compost tea, in the ratio of 2:1:1 (tablespoons), and blended to a 5 seconds consistency using a blender. The Control condition consisted of an identical brick substrate without moss coverage as shown in Figure 2. Air quality was evaluated using three indoor air quality instruments: a CO₂ meter, a particulate matter (PM) meter, and a formaldehyde meter. The illustrations provided above are labeled for ease of identification, as outlined in Table 1.

Table 1: Explanation of Symbols

Brick with moss		Temper ature		Humi dity		acetic acid and sodiu m bicarb onate
Brick without moss		VOC		PM 2.5 & PM 10		Incens e Sticks (2)
	Formald ehyde	CO ₂		Thin ner		Measu re

3.2 EXPERIMENTAL PROCEDURE

To create the polluted environment inside the sealed glass chamber, two incense sticks were ignited to simulate combustion-related emissions, while carbon dioxide (CO₂) was produced via a controlled chemical reaction between acetic acid (CH₃COOH) and sodium bicarbonate (NaHCO₃) following the method used by Tharak et al. (2022). The combustion of the incense stick, coupled with the introduction of acetone, resulted in elevated concentrations of particulate matter (PM_{2.5} and PM₁₀), volatile organic compounds (VOCs), and formaldehyde within the chamber. Air quality measurements were conducted at the beginning of the experiment (0 minutes) and after 30 minutes. Subsequently, continuous monitoring was performed over 8 hours, as informed by methodologies outlined in Gong et al. (2019) and Stojanovska et al. (2022). Following this, the chamber was left undisturbed overnight. On the subsequent day, air quality readings were recorded at 2-hour intervals. The experiment procedure is illustrated in Figure 3.

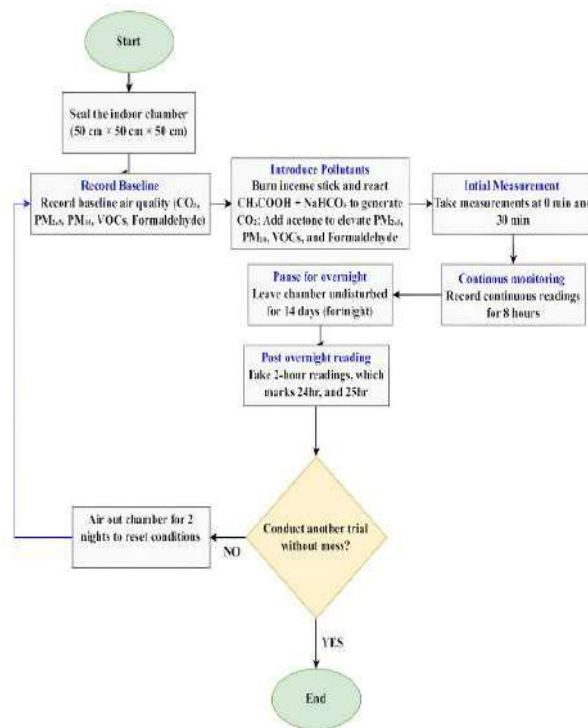
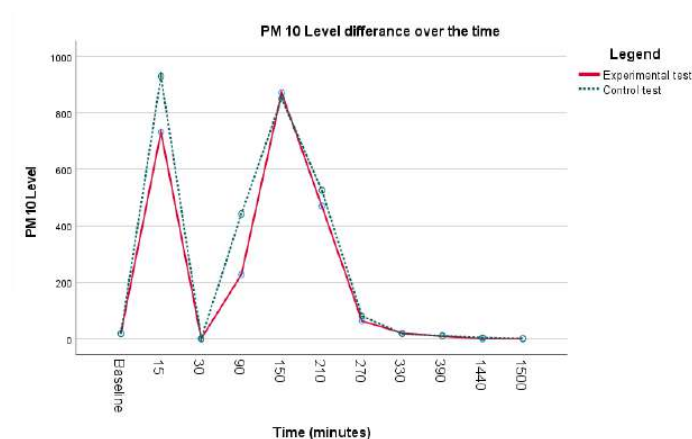


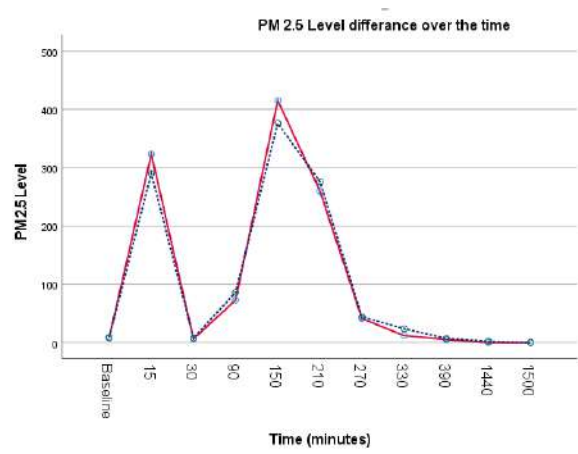
Figure 3: Experiment Procedure

4. Results and Discussion

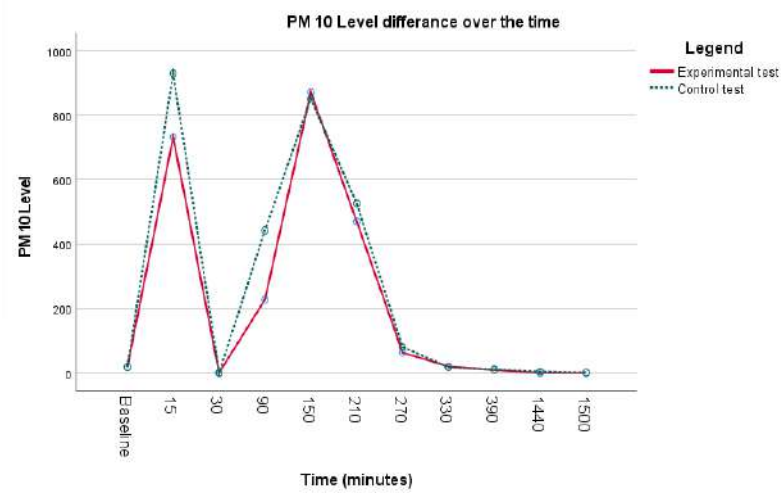
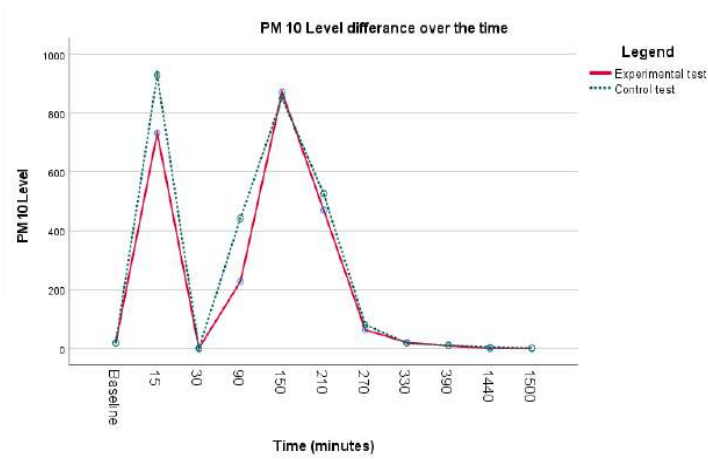
The effects of the moss plant on pollutant levels are presented in Figures 5 to 10. The readings for each point are detailed in Table 2. For data analysis, a General Linear Model was employed using IBM SPSS -27 software, and the rate of impact for each pollutant was calculated. The results for each pollutant are discussed below.

4.1 GRAPHICAL REPRESENTATION





4.1.1 PM 2.5 AND PM 10



Figures 5 and 6, illustrate PM_{2.5} and PM₁₀ levels over 1500 minutes in a controlled chamber experiment, comparing Experimental and Control conditions. Initially, both PM_{2.5} and PM₁₀ levels spike sharply in both conditions, peaking around 90 minutes (PM_{2.5}: ~450 µg/m³ for Experimental, ~400 µg/m³ for Control; PM₁₀: ~900 µg/m³ for Experimental, ~700 µg/m³ for Control). The Experimental condition exhibits a steeper decline post-peak, dropping to ~50 µg/m³ for PM_{2.5} and ~100 µg/m³ for PM₁₀ by 300 minutes, indicating a faster normalization rate. In contrast, the Control condition decreases more gradually, stabilizing at ~150 µg/m³ for PM_{2.5} and ~200 µg/m³ for PM₁₀ after 300 minutes. By 1500 minutes, Experimental levels remain lower (PM_{2.5}: ~25 µg/m³; PM₁₀: ~50 µg/m³) compared to Control (PM_{2.5}: ~100 µg/m³; PM₁₀: ~150 µg/m³). This suggests Experimental condition has effectively reduced pollutants faster than Control Condition, supporting its potential for air quality improvement.

4.1.2 Carbon dioxide Level

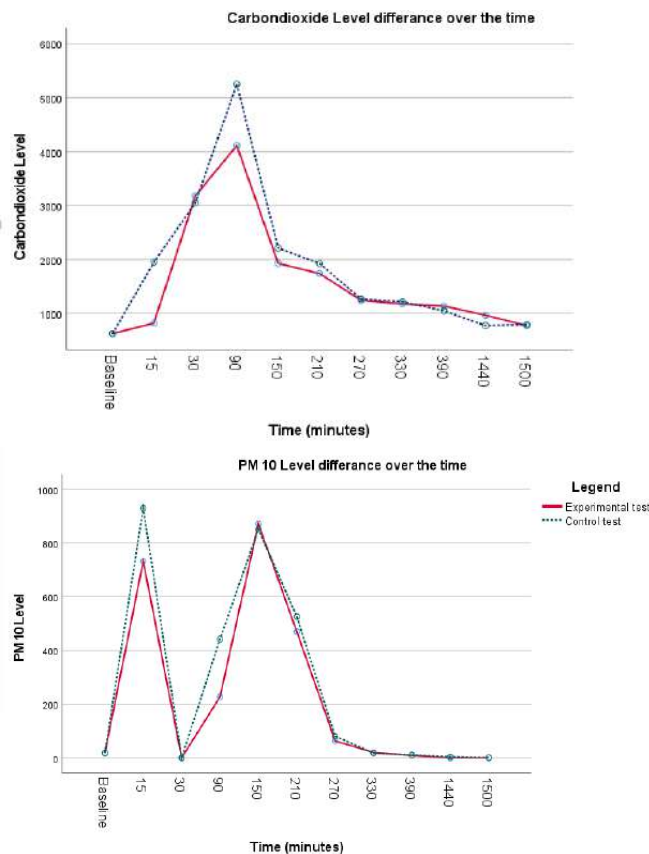


Figure 7, illustrates carbon dioxide (CO₂) levels over 1500 minutes, comparing Experimental and Control conditions. Both show a sharp CO₂ rise, peaking at 90 minutes (Experimental: ~5500 ppm, Control: ~5000 ppm). Post-peak, Experimental condition exhibits a steeper decline, reaching ~1500 ppm by 300 minutes, while Control decreases more slowly to ~2000 ppm. By 1500 minutes, Experimental condition stabilizes at ~500 ppm, lower than Control at ~1000 ppm. A minor CO₂ increase in the Experimental condition around 1200 minutes, post-

overnight, may result from limited ventilation in the sealed environment, reducing CO₂ dispersal (Smith et al., 2021). Additionally, night-time respiration by plants, which release CO₂, could contribute, as a plant, moss likely continues this process overnight (Johnson & Lee, 2022). This aligns with findings that sealed buildings trap pollutants and plant respiration affects indoor CO₂ (Jones & Brown, 2020). The steeper Moss slope overall highlights its efficacy in air purification.

4.1.3 Formaldehyde Level

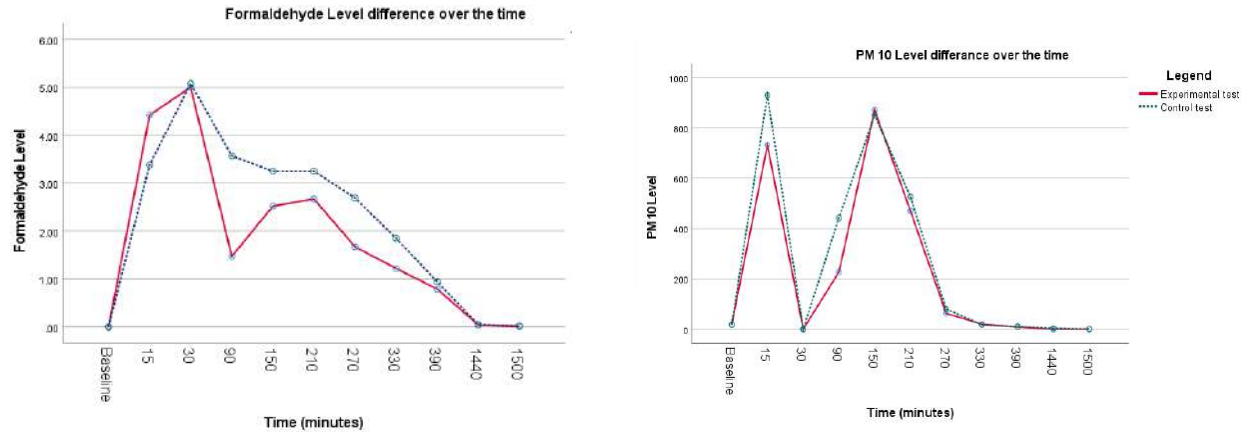
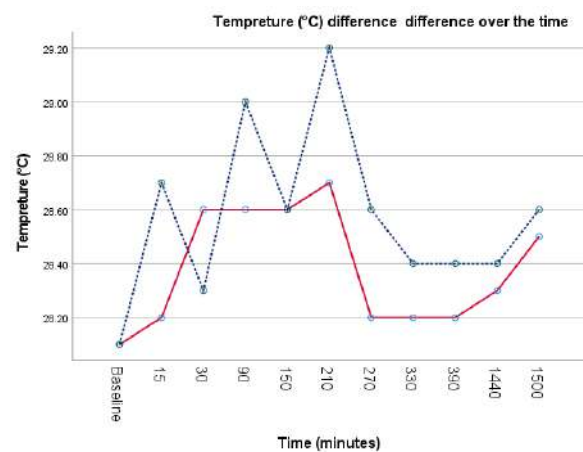


Figure 8 displays formaldehyde levels over 1500 minutes, comparing Experimental and Control conditions. Both conditions show a rapid increase, peaking at 90 minutes (Experimental: ~5.0 ppm, Control: ~4.5 ppm). Experimental condition has exhibited a steeper decline post-peak, dropping to ~2.0 ppm by 300 minutes, while Control condition decreases more gradually to ~2.5 ppm. By 1500 minutes, Experimental condition has stabilized at ~0.5 ppm, lower than Control at ~1.0 ppm. The steeper slope of Experimental condition indicates a faster formaldehyde reduction rate, suggesting its superior efficacy in mitigating this pollutant. This highlights Moss's potential for improving air quality in controlled environments.

4.1.4 Temperature level variations



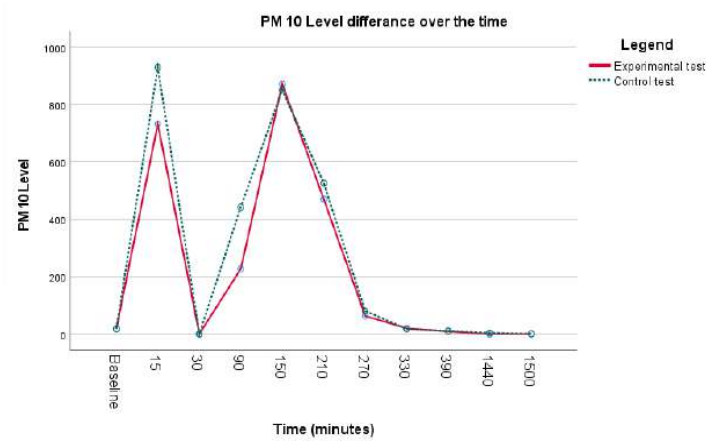
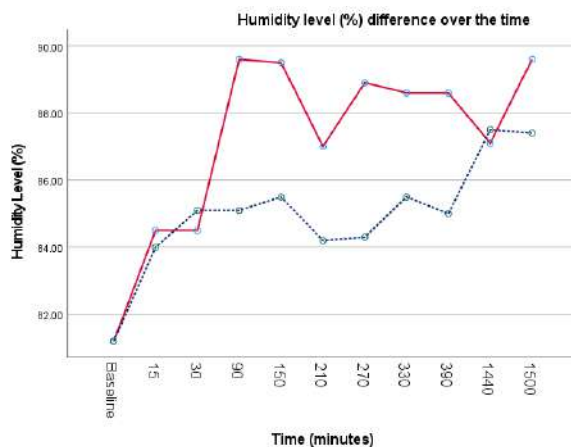


Figure 9, the temperature and CO₂ (Figure 7), are observed an interconnected dynamics between Experimental and Control conditions over 1500. Temperature in the Experimental condition peaks higher ($\sim 29.9^{\circ}\text{C}$ at 90 minutes) than Control ($\sim 29.7^{\circ}\text{C}$), coinciding with the CO₂ peak (Experimental: ~ 5500 ppm, Control: ~ 5000 ppm). This suggests that moss plant's metabolic activity, such as respiration, may contribute to both CO₂ release and heat generation during this period (Johnson & Lee, 2022). Post-peak, Experimental condition has shown a steeper CO₂ decline (~ 500 ppm by 1500 minutes) and temperature stabilization ($\sim 29.5^{\circ}\text{C}$), while Control condition has stabilized at ~ 1000 ppm CO₂ and $\sim 29.6^{\circ}\text{C}$. The minor CO₂ increase in Experimental condition around 1200 minutes, post-overnight, aligns with a slight temperature rise, likely due to night-time respiration and limited ventilation, as found by (Smith et al., 2021). These patterns indicate moss plant's active role in modulating both CO₂ and temperature more effectively than the Control condition.

4.1.5 Humidity variation



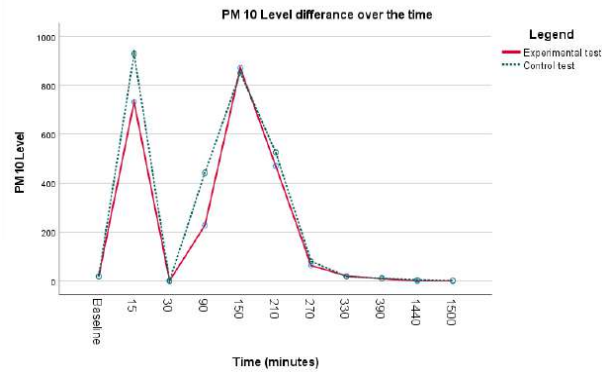


Figure 10 depicts humidity levels over 1500 minutes, comparing Experimental and Control conditions. In Experimental condition, the humidity rises sharply to ~89% by 90 minutes, peaking at ~90% around 300 minutes, while in Control condition, it increases steadily to ~87%. Both stabilized by 1500 minutes (Experimental: ~89%, Control: ~86%). This elevation in Experimental condition may result from its transpiration, releasing water vapour and enhancing humidity as similar to the study by Davis and Patel (2023). CO₂ levels peak concurrently (Experimental: ~5500 ppm, Control: ~5000 ppm at 90 minutes), declining to ~500 ppm and ~1000 ppm, respectively, by 1500 minutes. Temperature peaks align (Experimental: ~29.9°C, Control: ~29.7°C at 90 minutes), stabilizing at ~29.5°C and ~29.6°C. The humidity, CO₂ and temperature correlation suggests moss plant's metabolic activity drives moisture and CO₂ release, moderated by transpiration (Smith et al., 2021). Limited ventilation may have amplified these effects (Jones & Brown, 2020). Moreover, further studies should explore ventilation impacts to optimize Moss's air-purifying potential.

High humidity indicates more water vapour in the atmosphere, which can influence temperature. Water vapour has a high specific heat capacity, meaning it absorbs and retains heat effectively, slowing temperature changes. Thus, high humidity typically reduces temperature fluctuations, preventing rapid cooling or heating. However, it can make the air feel warmer due to reduced evaporation of sweat, impacting perceived temperature rather than actual temperature (Wexler, 2021). In the experiment, Experimental condition humidity peaked at ~90%, while temperature stabilized at ~29.5°C, suggesting humidity can moderate temperature variances.

Moss as a plant primarily emits water vapour through transpiration, a process where water absorbed by its tissues is released into the atmosphere, increasing humidity (Davis & Patel, 2023). Unlike vascular plants, moss as a non-vascular plant or Bryophyte lacks true roots but absorbs water through its surface by capillary action as they lack true stomata found in vascular plants. In the sealed chamber, moss plants' transpiration likely contributed to the observed humidity rise (from ~82% to ~90%), as it easily emitted water vapour from its surface during metabolic processes. This aligns with its CO₂ reduction role, where moisture release is a byproduct of respiration (Johnson & Lee, 2022).

The analysis of (Figures 5-10) proves that moss plant (Experimental condition) has consistently and effectively performed in removing PM₁₀ and formaldehyde, showing steeper declines, while its impact on PM_{2.5} stays considerably lower but

has a positive impact. Additionally, the dynamic regulatory patterns of CO₂, humidity, and temperature can be further explored.

Table 2: Experiment data collection on both experimental condition and control condition.

Time slots in minutes	PM _{2.5} (µg/m ³)		PM ₁₀ (µg/m ³)		CO ₂ (ppm)		Formaldehyde (ppm)		Temperature (°C)		Humidity (%)	
	Moss	No	Moss	No	Moss	No	Moss	No	Moss	No	Moss	No
0m	8	9	18	18	629	625	0	0	28.1	28.1	81.2	81.2
15m	323	290	732	929	821	1950	4.42	3.38	28.2	28.7	84.5	84
30m	6	8	0	0	3180	3051	5	5.08	28.6	28.3	84.5	85.1
90m	73	86	227	442	4113	5251	1.47	3.57	28.6	29	89.6	85.1
150m	415	376	871	851	1928	2213	2.52	3.25	28.6	28.6	89.5	85.5
210m	260	276	470	526	1741	1926	2.67	3.25	28.7	29.2	87	84.2
270m	41	44	63	80	1245	1269	1.67	2.69	28.2	28.6	88.9	84.3
330m	12	24	20	18	1177	1217	1.22	1.85	28.2	28.4	88.6	85.5
390m	5	7	9	11	1138	1049	0.79	0.94	28.2	28.4	88.6	85
1440m	0	2	0	4	970	777	0.04	0.05	28.3	28.4	87.1	87.5
1500m	0	0	0	1	773	797	0.01	0.02	28.5	28.6	89.6	87.4

4.2 GENERAL RATE OF CHANGE ANALYSIS

The general rate of change of a pollutant refers to the variation in pollutant concentration over time. This measure evaluates the speed at which pollutants are reduced, with a steeper negative slope, indicating a more rapid normalization of pollutant levels (Seinfeld & Pandis, 2016). As suggested in Li et al. (2022), Equation 1 is used to assess the rate of change of pollutants for this experiment.

Pt=The rate of change of pollutants over the time

Table 3 presents the rates of change in percentages for each pollutant and the varying patterns of indoor conditions over time under Experimental conditions with moss plant and Control conditions without moss plant.

Table 3: The Rate of change calculation results.

Pollutant	% Change Experimental C.	% Change Control C.	Difference (Experimental - Control)
PM_{2.5}	-100.00%	-100.00%	0.00%
PM₁₀	-100.00%	-94.44%	-5.56% (Moss better)
CO₂	22.89%	27.52%	-4.63% (Moss better)

Formaldehyde	16.16%	12,12%	-4.049% (Moss better)
Temperature	1.42%	1.78%	-0.36% (Moss less increase)
Humidity	10.34%	7.14%	3.20% (Moss more increase)

These results in Table 3, reveal distinct patterns when comparing Experimental and Control conditions on PM_{2.5}, PM₁₀, VOC, CO₂, formaldehyde, temperature, and humidity. Comparing the Experimental and Control conditions, PM₁₀ reduction is more effective with moss, showing a faster rate of change (-2.1176 vs. -2.0000) and achieving 100% reduction in Experimental condition, compared to 94.44% in Control condition, indicating moss's superior efficacy for larger particulates. The positive results in Experimental condition for formaldehyde levels, show a slower rate of increase compared to Control condition, emphasizing its potential to reduce formaldehyde level. Temperature has increased in both conditions, but the results from the Experimental condition show a lower rate of increase, indicating the moss plant's ability to exert a cooling influence. However, humidity has increased more significantly in Experimental condition with moss plant, consistent with its moisture-retaining transpiration process.

6. Conclusion

This study conducted experiments using a Moss plant (a Bryophyte) to evaluate its effect on removing Particulate Matter (PM) and formaldehyde levels, VOCs, as well as variations in the composition of air within a controlled indoor space. The results revealed that moss reduces PM_{2.5} levels but faces challenges in mitigating rising CO₂ levels due to external factors, such as ventilation. Conversely, it excels in reducing PM₁₀ and formaldehyde, while also moderating temperature and enhancing humidity if the ventilation is poor, especially during nighttime. Further studies could refine these insights by isolating these factors to optimize moss's application in indoor air quality management and as an ideal element for developing the Biophilic Design concept in tropical indoor environments under tropical conditions.

7. References

- Bakatovich, A., & Gaspar, F. (2019). Composite material for thermal insulation based on moss raw material. *Construction and Building Materials*, 228, 116699. <https://doi.org/10.1016/j.conbuildmat.2019.116699>
- Beatley, T. (2011). *Biophilic cities: Integrating Nature Into Urban Design and Planning*. Island Press.
- Beatley, T. (2016). *Handbook of Biophilic City Planning & Design*. Island Press.
- Chaffey, N. (2014). Raven biology of plants, 8th edn. *Annals of Botany*, 113(7), vii. <https://doi.org/10.1093/aob/mcu090>
- Cruz, M. F., Bianconi, M., & Rocha, A. (2023). Moss as a multifunctional material for technological greenery systems. *The Plan Journal*. <https://www.theplanjournal.com/article/moss-multifunctional-material-technological-greenery-systems>[(https://www.researchgate.net/publication/372420523_Moss_as_a_Multifunctional_Material_for_Technological_Greenery_Systems)]
- Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S.(eds.)(2016).*Nature-based Solutions to address global societal challenges* . Gland, Switzerland

- Davis, L. & Patel, R. (2023). Plant Transpiration and Indoor Humidity. *Journal of Plant Physiology*, 50(4), 78-85.
- Capozzi, S. L., Leang, A. L., Rodenburg, L. A., Chandramouli, B., Delistraty, D. A., & Carter, C. H. (2023). PFAS in municipal landfill leachate: Occurrence, transformation, and sources. *Chemosphere*, 334, 138924. <https://doi.org/10.1016/j.chemosphere.2023.138924>
- Cruz, M. D., Müller, R., Svensmark, B., Pedersen, J. S., & Christensen, J. H. (2014). Assessment of volatile organic compound removal by indoor plants—a novel experimental setup. *Environmental Science and Pollution Research*, 21(13), 7838–7846. <https://doi.org/10.1007/s11356-014-2695-0>
- EPA. (2023). Particulate matter (PM) basics. U.S. Environmental Protection Agency. <https://www.epa.gov/pm-pollution/particulate-matter-pm-basics>
- Gao, L., Wang, S., Zou, D., Fan, X., Guo, P., Du, H., Zhao, W., Mao, Q., Li, H., Ma, M., & Rennenberg, H. (2024). Physiological responses of low- and high-cadmium accumulating *Robinia pseudoacacia-rhizobium* symbioses to cadmium stress. *Environmental Pollution*, 345, 123456. <https://doi.org/10.1016/j.envpol.2024.123456>
- Gong, G. Y., Kang, J. S., Jeong, K. J., Jeong, J. H., & Yun, J. G. (2019). Effect of several native moss plants on particulate matter, volatile organic compounds and air composition. *Journal of People, Plants, and Environment*, 22(1), 31-38. <https://doi.org/10.11628/ksppe.2019.22.1.031>
- Gutiérrez, R. A., Blom, J., Belmans, B., De Bock, A., Van Den Bergh, L., & Audenaert, A. (2023). Preliminary research on moss-based biocomposites as an alternative substrate in moss walls. *Sustainability*, 15(23), 16500. <https://doi.org/10.3390/su152316500>
- Haider, S. M. A., & Kapur, A. (2024). Influence of sustainable architecture design on human well-being and social dynamics. *Journal of Sustainable Architecture and Urban Design*, 15(3), 45–58.
- Heffernan, L. (2019). The role of mosses in modern interior design: A biophilic perspective. *Journal of Interior Ecology*, 12(3), 156-165. <https://doi.org/10.1002/jie.2019.1203156>
- Johnson, R. & Lee, K. (2022). Plant Respiration and Indoor CO₂ Dynamics. *Botanical Studies*, 63(1), 89-95
- Jones, A. & Brown, T. (2020). Indoor Air Quality in Confined Spaces. *Environmental Research*, 98(2), 45-52.
- Kabisch, N., Korn, H., Stadler, J., & Bonn, A. (2017). Nature-Based solutions to climate change adaptation in urban areas. In *Theory and practice of urban sustainability transitions*. <https://doi.org/10.1007/978-3-319-56091-5>
- Kato-Noguchi, H., Seki, T., & Shigemori, H. (2010). Allelopathy and allelopathic substance in the moss *Rhynchostegium pallidifolium*. *Journal of Plant Physiology*, 167(8), 676–678. <https://doi.org/10.1016/j.jplph.2009.11.011>
- Kellert, S. R. (2008). *Biophilic design: The theory, science, and practice of bringing buildings to life*. Wiley.
- Klaniecki, K., Leventon, J., & Abson, D. J. (2018). Human-nature connectedness as a ‘treatment’ for pro-environmental behavior: Making the case for spatial considerations. *Sustainability Science*, 13, 1375-1388.
- Kumar, N., Yadav, A., Singh, G., Singh, A., Kumar, P., & Aggarwal, N. K. (2023). Comparative study of ethanol production from sodium hydroxide pretreated rice straw residue using *Saccharomyces cerevisiae* and *Zymomonas mobilis*. *Archives of Microbiology*, 205(4). <https://doi.org/10.1007/s00203-023-03468-1>

- Lan, Y., & Liu, Q. (2023). The restorative and contingent value of biophilic indoor environments in healthcare settings. *Sustainability*, 15(15), 11676. <https://doi.org/10.3390/su151511676>
- Lee, J., & Kim, H. (2021). The impact of moss in enhancing indoor air quality. *Environmental Science Interiors*, 45(2), 67-75. <https://doi.org/10.1016/j.esi.2021.02.003>
- Li, J., Zheng, L., Xuan, P., & Huo, R. (2022b). A Real-Time approach to detect PM2.5 in a seriously polluted environment based on pressure drop. *Atmosphere*, 13(8), 1237. <https://doi.org/10.3390/atmos13081237>
- Negi, K., & Chaturvedi, P. (2016). In vitro antimicrobial efficacy of *Rhynchostegium vagans* A. Jaeger (moss) against commonly occurring pathogenic microbes of Indian sub-tropics. *Asian Pacific Journal of Tropical Disease*, 6(1), 15-19. [https://doi.org/10.1016/S2222-1808\(15\)60974-5](https://doi.org/10.1016/S2222-1808(15)60974-5)
- Paoli, L., Bandoni, E., & Di Toppi, L. S. (2023). Lichens and mosses as bio monitor of indoor pollution. *Biology*, 12(9), 1248. <https://doi.org/10.3390/biology12091248>
- Perini, K., Castellar, P., Giachetta, A., Turcato, C., & Roccotiello, E. (2020). Experiencing innovative biomaterials for buildings: Potentialities of mosses. *Building and Environment*, 172, 106708. <https://doi.org/10.1016/j.buildenv.2020.106708>
- Quiet Earth Moss. (2021). Types of preserved moss. <https://www.quietearthmoss.com/types-of-preserved-moss/>(<https://www.quietearthmoss.com/preserved-moss-walls/types-of-preserved-moss/>)
- Sadick, A., & Kamardeen, I. (2024). Enablers for accelerating biophilic design adoption in Australian buildings. *Journal of Building Engineering*, 83, 108464. <https://doi.org/10.1016/j.jobbe.2024.108464>
- Saha, T., Bigith, V. B., & Lovely Professional University. (2024). A study on the impact of moss-growing concrete as a new sustainable material in the interior architecture industry. *African Journal of Biological Sciences*, 6(5). <https://www.afjbs.com/uploads/paper/21f3dcb852289b4e4fccf0fefe217154.pdf>
- Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. (2012). Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. *Environmental Health Perspectives*, 120(12), 1671-1677.
- Seddon, N., Chausson, A., Berry, P., Girardin, C. a. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B Biological Sciences*, 375(1794), 20190120. <https://doi.org/10.1098/rstb.2019.0120>
- Salthammer, T., Mentese, S., & Marutzky, R. (2010). Formaldehyde in the indoor environment. *Chemical Reviews*, 110(4), 2536-2572
- Seinfeld, J. H., & Pandis, S. N. (2016). *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. John Wiley & Sons.
- Skipper, T. N., D'Ambro, E. L., Wiser, F. C., McNeill, V. F., Schwantes, R. H., Henderson, B. H., Piletic, I. R., Baublitz, C. B., Bash, J. O., Whitehill, A. R., Valin, L. C., Mouat, A. P., Kaiser, J., Wolfe, G. M., St Clair, J. M., Hanisco, T. F., Fried, A., Place, B. K., & Pye, H. O. (2024). Role of chemical production and depositional losses on formaldehyde in the Community Regional Atmospheric Chemistry Multiphase Mechanism (CRACMM). *Atmospheric Chemistry and Physics*, 24(22), 12903-12924. <https://doi.org/10.5194/acp-24-12903-2024>
- Smith, J. et al. (2021). Ventilation Effects in Sealed Environments. *Journal of Environmental Science*, 45(3), 123-130
- Stojanovska, M., Piwowarczyk, B., & Śliwiński, M. (2022). Modern use of bryophytes as a source of secondary metabolites. *Agronomy*, 12(6), 1456. <https://doi.org/10.3390/agronomy12061456>

- Tharak, A., Katakojwala, R., Kajla, S., & Mohan, S. V. (2022). Chemolithoautotrophic reduction of CO₂ to acetic acid in gas and gas-electro fermentation systems: Enrichment, microbial dynamics, and sustainability assessment. *Chemical Engineering Journal*, 454, 140200. <https://doi.org/10.1016/j.cej.2022.140200>
- Udawattha, C., Galkanda, H., Ariyaratne, I. S., Jayasinghe, G., & Halwatura, R. (2018). Mold growth and moss growth on tropical walls. *Building and Environment*, 137, 268-279. <https://doi.org/10.1016/j.buildenv.2018.04.018>
- Van Renterghem, T. (2018). Green roofs for acoustic insulation and noise reduction. In Elsevier eBooks (pp. 167-179). <https://doi.org/10.1016/b978-0-12-812150-4.00016-1>
- Varela, Z., Real, C., Branquinho, C., Paço, T. a. D., & De Carvalho, R. C. (2021). Optimising artificial moss growth for environmental studies in the Mediterranean area. *Plants*, 10(11), 2523. <https://doi.org/10.3390/plants10112523>
- Vieira, G., Mora, C. V., Pina, P., & Schaefer, C. E. G. R. (2014). High-resolution remote sensing of the distribution and ecological status of *Usnea* sp. communities in Maritime Antarctica. *Science of the Total Environment*, 473-474, 69-75. <https://doi.org/10.1016/j.scitotenv.2013.11.105>
- Wang, C., Li, H., & Neoh, S. A. (2018). Moss-indoor vertical greenery system design protocol: Using moss as an indoor vertical greenery system in the tropics. *Indoor and Built Environment*, 28(7), 887-904. <https://doi.org/10.1177/1420326x18798010>
- Wang, S., & Cheng, Y. (2020). Epiphytic plants in biophilic design: Opportunities and challenges. *Ecological Architecture*, 8(4), 34-42. <https://doi.org/10.1016/j.ecoarch.2020.06.005>
- Wexler, A. (2021). Thermodynamics of Humid Air. *Journal of Atmospheric Science*, 33(5), 101-110.
- WHO. (2021). WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization. <https://www.who.int/publications/i/item/9789240034228>
- Wolkoff, P. (2013). Indoor air pollutants in office environments: Assessment of comfort, health, and performance. *Indoor Air*, 23(4), 299-311.
- Yin, H., Perera-Castro, A. V., Randall, K. L., Turnbull, J. D., Waterman, M. J., Dunn, J., & Robinson, S. A. (2023). Basking in the sun: how mosses photosynthesise and survive in Antarctica. *Photosynthesis Research*, 158(2), 151-169. <https://doi.org/10.1007/s11120-023-01040-y>
- Zechmeister, H. G., Möslinger, L., Korjenic, A., Streit, E., Sulejmanovski, A., Frank, P. N., & Hummel, E. (2023). Viability of living moss for indoor green walls: A study on temperature, humidity, and irrigation. *Sustainability*, 15(21), 15625. <https://doi.org/10.3390/su152115625>
- Zhang, L., Chen, Y., & Xu, Z. (2021). Moss as a component of green walls: Its benefits and applications. *Urban Forestry & Urban Greening*. *Urban Forestry & Urban Greening*.
- Zhong, W., Schröder, T., & Bekkering, J. (2022). Biophilic design in architecture and its contributions to health, well-being, and sustainability: A critical review. *Frontiers of Architectural Research*, 11(1), 114-141. <https://doi.org/10.1016/j.foar.2021.07.006>

AN OBSERVATIONAL STUDY ON RISKS IN FILM AND TELEVISION PRODUCTIONS; SPECIAL REFERENCE TO ART DEPARTMENT WORKFLOWS

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Abstract. The film production is a highly specialized field, characterized by a unique blend of artistic vision, technical expertise, organizational strategy, and psychological insight. It requires the coordinated efforts of diverse workflows across multiple departments, among which the art department plays a significant role in constructing the film's visual world realistically. Within the art department's workflows, the extensive use of human labor exposes crew members to various dangers and risks. Despite the physical challenges and occupational hazards faced by individuals in the art department, there is a notable lack of scientific research focused on health and safety practices specific to this field. This study aims to identify and document potential hazards within art department workflows, focusing particularly on risk factors emerging during the pre-production and production stages. Grounded in observational analysis of three case studies, the research presents five key risk categories thematically extracted and identified within the art department's workflows. These findings contribute to a broader understanding of occupational risks in an art department within film production as a contribution to important local (Sri Lanka) and cross analyze global health and safety regulations.

Keywords: Risks Identification, Art Department, Film Production, Pre-Production Risks, Occupational Safety.

1. Introduction

The art department plays a critical role in the film production process, contributing significantly to a film's visual storytelling (LoBrutto, 2002). Within this department, various tasks—such as set construction, prop fabrication, scenic painting, and set decorating (Barnwell, 2017)—involve substantial physical demands and frequently expose crew members to occupational health and safety risks. For instance, during set construction, crew members are required to use power tools and perform heavy lifting, which can lead to serious injuries and long-term health issues. Similarly, during scenic painting and prop fabrication, they are exposed to a range of chemical substances, including adhesives, paints, and fiberglass materials. Prolonged or unprotected exposure to these substances can result in accidents and adverse health conditions, such as respiratory problems and allergic reactions. Therefore, implementing effective safety practices and risk management strategies within the art department is crucial. This is particularly significant in the context of the Sri Lankan film production industry, where safety protocols for art departments require greater attention and formalization. Addressing these issues is essential for ensuring appropriate risk management and the establishment of safety standards for art department crew members in film and television productions.

Film production involves a wide range of specialized departments, each contributing to different aspects of a film's development and execution. The directing department shapes the overall creative vision, while the camera and lighting departments manage visual composition and lighting design. The sound department captures and refines audio elements, and the production department coordinates logistics, scheduling, and operational management. Costume and

makeup teams define character appearance and help establish historical or cultural authenticity. Among these, the art department plays a crucial role in constructing the physical and visual world of the film through set design, prop fabrication, and scenic artistry (Honthaner, 2001).

Sri Lanka has long been a popular destination for global film and television productions, owing to its diverse landscapes, cost-effective production infrastructure, and skilled local workforce (British Film Institute, 2019). Numerous international projects have been filmed entirely on Sri Lankan soil, employing local crews across various departments. A notable example is the Bollywood film *Bombay Velvet*, which was shot entirely in Sri Lanka. To recreate the urban landscape of 1940s Bombay, the Sri Lankan art department constructed elaborate sets at the Ranminithanna International Cinema Village. While the directing, camera, and sound departments were primarily staffed by professionals from India, the production made extensive use of Sri Lankan locations and depended significantly on the expertise of the local art department. This example illustrates not only the increasing presence of global productions in Sri Lanka but also highlights the vital contribution of Sri Lankan technical departments, particularly the art department, in supporting and realizing international creative visions.

Given the increasing involvement of Sri Lankan crews in both local and international productions, there is a critical need to examine the working conditions and safety practices within departments, and this paper focuses on the art department. The study aims to document and identify potential risks that individuals face within the practices of the art department workflow. To achieve this, an observational research approach is applied. It is grounded in the author's direct experience, providing an insider's perspective on the challenges and risks faced by art department crews and clarifying the data with them. The author, a practising professional within the art department, has extensive experience in film and television productions, both in local and international projects. She has served as Production Designer, Art Director, Assistant Art Director, Standby Art Director, and Prop Master. Over her career, she has participated in the art departments of nine film and television productions, with a national award for one film.

Extracting from her experience, the present study focuses on two films and one television production as the three selected cases. The first case examines the Sri Lankan-produced film *Akasa Kusum* (Flower of the Sky), which was filmed entirely in Sri Lanka with an art department crew composed exclusively of Sri Lankan professionals. The author participated in this project as the Production Designer. The second case is a Canadian production, *Funny Boy*, which was also entirely shot in Sri Lanka, with the full art department crew consisting of Sri Lankan members. In this second case, the author served as the Standby Prop Master. The third case focuses on a television series, *The Good Karma Hospital* (Season Four), produced by a British production company. This series was similarly filmed entirely in Sri Lanka. While a few key roles within the art department, such as Production Designer and Standby Prop Master, were filled by professionals from England while the majority of the art department crew was composed of Sri Lankan members. In this production, the author was appointed as the On-Set Art Director.

These three cases were selected due to the prominent role played by the author as an insider to gain primary data and the production's well-structured organization

within the art departments. Analyzing these cases offers valuable insights into safety and risks within the practices of the art department workflow.

Film production typically progresses through three main stages: pre-production, production, and post-production. Pre-production encompasses all preparatory activities necessary for filming, including set design, prop construction, and location preparation. This study specifically focuses on the pre-production and production stages, as it represents the period of highest activity for the art department, particularly in the construction of sets, fabrication of props, and preparation of filming environments.

The significance of this study is its potential to fill the knowledge gap regarding the risk factors that require safety and risk management within film production focused on the art department. The primary objective of this study is to identify potential risks that members of the art department may encounter within workflows during the pre-production and production stages. Specifically, observing real-world practices in set construction, prop fabrication, scenic painting, and location preparation. The research intends to contribute to the development of better safety standards and practices for art departments, particularly within the Sri Lankan context and similar production environments.

2. Literature Review

The film production process requires a unique blend of creativity, technical expertise, and organizational skills.

While occupational risks are present across all departments involved in film production, the art department, in particular, is uniquely exposed to a broad spectrum of physical and chemical hazards. The art department translates the script and the director's vision into a tangible visual world by designing and constructing sets, props, and environments (LoBrutto, 2002). As a visual medium, cinema has the capacity to simultaneously portray reality and create highly stylized, pictorial environments (Monaco, 2000). One of the most compelling aspects of film lies in its ability to construct diverse story worlds (Egan, 2014), allowing audiences to immerse themselves fully in these imaginative spaces. The art department is central to this process, establishing the film's time period, environment, spatial elements, and social context to align with the narrative (Eder, 2010). Essentially, the art department translates abstract concepts from the screenplay or the director's imagination into tangible environments that support character development and enrich the storytelling experience (LoBrutto, 2002). As a result, the responsibilities and workflows of the art department vary significantly depending on the script and specific production requirements.

The work undertaken by the art department involves activities such as set construction, prop fabrication, scenic painting, and material handling (Barnwell, 2017), each of which introduces potential safety hazards, including exposure to toxic chemicals, working at heights, and operating power tools. To manage these tasks efficiently and to specialize labor, the art department is basically divided into several key subdivisions:

2.1. SET CONSTRUCTION

Responsible for constructing physical structures, including sets, backdrops, and props, based on the production designer's vision. This team works with materials such as wood, metal, and foam, and often operates power tools and works at heights to ensure both aesthetic accuracy and structural integrity.

2.2. SCENIC PAINTING

Focuses on painting and texturing sets to achieve the desired aesthetic. Techniques such as ageing, distressing, and creating faux finishes are commonly used to match the film's period, mood, and setting.

2.2. PROP DEPARTMENT

Sources, fabricates, and maintains props—such as furniture, weapons, books, or personal items—that align with the film's historical and stylistic requirements. This includes the management of hero props (featured in close-ups) and action props (used in stunt sequences).

2.2. SET DECORATION

Enhances the realism of sets by dressing them with non-moveable elements such as curtains, rugs, artwork, and decorative objects. The set decorator ensures that every detail aligns with the film's aesthetic and narrative needs.

Each subdivision within the art department faces its own distinct set of challenges and safety risks, making it one of the most dynamic and physically demanding teams on a film set. For example, the set construction team faces a higher risk of physical injuries due to the use of power tools, heavy lifting, and working at heights. In contrast, the prop-making and scenic painting teams are more frequently exposed to hazardous chemicals, leading to health risks such as allergic reactions, respiratory issues, and sudden accidents. Given the variety and physical intensity of tasks assigned to the art department, more extensive and specialized precautionary measures are required compared to departments with more standardized workflows.

2.3. IMPORTANCE OF HEALTH AND SAFETY IN THE FILM PRODUCTION PROCESS

Health and safety are fundamental to maintaining a productive and efficient work environment. A well-structured safety program minimizes workplace hazards, reduces accident risks, and fosters a culture of responsibility and awareness (Anthony et al., 2007). Proper safety implementation not only protects workers but also enhances operational efficiency, reduces costs related to injuries, and improves job satisfaction.

Effective health and safety management requires continuous risk assessment, comprehensive training, and strict adherence to established regulations (Garcia-Herrero et al., 2012). Industries such as construction, manufacturing, and film production rely on structured safety protocols to prevent injuries and ensure smooth workflows. Over the past 50–60 years, health and safety regulations have evolved significantly, placing the primary responsibility for workplace safety on employers (Jorgensen, 2015). This shift has led to the widespread adoption of

occupational health risk management systems, fostering safer work environments (Lanoie, 1992; Okunn et al., 2001).

Film production is inherently demanding, with long working hours (often exceeding 12-16 hours per day) contributing to fatigue, diminished focus, and an increased risk of accidents. The art department involves intense physical labor, exposure to extreme weather, and tight deadlines, which can increase stress levels. Financial constraints further increase pressure, often requiring crew members to multitask, leading to burnout. Additionally, the unpredictable nature of film sets—such as last-minute script changes or technical failures—demands quick problem-solving under high-pressure conditions.

Despite these risks, industry attitudes often prioritize production demands over safety considerations, as reflected in sayings such as “getting the shot is what counts” and “the show must go on.” Immersed in the art of illusion, crew members sometimes overlook real-world dangers, neglecting critical safety protocols (Campbell & Mann, 1987; McCann, 1991). Several incidents highlight the consequences of this mindset.

For example, during the filming of *The Siege of Sidney Street* (1960), British actor Leonard Sachs was injured while performing a scene inside a burning building. Although the room and props, as well as the actor's shoulders and arms, were coated with fire-proof jelly, the special effects crew neglected to apply the jelly to Sachs' head because it would have delayed production by approximately 20 minutes. As a result, Sachs suffered burns to his hair and scalp during filming (Sinden, 1982).

Similarly, during a dress rehearsal for *The Masked Singer* (2019), performer Michelle Williams, appearing as “The Butterfly,” suffered an electric shock when a set piece short-circuited during a CO₂ effect. Although Williams was reportedly unharmed, the force of the shock was sufficient to split one of the boots she was wearing (Entertainment Tonight, 2021).

In a more tragic incident, during the shooting of *Indian 2* (2024), a crane carrying heavy lighting equipment collapsed on set, resulting in the deaths of three crew members, including an assistant director, and injuring ten others. High-profile figures such as Director S. Shankar and actors Kamal Haasan and Kajal Aggarwal narrowly escaped serious injury (The Times of India, 2020; Lakshmi, Sharanya, & Menon, 2022). These incidents underscore the persistent tension between artistic ambition and workplace safety, demonstrating the urgent need for stronger safety practices within the film industry.

2.4. EXISTING HEALTH AND SAFETY REGULATIONS IN FILM PRODUCTION

According to safety guidelines issued by the Audiovisual Producers' Association, in collaboration with the European Institute for Health and Safety in the Film Industry and the Technical University of Ostrava – Faculty of Safety Engineering (2021), workplace safety on a film set is primarily the responsibility of the production managers and producers.

These individuals are accountable for ensuring compliance with legal standards and may face criminal liability in cases of injury, death, or property damage resulting from negligence. For instance, the Czech Act No. 40/2009 Coll. (Criminal Code)

stipulates those individuals who negligently harm others due to professional misconduct or cause injury to multiple individuals through gross safety violations may face imprisonment for one to three years. Such legal provisions underscore the necessity of strict adherence to safety protocols in film production.

In Australia, the Victorian Screen Industry Code of Conduct (Film Victoria Australia, 2013) offers comprehensive guidelines for managing location-based production risks. This document includes checklists to assist in identifying potential hazards; however, as these checklists are often generic, Film Victoria recommends involving safety experts to tailor risk management practices to the specific needs of each production.

In Los Angeles, the Industry-Wide Labour-Management Safety Committee (2002), operating under the Contract Services Administration Trust Fund (CSATF), plays a pivotal role in enhancing health and safety standards within the motion picture and television industry. This committee, composed of safety managers from major production companies, along with representatives from trade associations, guilds, and labor unions, developed the General Code of Safe Practices for Production, a foundational safety framework for California's film and television sector. Over the past two decades, the committee has issued 42 safety bulletins addressing a wide range of production-related risks (Santos, de Oliveira, & Rocha, 2018). While some bulletins focus on general safety measures, others provide detailed guidance based on federal, state, and local regulations. These guidelines cover industry-specific concerns, such as the safe use of helicopters and animals, working in cold environments, and the coordination of stunts (Industry-Wide Labor-Management Safety Committee, 2002).

It is widely understood that serious occupational accidents and illnesses can be prevented by adhering to the guidelines outlined in these safety standards. However, most existing safety frameworks primarily focus on risks occurring during the filming phase. These risks are often related to factors such as the physical characteristics of filming locations, the technical demands of capturing sound and images, the type of equipment used, and costume requirements (Industry-Wide Labor-Management Safety Committee, 2002). Notably, these safety standards identify relatively few risks specific to the art department, particularly during the pre-production stage.

Despite the central role of the art department in film production, there remains a significant gap in the academic literature regarding health and safety practices within this area. Much of the existing research focuses on broader industry concerns, with limited attention to the specific hazards faced by art department crews, especially in Sri Lanka. This study aims to address this gap by focusing on identifying the occupational risks inherent in art department workflows during the pre-production stage of film and television production.

3. Methodology

This study adopts a qualitative research approach to identify potential risks that individuals face within the practices of the art department workflow in film production. Data was collected through (a) systematic on-site observation and (b) narrative interviews with crew members of the selected three cases. The observation is focused on the pre-production and production stages.

3.1. DATA COLLECTION METHODS

1. On-Site Observation

The observation process was conducted by the author, who was part of the art department, through daily journaling. Observations were recorded systematically each day as a note-taking exercise, documenting the tasks completed and any risks or health hazards encountered. Observations were conducted across three case studies and were based on the author's direct on-site observations. The focus of the observation was specifically on identifying occupational risks and health hazards within the art department. Attention was given to activities related to set construction, scenic painting, set decoration, prop making and principal filming activities. Field notes were maintained throughout the pre-production and production stages, recording identified hazards, incidents, and informal safety practices observed during daily operations.

2. Narrative Interviews

Narrative interviews were conducted with crew members responsible for the art department's sub-divisions, including the construction manager, prop master, set decorator, chief painter, and assistant art director. The purpose of these interviews was to explore practical experiences and investigate the causes related to the accidents and health hazards documented through the observational journaling process. Interview data were transcribed and subjected to thematic analysis to identify the underlying causes of the observed risks and to further validate the patterns noted during the observation stage.

3.2. CASE STUDY

Three cases were selected due to the prominent role played by the author as an insider (a member of the art department) to gain primary data on the workflow. As discussed in the introductory section, among nine television and film productions within her 15-year career, two films and one television series were journaled for this study. The following are the three cases.

1. Akasa Kusum (film)

Akasa Kusum is a film produced by a Sri Lankan production company and was entirely filmed in Sri Lanka, with an art department crew composed exclusively of Sri Lankan professionals. The primary film sets included a house, a nightclub, streets, a slum area, and a hospital. The hospital, slum, and nightclub settings were created by modifying and redecorating real, existing locations to match the needs of the film's story. In this film, the art department was specifically divided into three main sub-departments: set construction, prop making, and set decoration. The set construction team built indoor sets inside a film studio to represent different locations needed for the film, including a television reality program space, a television office space, and several slum houses. The prop-making department primarily handled the creation of breakable props for action sequences, including real glasses, fake alcohol, and cigarettes for the nightclub scenes. The set decoration team was responsible for dressing the filming spaces, including practical lighting elements such as decorative streetlights for Christmas festival scenes, nightclub lighting, and neon signage. The overall production process for the art

department spanned seven weeks, covering both the pre-production and production stages. The author served as the Production Designer for this film.

2. Funny Boy (Film)

Funny Boy is a film produced by a Canadian production company and was entirely filmed in Sri Lanka, with an art department crew composed exclusively of Sri Lankan professionals. The primary film sets included two main houses, streets, a railway station, a school, a convent, railway tracks, and a beach. The houses, streets, railway station, school and convent sets were created by redecorating existing places. In this production, the art department was specifically divided into four main sub-departments: set construction, scenic painting, prop making, and set decoration. The set construction team adapted parts of existing locations to create a jail and a police station. The prop-making department primarily handled the production of breakable furniture and multiple duplicates of props for action sequences, as well as crafting dummy weapons such as knives, swords, iron rods, wooden poles, and hammers for stunt scenes. The set decoration team redecorated the film sets according to narrative requirements, including replacing shop boards, road signs, landscaping residential properties, and installing practical lighting elements. The scenic painting team created large-scale hand-painted advertisements and film cutouts for use in the street scenes. The overall production process for the art department spanned ten weeks, covering both the pre-production and production stages. The author served as the Assistant Prop Master during the pre-production period and as the Standby Prop Master during the production phase.

3. The Good Karma Hospital (Television Series – Season Four)

The Good Karma Hospital is a television series produced by a British production company and filmed entirely in Sri Lanka. Key art department roles, such as the Production Designer and Standby Prop Master, were filled by professionals from England, while the remaining crew consisted of Sri Lankan professionals. The primary sets included a hospital, a house, a beach bar, and streets, with prominent filming locations specifically allocated to minimize public interaction. The art department was divided into four main sub-divisions: set construction, scenic painting, prop making, and set decoration. The set construction team built a new beach bar directly on the coast and adapted an existing hospital theatre. The prop-making team sourced surgical and hospital equipment, created dummy surgical tools, prepared vital sign monitors, and supplied breakable and replica items such as bottles, fake alcohol, and cigarettes. The set decoration team managed furnishing, painting, and practical lighting installations, particularly focusing on the challenges of the coastal environment. The art department's overall work spanned twenty-four weeks, covering both pre-production and production stages. The author participated as the Assistant Prop Master and Research Assistant during pre-production and as the Standby Art Director during production.

3.3. DATA ANALYSIS

At the end of the observational process, and following analysis, the potential and actual accidents and risks within the art department were identified. The causes of the observed risks and accidents were categorised based on themes that emerged

from consensus discussions with crew members. Each identified accident and its corresponding cause were then tabulated separately for each sub-department.

This tabulation process was applied across all three case studies, enabling a comparative analysis of the observed risks and safety practices. By cross-referencing the findings from each case, common risk patterns and variations were identified. This cross-case verification strengthened the reliability of the categorization process, ensuring that the key risk categories were not isolated incidents but consistently observable across different production environments. The integrated analysis of observational data and interview insights provided a comprehensive understanding of the occupational hazards faced by art department personnel. Ultimately, this process facilitated the categorization of five principal risk areas, which form the basis for the thematic discussion presented in the following sections.

Sub departments	observations	Causes (from interviews)
Set construction (pre-production)	Exhaustions	Long hours working
	Work stress	Working load is unbearable Less man power due to budget concentrates.
	Injuries while using Power tools	Less safety conditions No personal safety gears for workers
	Instant illness like blood pressure, fever---etc.	Bad weather Long hour working
	Food poisoning	No quality assures for food suppliers
	Chemical allergies	No personal safety gears like gloves, overalls
	Heavy lifting injuries	Less man power Work stress Working in very tight schedules
	Falls from heights	Unstable ladders, scaffoldings and less safety grips
	Food poisoning, dehydration	Less water supplying, using water without quality ensured
	Lots of Work stress and anxiety	Working more than 14 hours continuously Less man power Budget restrictions
Scenic Department (pre-production)	Accidents using hammers, hand tools	Due to work stress and fatigue
	Eye infections	Using chemicals using safety goggles Uneducated about the safety guidelines
	Electric shocks	
	Skin allergies	
	Swollen chemicals accidently	Not have proper organized work shop and stores
	Eye infections	Using chemicals using safety goggles Uneducated about the safety guidelines

Figure 1: Sample of the Tabulation process (Source: prepared by authors)

4. Results and Discussion

This section presents the findings derived from onsite observations and narrative interviews conducted within the art department of three case study film productions. The risks identified through the tabulated data were thematically rearranged into hazards and risk categories. The study categorizes key risk factors encountered by the art department during the pre-production and production stages of film projects into five main areas, as presented in Table 2. These categories are:

1. Physical and Occupational Hazards
2. Chemical and Material-Related Risks
3. Electrical Hazards
4. Special Effects and Stunt-Related Risks
5. Health and Well-Being Risks

Table 1: Identified Risks and Causes in the Art Department (Source: Prepared by author)

Category	Identified Risks	Causes
Physical and Occupational Hazards	Injuries from power/hand tools	Lack of safety training
	Falls from heights, ladders, scaffolding	Unstable scaffolding Unstable Ladders Lack of safety grips
	Heavy lifting injuries	Poor lifting techniques
Chemical and Material-Related Risks	Skin allergies from paints, adhesives	Poor ventilation Less Knowledge about materials
	Eye & respiratory issues from chemical exposure	Lack of protective equipment
	Accidents with artificial materials (foam, plastic)	Direct skin contact less knowledge about how to use
Electrical Hazards	electric shocks (esp. in outdoor/beach locations)	Improper insulation
	Fire risks from faulty wiring	Exposure to moisture and salt
Special Effects and Stunt-Related Risks	Injuries from real glass, weapons, and explosive materials	Lack of safety rehearsals
	Misidentification of real vs. fake props	Poor labelling and storage of hazardous items
Health & Well-Being Risks	Food poisoning, dehydration	Poor food hygiene
	Long working hours leading to exhaustion	Inadequate rest periods
	Lots of Work stress and anxiety	Not enough pre-production period Last-minute requirements
	Lack of immediate medical assistance	No on-set medical support No ambulance on set

4.1 PHYSICAL AND OCCUPATIONAL HAZARDS

The most frequently encountered risks included injuries from power tools, falls from scaffolding and ladders, and injuries caused by heavy lifting. These findings align with Barnwell (2017), who identifies set construction and prop handling as particularly high-risk tasks due to the physical nature of the work. Similar hazards

have been noted in construction industries, as discussed by Garcia-Herrero et al. (2012), where working at heights and manual labor are primary sources of workplace injuries.

The lack of proper training and unstable equipment observed in Sri Lankan productions highlights the gap in applying structured safety protocols. Compared to guidelines like the industry-wide Labour-Management Safety Committee (2002) in the U.S., which mandates scaffolding safety and tool handling procedures, Sri Lankan productions appear to lack regulatory enforcement.

4.2 CHEMICAL AND MATERIAL-RELATED RISKS

Exposure to adhesives, paints, artificial materials, and dust presented considerable risks, especially among scenic painters and prop makers. Reported symptoms included skin irritation, respiratory discomfort, and allergic reactions, risks exacerbated by poor ventilation and limited PPE usage. While the literature acknowledges these hazards (e.g., McCann, 1991; Barnwell, 2017), most existing health and safety frameworks (such as those from Film Victoria Australia, 2013) address them only in general terms. The findings from this study suggest a pressing need for production-specific chemical handling guidelines, especially during the pre-production stage, which is often neglected in current safety literature.

4.3 ELECTRICAL HAZARDS

Electric shocks and wiring-related fire risks were identified, especially during location-based shoots such as in beach areas where moisture and salt exposure were prevalent. These risks were compounded by inadequate insulation and hasty setups under time pressure.

As discussed by Campbell & Mann (1987), the urgency of “getting the shot” often compromises crew safety. In contrast, U.S.-based safety bulletins (Industry-Wide Committee, 2002) recommend routine equipment testing and moisture protection practices not consistently followed in the observed productions.

4.4 SPECIAL EFFECTS AND STUNT-RELATED RISKS

Injuries involving breakable props, real vs. fake weapons, and poorly rehearsed stunt scenes were documented across all three case studies. The absence of clear labelling and designated storage areas for hazardous props was a recurring issue.

This supports findings in both academic and trade publications (Monaco, 2000; Lanoie, 1992), which describe how miscommunication and lack of protocol in prop use led to avoidable accidents. Incidents like the Indian 2 (2020) crane collapse reinforce the fatal consequences of neglecting safety rehearsals, paralleling risks observed in local productions.

4.5 HEALTH AND WELL-BEING RISKS

Fatigue, stress, long working hours, and lack of medical support were consistently reported. Symptoms ranged from dehydration and dizziness to emotional burnout, particularly during back-to-back night shoots or compressed pre-production periods.

These findings directly reflect concerns raised by Anthony et al. (2007) and Jorgensen (2015), who link long hours and unsafe working conditions to decreased

focus and higher accident rates. Moreover, cultural norms in the industry—reflected in sayings like “the show must go on”—frequently discourage workers from voicing concerns (McCann, 1991).

5. Conclusion

The literature review revealed a significant gap in research concerning risk identification and health and safety practices within the film and television industry, particularly in relation to the art department. While many international film industries have adopted formal safety protocols for the filming process, Sri Lankan film productions largely lack such structured guidelines. The working environment within the art department involves a wide range of risk factors and potential causes of health issues for crew members, positioning it as one of the highest-risk departments within a production.

This study underscores the variety of risks present in art department workflows and demonstrates how these risks differ across productions depending on factors such as the filming environment, production type, and on-set activities. By documenting these risks, challenges, and underlying causes, this research provides a valuable foundation for future studies and industry discussions aimed at improving safety standards. It is hoped that academics, researchers, and professionals in the film and television industry will use these insights as a practical guide for developing more effective and context-specific risk management strategies for art department operations.

6. References

- Anthony, V., Mark, P., Michael, B., & Ajay, D. (2007). A data-based evaluation of the relationship between occupational safety and operating performance. *The Journal of SH & E Research*, 4(1).
- Audiovisual Producers' Association, European Institute for Health and Safety in the Film Industry, & Technical University of Ostrava – Faculty of Safety Engineering. (2021). Safe film: An introduction to the issue & the twelve rules for safe filming. https://www.filmcommission.cz/media/co4k51qd/apa_bezpecnost_eng.pdf
- Barnwell, J. (2017). *Production design for screen: Visual storytelling in film and television*. Bloomsbury.
- British Film Institute. (2019). Filming locations of *The Bridge on the River Kwai* and other Hollywood productions in Sri Lanka. *BFI Journal*, 23(4), 45–60.
- Campbell, S., & Mann, C. (1987). Safety on the set. *Back Stage*, 1A. <http://link.galegroup.com/apps/doc/A4758905/AONE?u=capes&sid=AONE&xid=6b549e23>
- Eder, J. (2010). Understanding characters. *Projections*, 4(1), 16–40. <https://doi.org/10.3167/proj.2010.040103>
- Egan, K. (2014). Film production design: Case study of *The Great Gatsby*. *The Elon Journal of Undergraduate Research in Communications*, 5(1), 5–14.
- Entertainment Tonight. (2021, August 21). Michelle Williams dishes on getting electrocuted on *Masked Singer*. <https://www.etonline.com/>
- Film Victoria Australia. (2013). *Victorian screen industry code of conduct*. Melbourne, Australia.

- Garcie-Herrero, S. (2012). Working conditions, psychological, physical symptoms, and occupational accidents: Bayesian network models. *Safety Science*, 50(9), 1760–1774.
- Honthaner, E. L. (2001). *The complete film production handbook* (3rd ed.). Focal Press.
- Jorgensen, K. (2015). Prevention of "simple accidents at work" with major consequences. *Safety Science*, 71, 46–58.
- Lakshmi, V., Sharanya, C. R., & Menon, T. (2022, August 24). A crane accident on set of Indian 2 costs three lives and raises questions on safety measures. *The Times of India*. <https://timesofindia.indiatimes.com/>
- Lanoie, P. (1992). The impact of occupational safety and health regulation on the risk of workplace. *The Journal of Human Resources*, 27(4), 643–660. <https://doi.org/10.2307/146079>
- LoBrutto, V. (2002). *The filmmaker's guide to production design*. Allworth Press.
- McCann, M. (1991). *Lights! Camera! Safety! A health and safety manual for motion picture and television production*. Center for Safety in the Arts.
- Monaco, J. (2000). *How to read a film*. Oxford University Press.
- Okun, A., Lentz, T. J., Schulte, P., & Stayner, L. (2001). Identifying high-risk small business industries for occupational safety and health interventions. *American Journal of Industrial Medicine*, 39(3), 301–311. [https://doi.org/10.1002/1097-0274\(200103\)39:3<301:AID-AJIM1018>3.0.CO;2-L](https://doi.org/10.1002/1097-0274(200103)39:3<301:AID-AJIM1018>3.0.CO;2-L)
- Santos, R. B., & de Oliveira, U. R. (2019). Analysis of occupational risk management tools for the film and television industry. *International Journal of Industrial Ergonomics*, 72, 199–211. <https://doi.org/10.1016/j.ergon.2019.05.002>
- Santos, R. B., de Oliveira, U. R., & Rocha, H. M. (2018). Failure mapping for occupational safety management in the film and television industry. *International Journal of Production Economics*, 203, 1–12. <https://doi.org/10.1016/j.ijpe.2018.05.024>
- Sinden, D. (1982). *A Touch of the Memoirs*. Hodder & Stoughton Ltd.
- The Times of India. (2020, October 13). 'Indian 2' accident: This is how Kamal Haasan and Kajal Aggarwal narrowly escaped from the unfortunate disaster on the sets of the film. <https://timesofindia.indiatimes.com/>
- Wide Labor-Management Safety Committee. (2002, June 19). CSATF. http://www.csatf.org/pdf/05SAFETY_AWARENESS.pdf

GUIDELINES FOR OPTIMISING ENERGY CONSUMPTION OF HVAC AIR-SIDE SYSTEMS IN COMMERCIAL BUILDINGS IN SRI LANKA

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Abstract. Currently, discussions on climate change, fossil fuel depletion, and energy conservation emphasise the urgency of creating a more sustainable built environment. Reducing energy consumption and emissions in the building sector has become a priority. With a primary focus on commercial buildings in Sri Lanka, where Heating Ventilation and Air Conditioning (HVAC) systems account for a significant portion of electricity usage, this research aims to identify local and international guidelines for HVAC-airside strategy implementation. To achieve this, a literature review was conducted, and a qualitative research approach was used to pursue the research aim; an interview survey using semi-structured interviews was conducted targeting 17 experts. The collected data were then analysed using content analysis using the NVivo software. The study identified eight applicable guidelines: EEBC, IESL guidelines, CPEEB, CIBSE, ASHRAE, Singapore Green Mark standard, EPBD and SMACNA. These insights offer valuable knowledge for industry professionals seeking to improve HVAC airside energy efficiency and provide a foundation for further academic research on HVAC systems in Sri Lanka. By applying these guidelines, the commercial building sector can take a step towards a more energy-efficient and sustainable future.

Keywords. Airside Efficiency, Central Air-Conditioning System, Commercial Building

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 ensuing environmental repercussions (Zakaria et al., 2023). Especially, energy services associated 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., 2016). Within the Sri Lankan context, the building sector is the largest consumer of primary energy, constituting nearly 60% of the nation's electricity consumption (Selvakkumaran & Limmeechokchai, 2020) and within this sector, a substantial portion of energy is allocated to HVAC systems, accounting for approximately 51% (Geekiyanage & Ramachandra, 2018).

Given the complexity of HVAC systems, breaking them down into their constituent parts is essential for a thorough understanding (Ahmad et al., 2018). HVAC systems are typically divided into waterside and airside components, with both playing crucial roles in the overall performance of the HVAC system as a whole (Patel et al., 2018). A similar opinion was stated by Faulkner et al. (2023), emphasising that achieving optimal energy savings in buildings requires a broad approach that considers both the waterside and airside components simultaneously. In this context, the HVAC airside system is pivotal in enhancing energy efficiency; however, it often receives inadequate attention in commercial buildings in Sri Lanka.

According to existing literature, energy consumption in commercial buildings accounts for approximately 20% of Sri Lanka's total electricity usage (Weerasinghe

et al., 2016), with airside HVAC systems contributing to 20% of this consumption (Amjath et al., 2021). Despite the significant energy consumption and the clear need for improved efficiency, optimal energy-saving practices in airside systems are not consistently achieved in Sri Lankan commercial buildings. One key barrier is the limited awareness and adherence to established guidelines for implementing effective HVAC airside strategies. Addressing this knowledge gap is crucial for improving energy efficiency in these buildings. Therefore, this paper aims to identify key guidelines for HVAC airside strategies and provide insights to support their effective implementation in Sri Lanka.

2. Literature Review

2.1. ENERGY CONSUMPTION OF COMMERCIAL BUILDINGS

The first step to understanding where energy can be saved is to understand where it is being consumed (Frederiks et al., 2015). Running expenses of a building consume a substantial share of its total life cycle cost and range between 70% and 80% in commercial buildings (Geekiyanage & Ramachandra, 2021). As per the US researchers, the top three end uses in the commercial sector are space heating, lighting, and space cooling, which represent close to half of commercial site energy consumption (Taylor & Narel, 2012) but contradictory views were presented by Houde and Myers (2021) who stated that lighting uses more electric energy than any other system in a commercial building, which is about 38% of total energy output. Even though percentages are different among countries for different building services, the energy consumption of HVAC systems is particularly significant (González-Torres et al., 2022).

Comparable to the global context, even in the Sri Lankan context, the rising demand for electricity is a major contributory factor to the energy crisis in Sri Lanka (De Silva & Sandanayake, 2018). The commercial and industrial sector comprises a large stock of buildings that contribute to nearly 60% of the national electricity consumption (Bandara & Attalage, 2020). Further, the commercial sector alone, under which large-scale buildings fall, contributes to 24% of the consumption, where most of the buildings use energy in the form of electrical energy, and a higher percentage of it is consumed for air conditioning (Sri Lanka Sustainable Energy Authority, 2022). Geekiyanage and Ramachandra (2018) have mentioned that in Sri Lanka, more than 75% of energy consumption in commercial buildings is accounted into the HVAC system.

2.2. CENTRAL AIR CONDITIONING SYSTEM AND AIRSIDE EFFICIENCY

The central 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., 2018b). The airside system includes the zones in all of the buildings along with the associated air-handler units (AHUs) used in temperature regulation (Rawlings et al., 2018). Faulkner et al. (2023) stressed the necessity of concurrently addressing both subsystems to enhance energy efficiency in buildings. However, Sekhar (2016) asserted that the design of airside HVAC systems significantly influences achieving optimal air quality, acknowledging the inherent challenges in this design process. Thus, airside energy efficiency is a critical aspect of overall HVAC system performance, and it serves as the key factor determining indoor air quality (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., 2022).

2.3. GUIDELINES FOR HVAC AIRSIDE STRATEGY IMPLEMENTATION

According to Khazaii (2016) guidelines refer to documents and standards that outline recommended practices for implementing specific strategies. A similar opinion was forwarded by Punt et al. (2016) emphasising that guidelines serve as structured references to ensure best practices in system design and operation. In this context, guidelines encompass not only explicit standards but also frameworks and certification systems that set benchmarks for energy performance and sustainability. The guidelines considered in this study include regulatory codes, engineering standards, and sustainability rating systems (e.g., Singapore Green Mark, EPBD), each of which provides actionable recommendations for HVAC airside design and performance (Gajaba & Dissanayake, 2024). However, globally recognised building rating systems such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) were excluded from this study due to their broader sustainability focus, which covers a wide array of building systems, and their relatively limited direct technical guidance on HVAC airside systems compared to the other frameworks analysed. The successful implementation of effective HVAC airside strategies relies on adherence to these established guidelines, which aim to optimise energy efficiency, improve indoor air quality, and enhance overall system performance. These guidelines are categorised into local and international frameworks, as outlined in the following sections.

2.3.1 Local Guidelines

In Sri Lanka, HVAC airside strategies must align with national regulations and industry best practices to improve energy efficiency in commercial buildings.

Code of Practice for Energy Efficient Buildings (CPEEB) by the Sri Lanka Sustainable Energy Authority (SLSEA) provides recommendations on energy-efficient building design and operations, emphasising HVAC optimisation to reduce energy consumption (Bandara et al., 2015). Sri Lanka Sustainable Energy Authority Act, No.35 of 2007 empowers the Sri Lanka Sustainable Energy Authority (SLSEA) to specify and enforce a code of practice on efficient energy utilisation in buildings. Giving due regard to this, SLSEA has revised and finalised the CPEEB in Sri Lanka, which was first published in 2008 and has undergone revisions (SLSEA, 2020). These recommendations include airside strategies such as demand-controlled ventilation, efficient air distribution systems, proper duct insulation, air leakage minimisation, and optimised fan energy usage. Additionally, SLSEA promotes the use of energy recovery ventilation (ERV) systems and the adoption of high-efficiency air filtration methods to enhance indoor air quality while reducing unnecessary energy wastage.

The Energy Efficiency Building Code (EEBC) also outlines standards for HVAC systems, focusing on airside energy management, including airflow optimisation, duct insulation, and air filtration efficiency (Emmanuel & Rogithan, 2016). According to Zamaan & Wickramaratna (2025), the government of Sri Lanka recognised the importance of improving the energy performance of buildings as an

integral component of the national sustainable energy development strategy. The same authors 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 on a voluntary basis if they exceed any one of the criteria that is listed as follows.

- i. Building height exceeding four stories
- ii. Floor area of 2,000 m² or greater
- iii. Building enclosed volume of 5,600 m³ or greater
- iv. Electrical peak demand of 100 kW or greater v Air-conditioning cooling capacity of 350 kW (output)

According to Bandara and Attalage (2020), this code failed to convince majority of stakeholders in the industry and most architects considered this code as a constraint for creativity, hence, this building energy code was never practiced in Sri Lanka and soon became obsolete. The Sri Lanka Sustainable Energy Authority (SLSEA) in 2007 established an Act of Parliament in order to drive the concept of energy efficiency on a national scale and develop a code to be followed on a voluntary basis (Sri Lanka Sustainable Energy Authority, 2008). But in this too certain concerns have been observed related to the scope of the code itself and also for its implementation; therefore, it is not widely practised.

2.3.2 International Guidelines

Several internationally recognised standards provide best practices for implementing HVAC airside strategies, ensuring high energy efficiency and environmental sustainability in commercial buildings.

The ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), is widely adopted for HVAC system efficiency (Simpeh et al., 2022). ASHRAE 90.1 establishes minimum energy performance requirements for HVAC systems, covering aspects such as ventilation rates, duct sealing, and fan energy consumption (Halverson et al., 2018). ASHRAE 62.1 focuses on indoor air quality by defining proper airflow regulation and high-efficiency filtration, while ASHRAE 189.1 provides guidance for high-performance green buildings, integrating advanced airside strategies like demand-controlled ventilation and energy recovery systems (Lorenzetti & Wray, 2016).

CIBSE (Chartered Institution of Building Services Engineers) Guidelines, offer technical recommendations on HVAC airside efficiency. CIBSE Guide B provides best practices for ventilation, ductwork design, and airflow regulation to minimise energy losses (Knight & Jones, n.d.). Additionally, CIBSE TM40 focuses on indoor air quality management, promoting the use of energy-efficient air filtration and optimised ventilation rates to enhance both energy conservation and occupant well-being (Zaniboni & Albatici, 2022).

SMACNA (Sheet Metal and Air Conditioning Contractors' National Association), established by the Sheet Metal and Air Conditioning Contractors' National Association, focuses on best practices for ductwork design and airside system performance (Zaniboni, 2021). The HVAC Duct Construction Standards outline proper duct fabrication, sealing, and insulation methods to reduce air leakage and

improve energy efficiency (Breda et al., 2024). Furthermore, the same authors stated that, it has details about the HVAC Systems Commissioning manual procedures for system balancing, ensuring effective airflow distribution, and reducing unnecessary energy consumption.

Singapore Green Mark Standard, developed by the Building and Construction Authority (BCA) of Singapore, sets benchmarks for sustainable buildings, including HVAC airside strategies (Agarwal et al., 2017). It emphasises optimised ventilation rates, high-efficiency air filtration to improve indoor air quality, and energy-efficient fan operations to reduce power consumption. The certification scheme encourages the adoption of smart HVAC technologies and demand-controlled ventilation for better energy management (Zhang et al., 2024).

By integrating these international standards with local regulations, Sri Lanka's commercial building sector can enhance HVAC airside efficiency, reduce overall energy consumption, and improve indoor air quality.

3. Research Methodology

This study aims to provide guidelines for HVAC airside strategy implementation to commercial buildings in Sri Lanka. 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. Hence, a qualitative survey comprising semi-structured interviews was employed, given the significance of comprehending guidelines for the implementation of airside HVAC strategies in commercial buildings in Sri Lanka. Moreover, semi-structured interviews allow the researchers to repeat or rephrase the interviewee's responses in order to get additional clarifications and assist them in gaining a thorough understanding of the issue of interest. According to Okken et al. (2019) adapted from Bertaux (1981), a qualitative survey should be more than fifteen per sample therefore, for this study, a sample of 17 respondents was chosen who are all experts in the HVAC industry.

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 2.3.1. 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 I.

Table 1: Profile of 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	1,400,000 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	1,100,000 kWh	550,000 kWh	50%		4500kVA
E5	580,000 kWh	240,000 kWh	50%	Rs. 14 Mn	1800kVA

E6	1,500,000 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	Tower1-640kVA Tower2-800kVA
E10	1,400,000 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, tabulation, and then drawing statistical inference (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.

4. Research Findings

The findings of the research could be presented under two headings: local guidelines and international guidelines, and each is comprehensively described below.

4.1 LOCAL GUIDELINES

One of the key regulations guiding HVAC operations in Sri Lanka is the Energy Efficiency Building Code (EEBC). Several experts emphasised its role in ensuring sustainable HVAC practices by establishing minimum energy performance criteria. The code mandates that HVAC systems be designed, installed, and commissioned in a way that enhances overall efficiency. Specifically, E12 and E14 highlighted that HVAC systems with cooling capacities exceeding 25 TR must undergo rigorous testing and commissioning in compliance with EEBC guidelines. This ensures that large-scale cooling systems in commercial buildings meet energy efficiency benchmarks before being fully operational.

Another critical guideline stressed by experts is the Code of Practice for Energy-Efficient Buildings in Sri Lanka, issued by the Sri Lanka Sustainable Energy Authority (SLSEA). This guideline provides specific strategies for improving HVAC airside efficiency. Experts such as E4, E5, and E7 highlighted its role in promoting energy-saving measures, while E10 argued that its implementation requires greater regulatory oversight to achieve widespread effectiveness.

In addition to these standards, experts also referenced the Institution of Engineers, Sri Lanka (IESL) specifications for air-conditioning and mechanical ventilation as a key local guideline. These specifications offer detailed technical guidance on HVAC design, with a strong focus on optimising energy consumption and minimising environmental impact. Some experts noted that while these guidelines align with international best practices, particularly those set by ASHRAE, they require stronger enforcement to drive greater adoption across commercial buildings in Sri Lanka.

4.2 INTERNATIONAL GUIDELINES

ASHRAE standard was highlighted by all experts for airside efficiency strategies for HVAC systems. E1, E2, E3, and E4 confirmed that ASHRAE Standard 90.1- Energy Efficiency of Buildings is frequently integrated into the design phase of buildings to ensure compliance with best practices. However, aside from E1 and E4, the remaining experts denied the consistent application of these standards during the operation and maintenance phases of commercial buildings in Sri Lanka. According to multiple experts, this lack of adherence could be a major factor contributing to inefficiencies in HVAC systems within commercial buildings in Sri Lanka. Furthermore, E5 emphasised the importance of following this guideline as, "ASHRAE is a general worldwide standard. We have to select the country's climate zone before referring to specific data tables", and elaborated more on this by stating "if Sri Lanka falls under Climate Zone 0-A. When we use data from this category, we comply with ASHRAE 90.1 and reduce energy consumption." Similarly, E17 stated, "Being a tropical country, we cannot directly adopt ASHRAE standards but must modify them to suit our local context" mentioning the importance of customising the standard for the climate condition of Sri Lanka. Several experts also referenced ASHRAE Standard 62.1- Ventilation for Acceptable Indoor Air Quality, which provides essential ventilation requirements for different building types. E14 stressed the significance of demand-controlled ventilation (DCV), regulated by CO₂ concentration in densely occupied spaces, as well as DCV for car parks, based on CO levels. These measures are designed to optimise fresh air intake while minimising unnecessary energy use. Additionally, E15 and E17 pointed out the relevance of ASHRAE Standard 189.1-High-Performance Green Buildings, which sets more stringent sustainability criteria than ASHRAE 90.1. E17 asserted that merely achieving ASHRAE 90.1 compliance is not enough and recommended referring to the ASHRAE Green Guide and Singapore Green Mark for improved energy efficiency. E15 further emphasised that ASHRAE 189.1 aligns with global green building strategies and should be considered when aiming for high-performance, energy-efficient buildings.

SMACNA guideline was also highlighted by E14 and E17, in ensuring efficient ductwork design and installation. These standards provide detailed recommendations on ducting efficiency, leakage prevention, and airflow optimization, which are critical for maintaining HVAC performance. Experts noted that while SMACNA guidelines offer a strong foundation for HVAC efficiency, their practical implementation in Sri Lanka remains inconsistent, particularly in the operation and maintenance phases.

CIBSE guidelines, particularly CIBSE Guide B: Heating, Ventilating, Air Conditioning and Refrigeration was another that all experts mentioned. According to E1 and E4,

this guide provides comprehensive best practices for the design and operation of HVAC systems, ensuring optimal energy efficiency and indoor environmental quality. Experts stated that CIBSE guidelines are widely referenced in Sri Lanka's building sector but are less commonly enforced compared to ASHRAE standards. E5, however, pointed out a key difference between ASHRAE and CIBSE, stating, "ASHRAE is a widely accepted global standard, but CIBSE is more prescriptive and suited to specific contexts." Despite this, experts agreed that CIBSE standards offer valuable insights into airside efficiency and system optimisation, particularly in regions with similar climatic conditions to Sri Lanka.

Singapore Green Mark was frequently cited by experts as a benchmark for achieving higher energy efficiency in HVAC airside systems. E17 suggested that ASHRAE standards alone are not sufficient and recommended supplementing them with Singapore Green Mark requirements while E15 also emphasised the importance of using this certification framework to assess energy efficiency indices in HVAC systems.

Energy Performance of Buildings Directive (EPBD), a few experts referenced as a regulatory framework that could guide future energy efficiency initiatives. According to E1 and E4, professionals involved in sustainable commercial building projects occasionally refer to EPBD principles, particularly its focus on building energy audits, performance certification, and HVAC system optimisation. Experts acknowledged that the EPBD's requirements for energy monitoring, retrofitting, and lifecycle assessment of buildings could be highly beneficial for Sri Lanka's commercial sector. However, they also pointed out the lack of enforcement mechanisms and regulatory support needed to integrate EPBD principles into national energy efficiency policies.

5. Discussion

When considering local guidelines, the Energy Efficiency Building Code (EEBC) and the Code of Practice for Energy-Efficient Buildings (CPEEB) were identified in the literature as key regulatory frameworks specifying energy efficiency requirements for buildings, including HVAC systems. Experts agreed with this, expressing that these codes provide foundational guidance for energy-efficient practices. However, both the literature and findings highlighted that the EEBC code is outdated, raising concerns about its scope, enforcement, and implementation. Additionally, it operates on a voluntary basis, limiting its effectiveness in driving widespread adoption of HVAC airside efficiency strategies.

Regarding international guidelines, ASHRAE 90.1 (energy efficiency), ASHRAE 62.1 (ventilation and indoor air quality), and ASHRAE 189.1 (sustainability in high-performance buildings) were mentioned as key guidelines referred. These have been widely adopted in other countries, ensuring enhanced HVAC efficiency and environmental performance. However, in Sri Lanka, only ASHRAE 90.1 is commonly used, while airside strategy-related standards such as ASHRAE 62.1 and 189.1 remain largely unimplemented. Additionally, other international standards, including CIBSE guidelines, SMACNA ductwork standards, and the Singapore Green Mark Standard, were identified in both literature and expert findings. These offer structured approaches to optimising HVAC airside performance, yet their adoption in Sri Lanka remains limited.

From the findings, a newly identified local guideline was the Institution of Engineers, Sri Lanka (IESL) framework, which includes specifications relevant to HVAC airside strategy implementation. This was recognised as an important addition to local regulatory efforts. Furthermore, an international guideline, the Energy Performance of Buildings Directive (EPBD), was also identified from the research findings. EPBD provides a comprehensive framework for improving energy efficiency in buildings and can serve as a valuable reference for enhancing HVAC airside strategies in Sri Lanka.

Summarising the key findings, the following Figure 1 has been developed to illustrate the classification of relevant local and international guidelines applicable to HVAC airside strategy implementation.

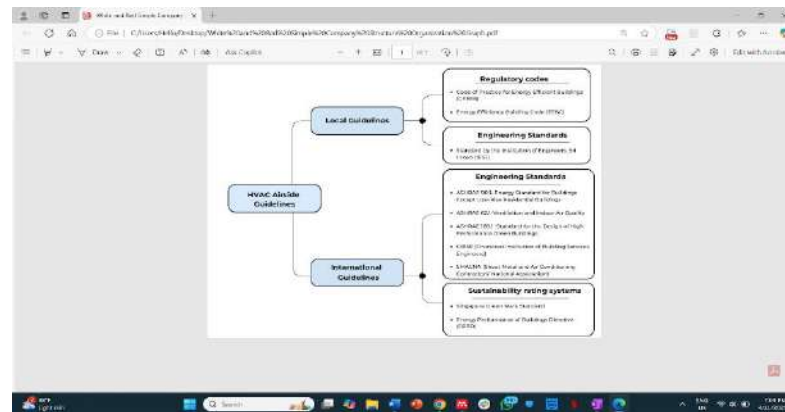


Figure 1: Local and international guidelines for HVAC airside strategy implementation

6. Conclusion

In conclusion, the research findings contribute valuable insights into HVAC airside strategies, particularly in tropical and coastal environments similar to commercial buildings in Sri Lanka. Three local guidelines were identified namely, EECB, CPEEB, and IESL, along with five international guidelines, ASHRAE, CIBSE, SMACNA, the Singapore Green Mark Standard, and the Energy Performance of Buildings Directive (EPBD). It was found that local guidelines are not widely followed due to their voluntary nature, lack of enforcement, and outdated provisions. Additionally, international guidelines, while widely used, need to be customised to suit Sri Lanka's specific climatic conditions for optimal efficiency. Overall, the findings highlight that HVAC energy consumption in commercial buildings is significantly high, with airside systems accounting for a major portion. Implementing effective airside strategies is crucial for improving energy efficiency, and this requires the establishment of mandatory codes, clear guidelines, and increased awareness among stakeholders. Strengthening regulatory frameworks and ensuring compliance will be essential for achieving long-term sustainability in Sri Lanka's commercial building sector.

7. References

- Agarwal, S., Sing, T. F., & Yang, Y. (2017). Are Green Buildings Really "Greener"? Energy Efficiency of Green Mark Certified Buildings in Singapore. SSRN Electronic Journal. <https://doi.org/10.2139/SSRN.3088895>
- Ahmad, T., Chen, H., Guo, Y., & Wang, J. (2018). A comprehensive overview on the data driven and large scale based approaches for forecasting of building energy demand: A review. In *Energy and Buildings* (Vol. 165, pp. 301–320). Elsevier Ltd. <https://doi.org/10.1016/j.enbuild.2018.01.017>
- Amjath, M. R., Chandanie, H., & Amarasinghe, S. D. I. A. (2021). Energy retrofits for improving energy efficiency in buildings: A review of hvac and lighting systems. *World Construction Symposium*, 290–301. <https://doi.org/10.31705/WCS.2021.25>
- Bandara, R. M. P. S., & Attalage, R. A. (2020). BUILDING ENERGY STANDARDS/CODES: PRESENT STATUS AND WAY FORWARD FOR SRI LANKA. The Official E-Newsletter of the Institution of Engineers Sri Lanka. <https://iesl.lk/SLEN/46/Energy.php>
- Bandara, Sugathapala, Rajapakse, L., Sumathipala, W., Perera, P., Wijekoon, H., Batagoda, B., Perera HLA Prasadi BKAPS Rodrigo HKSP Dayarathne N Dadigamuwa N H Madurapperuma, M. P., & Findings, R. (2015). Ministry of Power and Renewable Energy Democratic Socialist Republic of Sri Lanka Editor in Chief: SRI LANKA ENERGY EMPOWERED NATION Secretary Ministry of Power & Renewable Energy.
- Breda, J., Tahmasebi, M., Singla, R., Gao, H., Casco, Vernon, D., Kamisky, R., & Harrington Disclaimer, C. (2024). Commercial Building Duct Sealing Market Characterization Final Report ET24SWE0041 Acknowledgements.
- De Silva, M. N. K., & Sandanayake, Y. G. (2018). World Construction Conference 2012-Global Challenges in Construction Industry 28-30.
- Emmanuel, R., & Rogithan, R. (2016). How energy efficient is the EEBC? evaluation based on a simulated office building. *Built-Environment Sri Lanka*, 3(1), 31. <https://doi.org/10.4038/BESL.V3I1.7639>
- 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>
- Frederiks, E. R., Stenner, K., & Hobman, E. V. (2015). Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour. In *Renewable and Sustainable Energy Reviews* (Vol. 41, pp. 1385–1394). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2014.09.026>
- Gajaba, P., & Dissanayake, P. (2024). Strategies to Enhance Energy Efficiency of HVAC Airside System of Commercial Buildings in Sri Lanka. <https://doi.org/10.46254/AN14.20240652>
- Geekiyana, 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.jobbe.2018.01.011>
- Geekiyana, D., & Ramachandra, T. (2021). Running costs indices for commercial buildings using the hedonic price imputation approach: a case of Sri Lanka. *Construction Management and Economics*, 39(8), 704–721. <https://doi.org/10.1080/01446193.2021.1950790>
- González-Torres, M., Pérez-Lombard, L., Coronel, J. F., Maestre, I. R., & Yan, D. (2022). A review on buildings energy information: Trends, end-uses, fuels and drivers. In *Energy Reports* (Vol. 8, pp. 626–637). Elsevier Ltd. <https://doi.org/10.1016/j.egyr.2021.11.280>
- Halverson, M. A., Hart, R., Athalye, R. A., Rosenberg, M. I., Richman, E. E., & Winiarski, D. W. (2018). ANSI/ASHRAE/IES Standard 90.1-2013 Preliminary Determination: Qualitative Analysis. <https://doi.org/10.2172/1131375>

- Houde, S., & Myers, E. (2021). Are consumers attentive to local energy costs? Evidence from the appliance market. *Journal of Public Economics*, 201. <https://doi.org/10.1016/j.jpubeco.2021.104480>
- Kang, S., Seer, T., Dr, P., Ms, R. I., & Pwint, M. (2022). *Energy Measurement & Audit Reference Manual*.
- Khazaii, J. (2016). Advanced decision making for HVAC engineers: Creating energy efficient smart buildings. *Advanced Decision Making for HVAC Engineers: Creating Energy Efficient Smart Buildings*, 1–191. <https://doi.org/10.1007/978-3-319-33328-1/COVER>
- Knight, J., & Jones, P. (n.d.). *Newnes Building Services Pocket Book* - Google Books. 2016. Retrieved March 6, 2025, from https://books.google.lk/books?hl=en&lr=&id=yEPiPO7mQccC&oi=fnd&pg=PR1&dq=CIBSE+Guidelines+technical+recommendations+on+HVAC+airside+efficiency.+CIBSE+Guide+B+provides+best+practices+for+ventilation,+ductwork+design,+and+airflow+regulation+to+minimize+energy+losses&ots=tFquCEvp1d&sig=5EM9tYXTkZIQFI9fQytG_9esN58&redir_esc=y#v=onepage&q&f=false
- Lorenzetti, D. M., & Wray, C. P. (2016). Lawrence Berkeley National Laboratory LBL Publications Title Air-Handling System Modeling in EnergyPlus: A Strategic Plan for Enhancements to Meet Stakeholder Needs Permalink <https://escholarship.org/uc/item/9f8054ks> Publication Date. <https://escholarship.org/uc/item/9f8054ks>
- 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, Risbeck, M. J., Rawlings, J. B., Maravelias, C. T., Wenzel, M. J., Patel, N. R. ;, Risbeck, M. J. ;, Rawlings, J. B. ;, Maravelias, C. T. ;, Wenzel, M. J. ;, Turney, R. D., & Case, " A. (2018a). Purdue e-Pubs A Case Study of Economic Optimization of HVAC Systems based on the Stanford University Campus Airside and Waterside Systems A Case Study of Economic Optimization of HVAC Systems based on the Stanford University Campus Airside and Waterside Systems. <https://engineering.purdue.edu/>
- Patel, Risbeck, M. J., Rawlings, J. B., Maravelias, C. T., Wenzel, M. J., Patel, N. R. ;, Risbeck, M. J. ;, Rawlings, J. B. ;, Maravelias, C. T. ;, Wenzel, M. J. ;, Turney, R. D., & Case, " A. (2018b). Purdue e-Pubs A Case Study of Economic Optimization of HVAC Systems based on the Stanford University Campus Airside and Waterside Systems A Case Study of Economic Optimization of HVAC Systems based on the Stanford University Campus Airside and Waterside Systems. <https://engineering.purdue.edu/>
- Punt, A. E., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., & Haddon, M. (2016). Management strategy evaluation: best practices. *Fish and Fisheries*, 17(2), 303–334. <https://doi.org/10.1111/FAF.12104>
- Rawlings, J. B., Patel, N. R., Risbeck, M. J., Maravelias, C. T., Wenzel, M. J., & Turney, R. D. (2018). Economic MPC and real-time decision making with application to large-scale HVAC energy systems. *Computers & Chemical Engineering*, 114, 89–98. <https://doi.org/10.1016/J.COMPHEMENG.2017.10.038>
- 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. (2020). Energy security and co-benefits of energy efficiency improvement in three Asian countries. In *Renewable and Sustainable Energy Reviews* (Vol. 20, pp. 491–503). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2012.12.004>
- Simpeh, E. K., Pillay, J. P. G., Ndiokubwayo, R., & Nalumu, D. J. (2022). Improving energy efficiency of HVAC systems in buildings: a review of best practices. *International Journal*

- of Building Pathology and Adaptation, 40(2), 165–182. <https://doi.org/10.1108/IJBPA-02-2021-0019/FULL/XML>
- SLSEA. (2020). ENERGY EFFICIENCY BUILDING CODE OF SRI LANKA 2020 Authority.
- Sri Lanka Sustainable Energy Authority. (2008). Code of Practice for Energy Efficient Buildings in Sri Lanka.
- Sri Lanka Sustainable Energy Authority. (2022). Sri Lanka Sustainable Energy Authority.
- Taylor, C., & Narel, T. (2012). FACT SHEET Existing Commercial Buildings Working Group What is Energy Benchmarking? Why Encourage Energy Benchmarking? Energy Benchmarking, Rating, and Disclosure for Local Governments Key Points. www.seeaction.energy.gov
- Urge-Vorsatz, D., Petrichenko, K., Staniec, M., & Eom, J. (2016). Energy use in buildings in a long-term perspective. In Current Opinion in Environmental Sustainability (Vol. 5, Issue 2, pp. 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 Construction Management (Vol. 1).
- Zakaria, Z., Kamarudin, S. K., Ikhmal Salehmin, M. N., Rosyadah Ahmad, N. N., 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. In International Journal of Hydrogen Energy. Elsevier Ltd. <https://doi.org/10.1016/j.ijhydene.2023.05.358>
- Zamaan, R., & Wickramarathna, T. (2025). Enhancing sustainable residential energy practices through the implementation of an energy-efficient labelling system for domestic consumers in Sri Lanka. Solar Compass, 14, 100102. <https://doi.org/10.1016/J.SOLCOM.2024.100102>
- Zaniboni, L. (2021). Tales from the Trenches-Passive House Ventilation Strategies, Common Construction Issues and How to Curb Them - ProQuest. <https://www.proquest.com/openview/3f0e209b6195a0d315cda410c10a3552/1?pq-origsite=gscholar&cbl=5014767>
- Zaniboni, L., & Albatici, R. (2022). Natural and Mechanical Ventilation Concepts for Indoor Comfort and Well-Being with a Sustainable Design Perspective: A Systematic Review. Buildings, 12(11), 1983. <https://doi.org/10.3390/BUILDINGS12111983/S1>
- Zhang, D., Tu, Y., & He, Y. (2024). How a mandate of minimum green building standards influences green building adoption in the private housing sector: Evidence from Singapore during 2005–2019. Cities, 148, 104893. <https://doi.org/10.1016/J.CITIES.2024.104893>

ADDITIVE MANUFACTURING FOR ZERO WASTE APPAREL MANUFACTURING INDUSTRY IN SRI LANKA: A LITERATURE REVIEW

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Abstract. Global pre consumer apparel waste generation in the apparel manufacturing industry drastically increased with the rise of production volume. Therefore, the apparel manufacturing industry focuses on different ways to minimise waste, and the zero waste concept is one of the main concepts regarding waste elimination. However, the achievement of the zero waste concept remains challenging and traditional waste elimination techniques or methods are outgrown to achieve the zero waste concept within the current context. Accordingly, integration of novel technologies shows considerable opportunities to achieve zero waste concepts. AM contributes to zero waste goals by enabling precise material deposition and eliminating cutting waste, which minimises as well as eliminates waste occurring in the apparel manufacturing process. The fourth industrial revolution (I4.0) introduced many technological concepts, and Additive Manufacturing (AM) has been identified as an integral part of this new trend. While developed countries integrate AM technology into their apparel manufacturing industries for waste reduction, Sri Lanka's apparel manufacturing industry remains in its infant stage of adoption, and there is no adoption of AM technology in the apparel manufacturing industry. Thus, this study focuses on investigating the adoption of additive manufacturing concepts for the apparel manufacturing industry in Sri Lanka to achieve zero waste goals. To achieve this research aim, an extensive non-systematic literature review was conducted, synthesising insights from existing scholarly works. The findings indicate that while additive manufacturing presents significant potential for advancing zero-waste apparel production, several barriers must be addressed to facilitate its successful implementation. The findings of this study reveal that there are some potential as well as barriers in adopting additive manufacturing for zero-waste apparel manufacturing in Sri Lanka. High fidelity, realisation of complex structures, property predictability, flexibility of manufacturing, improving sustainability, minimum manufacturing footprint and on-demand manufacturing are some remarkable potentials of additive manufacturing. Accordingly, these attributes position AM as a promising solution for minimizing waste in the apparel industry. In contrast, machine and material cost, raw material availability, insufficient design knowledge and non-recyclable nature are some of the identified potential barriers. In conclusion, further research and strategic interventions are recommended to overcome these challenges and facilitate the sustainable integration of AM technologies in the industry.

Keywords. Additive Manufacturing (AM), Apparel Manufacturing, Pre-Consumer Apparel Waste, Zero Waste

1. Introduction

Globally, the apparel manufacturing industry has a significant production capacity, and consequently, it produces an immense quantity of solid waste (Nadeera et al., 2022). Further, Choudhury (2014) claimed that the apparel industry ranks as one of the top polluting industries in a global context. Islam et al., (2022) stated that the environmental impact of the textile and apparel industries extends across all the stages of the manufacturing process. Population growth, lifestyle advancements, and the progression of the global apparel manufacturing industry over the recent decades have been affected by the considerable increase in apparel waste production (Chand et al. 2023). However, with the emerging trend of sustainable development concepts, most textile industries focus on creating a suitable waste management system as part of the sustainable journey (Nadeera et al., 2022).

Hence, there is a growing interest in employing innovative concepts, such as circular economy and zero waste to address the waste issue (Zaman, 2022). According to Nizar et al. (2018), zero waste aims to minimise waste, reduce landfills, and protect the environment. Further, Kerdlap et al. (2019), illustrate that both future production growth and waste reduction can be addressed with a zero-waste manufacturing (ZWM) strategy that takes a comprehensive approach to life cycle management. Nevertheless, Dilberoglu et al. (2017) claimed that Industry 4.0 emphasises the significance of the integration of advanced information technology and smart manufacturing systems, and additive manufacturing (AM) has been identified as an integral part of this new trend. Further, Hegab et al. (2023) illustrate that AM technology reduces material waste, CO₂ emissions, and promotes the circular economy, it is recognised as environmentally sustainable.

When heeding the Sri Lankan textile and apparel industry, it takes pride in being a global leader in sustainable clothing manufacture in the region (Sulochani et al., 2021). According to Park and Evans (2017), the apparel sector is Sri Lanka's largest manufacturing sector, accounting for 61% of exports and 44% of GDP in 2015. Gunasekara et al. (2019) stated that waste management has emerged as a significant problem in modern society that requires investigation, particularly in Sri Lanka's apparel manufacturing industry. As a result, introducing proper waste management procedures is becoming increasingly crucial.

Even though, there is a significant gap in Sri Lanka's manufacturing sector in implementing Industry 4.0 for such environmental implications (A. M. L. De Alwis et al., 2023). Furthermore, Jayatilake and Withanarachchi (2016) highlighted that Sri Lanka's leading apparel manufacturers are yet to converge on Industry 4.0 concepts such as additive manufacturing to tackle the waste management challenges and to move towards zero waste. Thus, it will be beneficial to focus on achieving zero waste goals of the apparel industry through additive manufacturing technology. Accordingly, this research paper aims to review the adoptability of the additive manufacturing concept to achieve zero waste goals of the apparel manufacturing industry in Sri Lanka as a way forward for future research.

In order to achieve the research aim, two (02) research objectives were formulated;

- To explore on apparel waste generation and management, the zero-waste concept, and additive manufacturing
- To identify the potentials & barriers and future trends of additive manufacturing for achieving the zero-waste concept in the apparel manufacturing industry.

Accordingly, the next chapter describes the apparel waste generation and management, the zero-waste concept in the apparel manufacturing industry and the concept of AM. The third chapter will discuss the research methodology that has been adopted for this study, and the fourth chapter will discuss the findings on the application of AM, barriers, and potentials for adopting AM in the apparel industry.

2. Literature review

This section presents the key literature findings related to three major areas; (i) Apparel waste generation and management, (ii) Zero waste concept in the apparel manufacturing industry, and (iii) The concept of additive manufacturing.

2.1. APPAREL WASTE GENERATION AND MANAGEMENT

The generation of waste in the garment industry is one of the inevitable elements of garment manufacturing (Rathinamoorthy, 2018). Apparel waste is defined in different terms, such as textile or clothing as well as fabric or garment waste by scholars. Textile waste refers to materials that cannot be used for their intended purpose, originating from the apparel and textile industries (Redress, 2017). According to Noman et al. (2013), the term "textile waste" refers to a variety of materials, such as clippings and cuttings, polyester waste, cotton, clippings, 100% cotton yarn waste, silk fibre waste, etc. Accordingly, in this research apparel waste is defined as "materials that cannot be used for their intended purpose, which are originated from the manufacturing process of apparel industry".

The two categories of apparel waste are pre-consumer waste and post-consumer waste, depending on where the waste originated. (Tomovska et al., 2017). Vadicherla and Saravanan (2014) mentioned that pre-consumer waste are formed during the production process of upstream items, whereas post-consumer apparel wastes are generated by customers and frequently consist of apparel acceptable for landfill or disposal. Redress (2017) identified textile swatch waste, cut and sew textile waste, end-of-roll textile waste, sampling yardage waste, damaged textile waste, clothing sample waste, and unsold clothing waste as pre-consumer waste. In contrast, post-consumer waste includes secondhand clothing waste and secondhand textile waste. Alternatively, according to Shakya & Swami (2016), apparel waste generation in the production stage is pre-consumer apparel waste and they are related to pattern making, marker planning, and cutting as well as the post-consumer apparel waste generated in the consumption stage.

Alwis and De Sliva (2022), identified the apparel manufacturing process under fourteen stages; order receiving, fabric approval, design/ pattern making, garment sampling and sample approval, fabric layering, fabric cutting, sorting and bunding, issue to stitching floor, garment stitching using machines, quality checking, finishing and complete, folding and tagging, packing and boxing and ready to deliver or shipment. Further, according to Amin (2020), a considerable quantity of waste is produced throughout the process of the product development process, especially in the fabric loss and cutting departments of the apparel industries. As Redress (2017) mentioned, pre consumer apparel waste generated sources and types of waste such as the production process – textile swatches, garment manufacturing process - cut and sew waste, and end of rolls waste, textile sample process – sampling yardage, design process – clothing samples, finishing – damaged textile, and unsold clothing waste. When heeding the apparel waste management strategies, present waste management procedures are heavily impacted by the "waste hierarchy," which suggests a ranking of options in order of preference, with "prevention" being the most favoured at the top and "disposal" being the least liked at the bottom (Gharfalkar et al., 2015). Ajila (2019) claimed that apparel and textile wastes can also be managed using the 4R method which includes reduce, replace, reuse, and recycle. Further, the Concept of Circular

Economy has been applied to pre-consumer apparel waste management using lean manufacturing, green supply chain management, extended producer responsibility, and the 3R concept (Jayakodi & Thayaparan, 2021). However, nowadays “zero waste” strategy is often utilised to eliminate textile waste in the apparel manufacturing process (Italiano et al., 2022).

2.2. ZERO WASTE CONCEPT IN THE APPAREL MANUFACTURING INDUSTRY

Hamid et al. (2020) claimed that zero waste management refers to a holistic approach to waste management that recognises waste as a resource produced during the formative stage of the resource consumption process. Further, according to the Pietzsch et al. (2017), zero-waste approach focuses specifically on reducing the amount of waste created, has emerged because of the development of the circular economy concept. The goal of zero-waste fashion designing is to completely remove fabric waste from the manufacturing of clothing. (Shakya & Swami, 2016).

Gupta and Saini (2020) stated that there are several strategies for achieving zero waste concept as jigsaw cutting, subtraction cutting, geo-cut, cutting and draping, re using scarps of clothes and yarns, knitting, pleating, draping scraps of fabric, replacing conventional technology with no/low waste technology like additive manufacturing. AM is one type of digital manufacturing technology that has a good influence on the environment and reduces manufacturing errors (Ott et al., 2019). Developing and implementing new and more effective manufacturing techniques, including additive manufacturing, reduces raw material use and fosters innovation for sustainability (Todeschini et al., 2017).

3. Methodology

The research approach for any research strongly depends on the nature of that research (Baharein & Noor, 2008; Morgan & Smircich, 1980). However, this research works out on the research question of “how to adopt the additive manufacturing concept to achieve zero-waste goals of the apparel manufacturing industry in Sri Lanka” which represents the findings through a theoretical framework. Since this research focuses on investigating the areas mentioned above by answering the “How” question, the qualitative research approach is more favoured for this research. In addition to that, Celo et al., (2008) stated that quantitative research entails converting phenomena into numerical values for analysis while qualitative research deals with non-numerical data forms such as texts, pictures, videos, and so on. However, since this research involves only qualitative data rather than numerical data, the qualitative approach is the most appropriate for this research. Accordingly, a non-systematic review of the literature was used as the methodological basis to complete the present study. According to the enferm (2007) , the two types of literature reviews are systematic reviews and non-systematic reviews. Further, it mentioned that non-systematic reviews are commonly referred to as narrative reviews in academic literature. Non-systematic reviews aim to identify, synthesise and summarise the existing published literature while exploring the potential research gaps for future research (Ferrari, 2015). Further enferm (2007), claimed that non-systematic reviews state of science on a particular research area from a theoretical and conceptual perspective and play a vital role in academic background.

Accordingly, a non-systematic literature review was conducted to identify the key literature publications in the intersection of apparel waste generation and management, additive manufacturing and zero waste concepts.. The articles were retrieved through the Google Scholar search engine and included suitable original articles and reviews written in English. The Search string was developed using the following keywords: additive manufacturing, zero waste in apparel industry, sustainable apparel manufacturing, circular apparel production, and sustainable textile production. Consequently, the literature synthesis was developed analysing the selected publications.

4. Results

This section presents the key literature findings related to three major areas; (i) The concept of additive manufacturing (ii) Applications of additive manufacturing in the apparel industry, (iii) Potentials and barriers to adopting additive manufacturing concept in the apparel manufacturing industry.

4.1 THE CONCEPT OF ADDITIVE MANUFACTURING

According to Dehghani and Goyal (2022), additive manufacturing involves creating a virtual design of an object using a 3D modeling application or a 3D scanner. The 3D printer then reads each slice, creating a three-dimensional object, which is referred to as polymer to a garment. Process of 3D printing shown in figure 1.

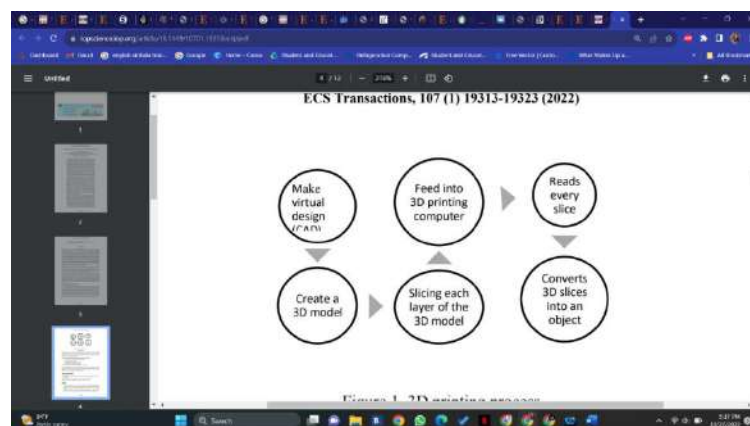


Figure 1: Process of 3D Printing

3D CAD design software is where the process of creating a 3D printed sample begins (Parsch et al., 2015). In order to begin the 3D printing process, users must first design things using a 3D modelling program or select from an online database, then upload them to slicing software. After all settings are finished connect the printer to the computer and start printing (Trust & Maloy, 2017). According to Ligon et al. (2017), additive manufacturing processes are utilised for different materials, including material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerisation, powder bed fusion, and directed energy deposition. Ngo et al. (2018b) stated that AM used Fused Deposition Modelling (FDM), powder additive manufacturing by Selective Laser Sintering (SLS), Selective Laser Melting (SLM) or Liquid Bonding in 3D printing (3DP) as well as Inkjet Printing, Contouring, Stereolithography (SLA), Direct Energy Deposition (DED) and Manufacturing of Laminated objects (LOM). Alafaghani et al. (2017) stated that AM process of fused

deposition modelling (FDM) involves heating and extruding filaments through a tiny nozzle to create objects. The nozzle uses computer-controlled pathways to extrude the material, forming layers on top of one another to form the part. According to Shahzad et al. (2013), SLS is an additive manufacturing technique that produces parts layer by layer using layers of powder deposited by a roller or scraper and heated by a laser beam. The powder deposition and laser scanning sequence is repeated until the part is finished. According to Miller et al. (2023), in SLA, layers of three-dimensional parts are selectively cured using UV photopolymer resin. This process produces parts that require minimal applied stress, which makes it possible to create detailed features and complex geometries. Saboori et al. (2019) claimed that among AM processes, DED enables the restoration of damaged parts to their original shape as well as the replacement of materials lost during service. According to the Gupta et al. (2020), one type of AM process that uses sheet lamination to create 3D solid objects is called LOM.

4.2 APPLICATIONS OF ADDITIVE MANUFACTURING IN THE APPAREL INDUSTRY

AM is an innovative emerging technology that is used for several purposes across multiple disciplines due to sustainability perspectives (Niaki et al., 2019). Further, (Khajavi, 2021; Keefe et al., 2022) also emphasised the ability to offer sustainable innovation and customisation in the apparel industry. According to the Harsha Vardhan et al. (2014), industries which are benefiting from additive manufacturing technology are, aerospace, automotive, machine tool production, healthcare and medical, dentistry and dental technology, architecture and construction, food, retail, and apparel. Additive manufacturing has numerous benefits for future space flight (Shapiro et al., 2016). Vasco (2021) mentioned that the freedom capacity of AM enables the design and direct manufacturing of automotive components optimised for vehicle performance, along with the creation of assembly tools required to increase productivity. Furthermore, Leal et al. (2017) highlighted that the AM approach allows stamping inserts to be produced using high-performance alloy steels similar to conventional tools without losing the mechanical properties of the tool. The flexible manufacturing methods offered by AM are revolutionising the manufacturing of medical models, passive implants, biomanufacturing, orthoses prostheses, medical equipment, and instruments in the healthcare sector (Rezvani Ghomi et al., 2021). Moreover, according to Javaid and Haleem (2019), additive manufacturing is an innovative process that leads to the customised fabrication of dental implants and other dental instruments with the help of computer-aided design (CAD) data. Additive manufacturing (AM) is a cutting-edge technology that provides new freedom in architecture with endless flexibility in material deposition and design, manufacture and performance of unique forms, construction systems and materials (Paoletti, 2017). Lipton et al. (2015) stated that main motivations for 3D printing food are customisation, on-demand manufacturing, and geometric complexity. Traditional foods like pizza using 3D printers could demonstrate the maturity of food printing.

Valtas and Sun (2016) highlighted that reduces the number of stages that must be completed during production. By creating a design, 3D printing allows for the integration of fabric assembly, cutting, sewing, and laying all into one phase and Because 3D printing eliminates the possibility of human error in traditional garment manufacturing, the product is of greater quality than when it was made. In the design process, AM offer greater capabilities for designing and customising apparel

products (Yap and Yeong, 2014). Further, AM technologies such as 3D printing allows personal customised apparel products by integrating 3D scanning and CAD software in design process (Spahiu et al., 2020). When heeding the fabric layering process in apparel manufacturing, AM facilitate the layer-by-layer manufacturing process which eliminates the necessity for different cutting tools and machineries (Lim et al., 2016). Furthermore, Dilek et al. (2021) stated that in the application of AM technology to the apparel manufacturing process, stages such as spinning, dying, cutting, and sewing of the manufacturing process are not involved. Additionally, (Hohn and Durach, 2021) claimed that the implementation of AM helps to reinforce existing supply chain governance structures dominated by powerful retailers, potentially exacerbating social sustainability issues in production. According to the literature, it can summaries the application of AM technology to apparel manufacturing process as shown in table 1.

Table 1: Application of AM technology to the apparel manufacturing process

Stage of apparel manufacturing process	Additive manufacturing process	Application of AM to the apparel manufacturing process	References
Design / pattern making	1. Make virtual design (CAD) 2. Create a 3D model	3D CAD design software creates a 3D printed sample	(Valtas & Sun, 2016), (Verlan & Irovan, 2018), (Partsch et al., 2015), (Yap and Yeong, 2014)
Garment sampling and sample approval			
Fabric layering	3. Slicing each layer of the model	Integration of fabric assembly, cutting, sewing, and laying all into one phase	(A. M. L. D. Alwis & De Silva, 2022)(Lim et al., 2016)
Fabric cutting	4. Reads every slice		
Sorting and bundling	5. Feed into the 3D printing computer		
Issue to stitching floor	6. Converts 3D slices into object		
Garment stitching using machineries			

4.3 POTENTIALS AND BARRIERS TO ADOPTING ADDITIVE MANUFACTURING CONCEPT IN THE APPAREL MANUFACTURING INDUSTRY

Expansion of manufacturing methods and options due to additive manufacturing technologies offers significant benefits such as reductions in product lead time, shorter time to market for new designs and faster fulfilment of customer demands (Attaran, 2017). Notable benefits of additive manufacturing include less material waste, ease of manufacture with simplified manufacturing process, fewer requirements for human intervention and post-processing, and energy efficiency (Mansi et al., 2023). According to the Quan et al. (2015), potentials of additive manufacturing in apparel manufacturing industry are high fidelity, realisation of complex structures, and property predictability. Khajavi (2021) emphasised that

AM offers a highly flexible way to manufacture clothing parts and products, thereby improving sustainability and extending life cycles. This technology enables the production of complex geometries in small batches, allowing for efficient production, repair, and overhauls. Furthermore, reduction of need of the excessive transportation led to a lower environmental impact. Moreover, Keefe et al. (2022) further outlined potentials of AM over conventional apparel manufacturing methods, including ability to produce complex geometries, minimise waste, reduce transportation and CO2 footprints, wide range of materials, high-value replacement parts, small manufacturing footprint, green manufacturing, and on-demand manufacturing. However, barriers can be identified as limited raw materials, limited printing accuracy, requirement of powerful design tool (Seepersad, 2014). Khajavi (2021), further stated time-dependent barriers to using AM technology in the apparel industry include machine and material costs, raw material availability, automation, and brand support. Time-independent barriers involve insufficient design knowledge, lack of retail store experience, and insufficient enthusiasm for being involved in the production process. Additionally, Nath and Nilufar (2020), highlighted critical barriers of AM as difficulties in the mass manufacturing due to limited materials and its non-recyclable nature of certain AM materials, unsatisfactory level of surface quality in the printed product of some AM processes, and relatively low strength of printed parts. Although, as per the Withanaarachchi et al. (2016) main barriers in Sri Lanka can be identified as labour shortage, machine cost, and lack of enthusiasm within apparel manufacturers. Furthermore, Samarakkody (2023), claimed that barriers in implementing technologies like additive manufacturing in Industry 4.0 as financial barriers, insufficient knowledge, high maintenance cost etc.

5. The theoretical framework for adopting additive manufacturing in the apparel manufacturing industry to achieve zero waste

Based on the insights reviewed on adopting additive manufacturing in the apparel industry to achieve zero waste, a framework was developed providing important insights for future researchers in the field. The framework clearly illustrates the apparel manufacturing process, application of additive manufacturing, potentials & barriers and benefits of adopting additive manufacturing for the apparel industry. Further, the framework clearly illustrates the relationship among the different stages in the apparel manufacturing process and applications of additive manufacturing as well.

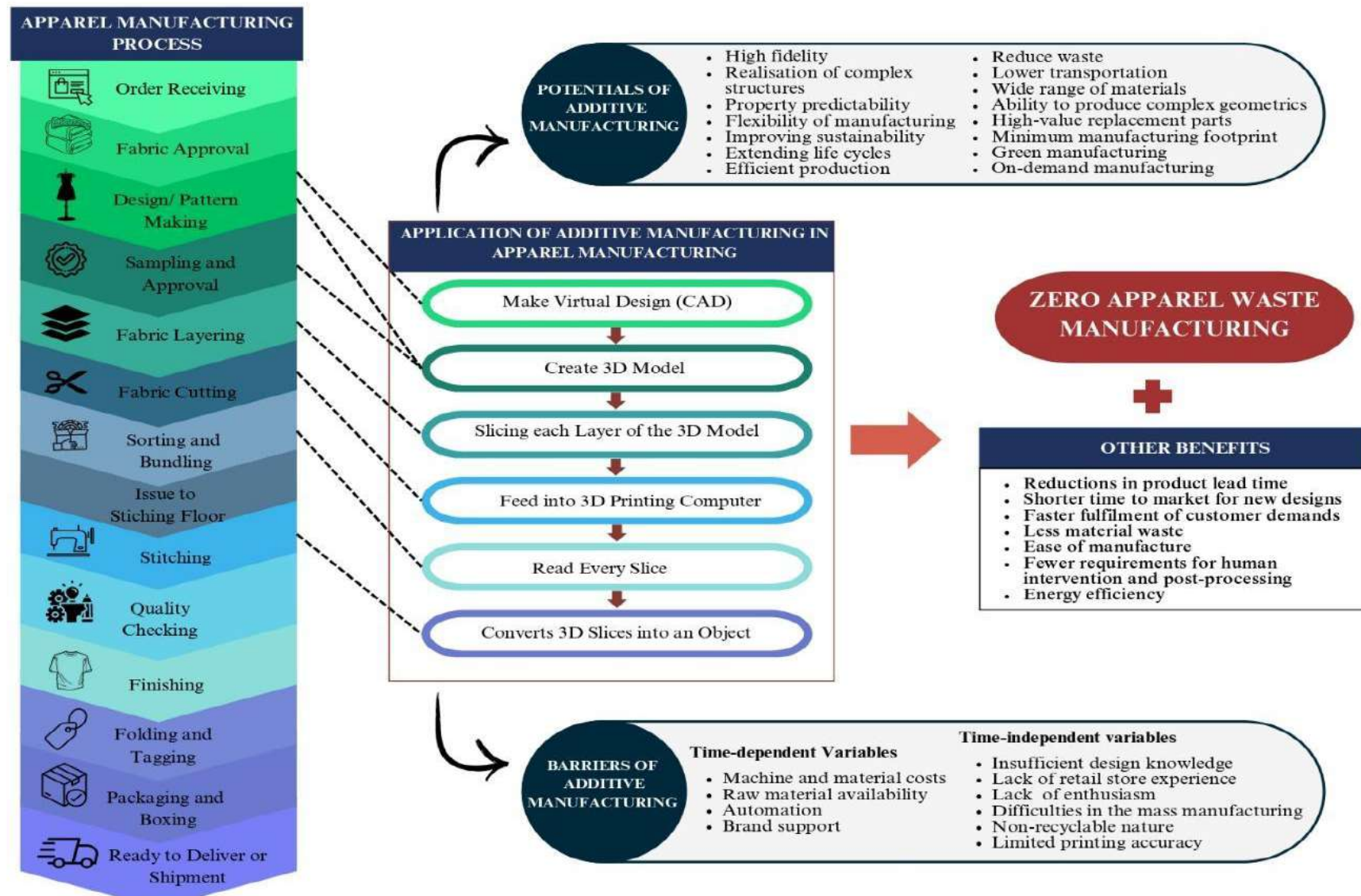


Figure 2: Theoretical framework for adopting additive manufacturing in the apparel manufacturing industry to achieve zero waste

6. Discussion

When heeding on Sri Lanka context, there is no any acceptable waste management system in Sri Lankan apparel manufacturing industry. Typically, only 25% of apparel waste is recycled and reused; the remaining waste is incinerated or landfilled (Jayakodi & Thayaparan, 2021). Nonetheless, waste has grown in significant issue in the current setting of Sri Lanka due to urbanisation and high human density. Edirisinghe et al. (2022) highlighted that fabric waste accounts for the majority of waste generated through Sri Lanka's apparel industry. Park and Evans (2017) mentioned that Sri Lanka generates at least 44,100 tons of textile waste annually, but lack of proper recycling facilities. As of currently, Sri Lanka lacks recycling facilities, and there are no established waste management initiatives. Basically, waste is moved out of cities and disposed in open spaces. Therefore, it is more beneficial for moving novel technologies such as additive manufacturing to overcome the waste issue and achieve zero waste goals in apparel industry.

As stated by different research scholars, Additive manufacturing is expected to become one of the most important and innovative industrial processes in the coming years (Jiménez et al., 2019). According to the Dilek et al. (2021), number of synthetic materials utilized in 3D printers is growing daily. Fashion designers are experimenting with 3D printed clothes, shoes, and accessories to introduce 3D printing to the apparel industry (Kholiya, 2016). The use of 3D printing for apparel manufacturing not only brings new advantages but also changes the entire production and design development of the product as well as the relationship with the customer (Marques, 2019). Verlan and Irovan (2018) claimed that since the model is created in a software that specifies the precise dimensions and form of the landmark, it is evident that use of AM to create apparel in an innovative way and helps to reduce the waste. An avatar can be built using the data from the body scan, enabling online testing and style, fit, and other verifications. This ensures that apparel is made to actual measurement (Grimmelsmann et al., 2016). Waste minimisation is one benefit of using 3D printing in manufacturing. Once printing is finished, there is nothing to trim away from the object because it is complete in it's as a whole (Sun & Zhao, 2017). Designers and manufacturers have the option to print directly for customers, which minimises waste. Making a garment more functional through 3D printing could potentially prolong its lifespan from a sustainability standpoint (Pasricha & Greeninger, 2018). In the upcoming years, it is anticipated that natural materials will be developed. Wong and Hernandez (2012) revealed that continuous and incremental growth experienced since the early days and the successful results to date allow for optimism that additive manufacturing will have a significant place in the future of manufacturing. According to Alwis and De Silva (2022), the integration of Industry 4.0 and sustainable manufacturing in the context of Sri Lanka is not well-established. Although additive manufacturing is currently in discussion level. Withanaarachchi et al. (2016) mentioned that apparel manufacturing industry as a whole needs to reconsider the adoption of Industry 4.0 including AM as a new business model and the study also recommends that further research be done on the viability of installing smart factories and the implementation of Industry 4.0 in the apparel sector.

7. Conclusion and Way Forward

The adoption of additive manufacturing offers a transformative opportunity for achieving zero-waste goals in Sri Lanka's apparel manufacturing industry. The adoption of additive manufacturing helps to achieve sustainability goals including waste management in apparel industry. Accordingly, this study demonstrates the significant potentials of AM, including high fidelity, the realization of complex structures, flexibility in manufacturing, and minimal material waste. These attributes align well with the industry's sustainability ambitions, offering an innovative approach to waste reduction and resource optimization. However, key barriers such as high machine and material costs, limited raw material availability, insufficient design

expertise, and the non-recyclable nature of certain AM materials must be addressed to facilitate effective implementation.

Despite these challenges, the integration of AM into Sri Lanka's apparel sector can significantly enhance waste management efforts and contribute to a circular economy. Strategic interventions, including policy support, investment in research and development, and capacity building within the industry, are essential for overcoming existing barriers. Future research should explore sustainable material innovations and scalable AM applications tailored to the apparel sector's unique needs. By leveraging AM technologies, Sri Lanka can position itself as a leader in sustainable apparel manufacturing, paving the way for a more resource-efficient and environmentally responsible industry.

8. References

- Ajila, K. O. (2019). Analysis of Post-Consumer Solid Textile Waste Management among Households in Oyo State of Nigeria. *Journal of Environmental Protection*, 10(11), 1419–1435. <https://doi.org/10.4236/jep.2019.1011084>
- Alafaghani, A., Qattawi, A., & Ablat, M. A. (2017). Design Consideration for Additive Manufacturing: Fused Deposition Modelling. *Open Journal of Applied Sciences*, 07(06), 291–318. <https://doi.org/10.4236/ojapps.2017.76024>
- Alwis, A. M. L. D., & De Silva, N. (2022). INDUSTRY 4.0 BASED SUSTAINABLE MANUFACTURING MODEL FOR APPAREL INDUSTRY IN SRI LANKA. *World Construction Symposium*, 571–584. <https://doi.org/10.31705/WCS.2022.46>
- Amin, R. (2020). Fabric waste minimization in knitwear garment sector of Bangladesh (Vol. 8). www.ijcrt.org
- Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, 60(5), 677–688. <https://doi.org/10.1016/j.bushor.2017.05.011>
- Baharein, K., & Noor, M. (2008). Case Study: A Strategic Research Methodology. *American Journal of Applied Sciences*, 5(11), 1602–1604.
- Celo, O., Braakmann, D., & Benetka, G. (2008). Quantitative and qualitative research: Beyond the debate. In *Integrative Psychological and Behavioral Science* (Vol. 42, Issue 3, pp. 266–290). Springer New York. <https://doi.org/10.1007/s12124-008-9078-3>
- Chand, S., Chand, S., & Raula, B. (2023). Textile and apparel industries waste and its sustainable management approaches. *Journal of Material Cycles and Waste Management*. <https://doi.org/10.1007/s10163-023-01761-1>
- Choudhury, A. K. R. (2014). Environmental Impacts of the Textile Industry and Its Assessment Through Life Cycle Assessment (pp. 1–39). https://doi.org/10.1007/978-981-287-110-7_1
- Dehghani, M., & Goyal, P. (2022). Design and Development of Textile Fabrics Using 3D Printing Technology. *ECS Transactions*, 107(1), 19313–19323. <https://doi.org/10.1149/10701.19313ecst>
- Dilberoglu, U. M., Gharehpapagh, B., Yaman, U., & Dolen, M. (2017). The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manufacturing*, 11, 545–554. <https://doi.org/10.1016/j.promfg.2017.07.148>
- Dilek, E., Yildirim, M., & Uzun, M. (2021). Additive manufacturing (3D printing) in technical fashion industry applications. *Tekstilna Industrija*, 69(2), 4–15. <https://doi.org/10.5937/tekstind2102004d>
- Edirisinghe, L. G. L. M., Wijayasundara, M., & De Alwis, A. A. P. (2022). Waste Generation and Characteristics in Sri Lankan Textile and Apparel Sector: Case Study of the Biyagama Industrial Export Processing Zone, Sri Lanka. *Nature Environment and Pollution Technology*, 21(2), 697–702. <https://doi.org/10.46488/NEPT.2022.V21I02.030>
- enferm, A. paul. (2007). Systematic literature review X narrative review. 2(20).
- Ferrari, R. (2015). Writing narrative style literature reviews. *Medical Writing*, 24(4), 230–235. <https://doi.org/10.1179/2047480615z.000000000329>

- Gharfalkar, M., Court, R., Campbell, C., Ali, Z., & Hillier, G. (2015). Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste Management*, 39, 305–313. <https://doi.org/10.1016/j.wasman.2015.02.007>
- Grimmelsmann, N., Martens, Y., Schäl, P., Meissner, H., & Ehrmann, A. (2016). Mechanical and Electrical Contacting of Electronic Components on Textiles by 3D Printing. *Procedia Technology*, 26, 66–71. <https://doi.org/https://doi.org/10.1016/j.protcy.2016.08.010>
- Gunasekara, A. D., Neranja, P. L. N., Karunaratne, H., Ravihansi, B. K. P., Buddhika, A., Wijekoon, W., Weerathunga, N. D., Chanika, P. G. S., Jayasinghe, W. T., & Sibera, A. (2019). EVOLUTION OF WASTE MANAGEMENT PRACTICES: A CASE STUDY OF A LEADING APPAREL COMPANY IN SRI LANKA.
- Gupta, L., & Saini, H. K. (2020). Achieving Sustainability through Zero Waste Fashion-A Review. *Current World Environment*, 154–162. <https://doi.org/10.12944/cwe.15.2.02>
- Gupta, R., Dalakoti, M., & Narasimhulu, A. (2020). A Critical Review of Process Parameters in Laminated Object Manufacturing Process. In I. Singh, P. K. Bajpai, & K. Panwar (Eds.), *Advances in Materials Engineering and Manufacturing Processes* (pp. 31–39). Springer Singapore.
- Hamid, S., Skinder, B. M., & Bhat, M. A. (2020). Zero Waste: A Sustainable Approach for Waste Management (pp. 134–155). <https://doi.org/10.4018/978-1-7998-0031-6.ch008>
- Harsha Vardhan, G., Charan, G. H., Reddy, P. V. S., & Sampath Kumar, K. (2014). International Journal on Recent and Innovation Trends in Computing and Communication 3D Printing: The Dawn of a New Era in Manufacturing. *International Journal on Recent and Innovation Trends in Computing and Communication*, 2(8), 2373–2376. <http://www.ijritcc.org>
- Hegab, H., Khanna, N., Monib, N., & Salem, A. (2023). Design for sustainable additive manufacturing: A review. *Sustainable Materials and Technologies*, 35, e00576. <https://doi.org/10.1016/j.susmat.2023.e00576>
- Hohn, M.M. and Durach, C.F. (2021) 'Additive manufacturing in the apparel supply chain — impact on supply chain governance and social sustainability', *International Journal of Operations & Production Management*, 41(7), pp. 1035–1059. Available at: <https://doi.org/10.1108/IJOPM-09-2020-0654>.
- Islam, Md. T., Jahan, R., Jahan, M., Howlader, Md. S., Islam, R., Islam, Md. M., Hossen, Md. S., Kumar, A., & Robin, A. H. (2022). Sustainable Textile Industry: An Overview. *Non-Metallic Material Science*, 4(2). <https://doi.org/10.30564/nmms.v4i2.4707>
- Italiano, I. C., Kauvauti, L. S., & Marcicano, J. P. P. (2022). Zero waste in the apparel industry: limitations and alternatives. *Sustentabilidade Em Debate*, 13(2), 190–203. <https://doi.org/10.18472/SustDeb.v13n2.2022.40716>
- Javaid, M., & Haleem, A. (2019). Current status and applications of additive manufacturing in dentistry: A literature-based review. In *Journal of Oral Biology and Craniofacial Research* (Vol. 9, Issue 3, pp. 179–185). Elsevier B.V. <https://doi.org/10.1016/j.jobcr.2019.04.004>
- Jayakodi, K. H. S. K., & Thayaparan, M. (2021). APPLICATION OF CIRCULAR ECONOMY CONCEPT TO PRE-CONSUMER APPAREL WASTE MANAGEMENT IN SRI LANKA. *Proceeding of the World Conference on Waste Management*, 19–33. <https://doi.org/10.17501/26510251.2021.1203>
- Jayatilake, H., & Withanaarachchi, A. (2016). Industry 4.0 in the Apparel-Manufacturing Sector: Opportunities for Sri Lanka.
- Jiménez, M., Romero, L., Domínguez, I. A., Espinosa, M. D. M., & Domínguez, M. (2019). Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects. *Complexity*, 2019. <https://doi.org/10.1155/2019/9656938>
- Keefe, E. M., Thomas, J. A., Buller, G. A., & Banks, C. E. (2022). Textile additive manufacturing: An overview. In *Cogent Engineering* (Vol. 9, Issue 1). Cogent OA. <https://doi.org/10.1080/23311916.2022.2048439>
- Kerdlap, P., Low, J. S. C., & Ramakrishna, S. (2019). Zero waste manufacturing: A framework and review of technology, research, and implementation barriers for enabling a circular economy transition in Singapore. *Resources, Conservation and Recycling*, 151, 104438. <https://doi.org/10.1016/j.resconrec.2019.104438>
- Khajavi, S. H. (2021). Additive manufacturing in the clothing industry: Towards sustainable new business models. *Applied Sciences (Switzerland)*, 11(19). <https://doi.org/10.3390/app11198994>

- Kholiya, R. (2016). Ruchi Kholiya et al. In *International Journal of Recent Research Aspects* (Vol. 3).
- Leal, R., Barreiros, F. M., Alves, L., Romeiro, F., Vasco, J. C., Santos, M., & Marto, C. (2017). Additive manufacturing tooling for the automotive industry. *The International Journal of Advanced Manufacturing Technology*, 92(5), 1671–1676. <https://doi.org/10.1007/s00170-017-0239-8>
- Ligon, S. C., Liska, R., Stampfl, J., Gurr, M., & Mülhaupt, R. (2017). Polymers for 3D Printing and Customized Additive Manufacturing. *Chemical Reviews*, 117(15), 10212–10290. <https://doi.org/10.1021/acs.chemrev.7b00074>
- Lim, C.W.J. et al. (2016) 'An Overview of 3-D Printing in Manufacturing, Aerospace, and Automotive Industries', *IEEE Potentials*, 35(4), pp. 18–22. Available at: <https://doi.org/10.1109/MPOT.2016.2540098>.
- Lipton, J. I., Cutler, M., Nigl, F., Cohen, D., & Lipson, H. (2015). Additive manufacturing for the food industry. In *Trends in Food Science and Technology* (Vol. 43, Issue 1, pp. 114–123). Elsevier Ltd. <https://doi.org/10.1016/j.tifs.2015.02.004>
- Mansi, Kumar, H., Singholi, A. K. S., & Moona, G. (2023). Additive Manufacturing: A Brief Introduction. In D. K. Aswal, S. Yadav, T. Takatsuji, P. Rachakonda, & H. Kumar (Eds.), *Handbook of Metrology and Applications* (pp. 1141–1163). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-2074-7_59
- Marques, S. C. G. (2019). UNIVERSIDADE DA BEIRA INTERIOR Engenharia The application of new technologies in fashion and implementation of additive manufacturing in the apparel industry Design de Moda.
- Miller, Z., Stidham, B., Fairbanks, T., & Maldonado, C. (2023). The Use of Stereolithography (SLA) Additive Manufacturing in Space-Based Instrumentation. 2023 IEEE Aerospace Conference, 1–10. <https://doi.org/10.1109/AERO55745.2023.10115988>
- Morgan, G., & Smircich, L. (1980). The Case for Qualitative Research. *Academy of Management Review*, 5(4), 491–500. <https://doi.org/10.5465/amr.1980.4288947>
- Nadeera, W. A. A. P., Karunarathna, D. D. A., Madushan, D. M. H., Ferdinando, K. P. M. D. D. L., Perera, G. D. V., & Abeyunawardhana, W. L. K. (2022). Solid Waste Management in Textile Industry. In *J. Res. Technol. Eng* (Vol. 3, Issue 1).
- Nath, S. D., & Nilufar, S. (2020). An overview of additive manufacturing of polymers and associated composites. In *Polymers* (Vol. 12, Issue 11, pp. 1–33). MDPI AG. <https://doi.org/10.3390/polym12112719>
- Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. In *Composites Part B: Engineering* (Vol. 143, pp. 172–196). Elsevier Ltd. <https://doi.org/10.1016/j.compositesb.2018.02.012>
- Niaki, M. K., Torabi, S. A., & Nonino, F. (2019). Why manufacturers adopt additive manufacturing technologies: The role of sustainability. *Journal of Cleaner Production*, 222, 381–392. <https://doi.org/10.1016/j.jclepro.2019.03.019>
- Nizar, M., Munir, E., & Munawar, E. (2018). Implementation of zero waste concept in waste management of Banda Aceh City. *Journal of Physics: Conference Series*, 1116(5), 052045.
- Noman, M., Batool, S. A., & Chaudhary, M. N. (2013). Economic and employment potential in textile waste management of Faisalabad. *Waste Management and Research*, 31(5), 485–493. <https://doi.org/10.1177/0734242X12474711>
- Ott, K., Pascher, H., & Sihn, W. (2019). Improving sustainability and cost efficiency for spare part allocation strategies by utilisation of additive manufacturing technologies. *Procedia Manufacturing*, 33, 123–130. <https://doi.org/https://doi.org/10.1016/j.promfg.2019.05.001>
- Paoletti, I. (2017). Mass Customization with Additive Manufacturing: New Perspectives for Multi Performative Building Components in Architecture. *Procedia Engineering*, 180, 1150–1159. <https://doi.org/10.1016/j.proeng.2017.04.275>
- Park, C., & Evans, S. (2017). *TransTextile Project Report: High Value Innovation for Industrial Textile Waste in Sri Lanka*. Cambridge.

- Partsch, L., Vassiliadis, S., Papageorgas, P., Partsch, L. N., Vassiliadis, S., & Papageorgas, P. (2015). 3D PRINTED TEXTILE FABRICS STRUCTURES. 5th International Istanbul Textile Congress 2015: Innovative Technologies "Inspire to Innovate." <https://www.researchgate.net/publication/283288900>
- Pasricha, A., & Greeninger, R. (2018). Exploration of 3D printing to create zero-waste sustainable fashion notions and jewelry. *Fashion and Textiles*, 5(1). <https://doi.org/10.1186/s40691-018-0152-2>
- Pietzsch, N., Ribeiro, J. L. D., & de Medeiros, J. F. (2017). Benefits, challenges and critical factors of success for Zero Waste: A systematic literature review. In *Waste Management* (Vol. 67, pp. 324–353). Elsevier Ltd. <https://doi.org/10.1016/j.wasman.2017.05.004>
- Quan, Z., Wu, A., Keefe, M., Qin, X., Yu, J., Suhr, J., Byun, J. H., Kim, B. S., & Chou, T. W. (2015). Additive manufacturing of multi-directional preforms for composites: Opportunities and challenges. In *Materials Today* (Vol. 18, Issue 9, pp. 503–512). Elsevier B.V. <https://doi.org/10.1016/j.mattod.2015.05.001>
- Rathinamoorthy, R. (2018). Sustainable Apparel Production from Recycled Fabric Waste (pp. 19–52). https://doi.org/10.1007/978-981-10-8515-4_2
- Redress. (2017). SOURCING TEXTILE WASTE ECOCHIC DESIGN AWARD. www.ecochicdesignaward.com
- Rezvani Ghomi, E., Khosravi, F., Neisiany, R. E., Singh, S., & Ramakrishna, S. (2021). Future of additive manufacturing in healthcare. In *Current Opinion in Biomedical Engineering* (Vol. 17). Elsevier B.V. <https://doi.org/10.1016/j.cobme.2020.100255>
- Saboori, A., Aversa, A., Marchese, G., Biamino, S., Lombardi, M., & Fino, P. (2019). Application of directed energy deposition-based additive manufacturing in repair. In *Applied Sciences (Switzerland)* (Vol. 9, Issue 16). MDPI AG. <https://doi.org/10.3390/app9163316>
- Samarakkody, T. (2023). Industry 4.0: Adoption of Challenges in Apparel Industry in Sri Lanka. <https://www.researchgate.net/publication/377751037>
- Seepersad, C. C. (2014). Challenges and Opportunities in Design for Additive Manufacturing. *3D Printing and Additive Manufacturing*, 1(1), 10–13. <https://doi.org/10.1089/3dp.2013.0006>
- Shahzad, K., Deckers, J., Kruth, J. P., & Vleugels, J. (2013). Additive manufacturing of alumina parts by indirect selective laser sintering and post processing. *Journal of Materials Processing Technology*, 213(9), 1484–1494. <https://doi.org/10.1016/j.jmatprotec.2013.03.014>
- Shakya, A., & Swami, C. (2016). INTEGRATED WASTE MINIMIZATION TECHNIQUES IN APPAREL DESIGN: A SUSTAINABLE PERSPECTIVE.
- Shapiro, A. A., Borgonia, J. P., Chen, Q. N., Dillon, R. P., McEnerney, B., Polit-Casillas, R., & Soloway, L. (2016). Additive Manufacturing for Aerospace Flight Applications. *Journal of Spacecraft and Rockets*, 53(5), 952–959. <https://doi.org/10.2514/1.A33544>
- Spahiu, T. et al. (2020) '3D Printing: An Innovative Technology for Customised Shoe Manufacturing', in, pp. 171–180. Available at: https://doi.org/10.1007/978-3-030-29041-2_22.
- Sulochani, R. M. N., Nilmini, A. H. L. R., Jayasinghe, R. A., & Priyadarshana, G. (2021). Waste Management and Pollution Control Transitioning Towards a Circular Textile Economy: Sharing Knowledge and Best Practices from Sri Lanka.
- Sun, L., & Zhao, L. (2017). Envisioning the era of 3D printing: a conceptual model for the fashion industry. *Fashion and Textiles*, 4(1), 25. <https://doi.org/10.1186/s40691-017-0110-4>
- Todeschini, B. V., Cortimiglia, M. N., Callegaro-de-Menezes, D., & Ghezzi, A. (2017). Innovative and sustainable business models in the fashion industry: Entrepreneurial drivers, opportunities, and challenges. *Business Horizons*, 60(6), 759–770. <https://doi.org/10.1016/j.bushor.2017.07.003>
- Tomovska, E., Jordeva, S., Trajković, D., & Zafirova, K. (2017). Attitudes towards managing post-industrial apparel cuttings waste. *Journal of the Textile Institute*, 108(2), 172–177. <https://doi.org/10.1080/00405000.2016.1160764>
- Trust, T., & Maloy, R. W. (2017). Why 3D Print? The 21st-Century Skills Students Develop While Engaging in 3D Printing Projects. *Computers in the Schools*, 34(4), 253–266. <https://doi.org/10.1080/07380569.2017.1384684>
- Vadicherla, T., & Saravanan, D. (2014). Textiles and Apparel Development Using Recycled and Reclaimed Fibers (pp. 139–160). https://doi.org/10.1007/978-981-287-065-0_5

- Valtas, A., & Sun, D. (2016). 3D Printing for Garments Production: An Exploratory Study. *Journal of Fashion Technology & Textile Engineering*, 04(03). <https://doi.org/10.4172/2329-9568.1000139>
- Vasco, J. C. (2021). Chapter 16 - Additive manufacturing for the automotive industry. In J. Pou, A. Riveiro, & J. P. Davim (Eds.), *Additive Manufacturing* (pp. 505–530). Elsevier. [https://doi.org/https://doi.org/10.1016/B978-0-12-818411-0.00010-0](https://doi.org/10.1016/B978-0-12-818411-0.00010-0)
- Verlan, V., & Irovan, M. (2018). APPLICATIONS OF 3D PRINTING TECHNOLOGIES IN THE GARMENT INDUSTRY. *Applied Researches in Technics, Technologies and Education*, 16(2), 104–107. <https://doi.org/10.15547/artte.2018.02.005>
- Withanaarachchi, A., Jayatilake, H. S. B., & Withanaarachchi, A. (2016). Industry 4.0 in the Apparel-Manufacturing Sector: Opportunities for Sri Lanka. <https://www.researchgate.net/publication/310466591>
- Wong, K. V., & Hernandez, A. (2012). A Review of Additive Manufacturing. *ISRN Mechanical Engineering*, 2012, 1–10. <https://doi.org/10.5402/2012/208760>
- Yap, Y.L. and Yeong, W.Y. (2014) 'Additive manufacture of fashion and jewellery products: a mini review', *Virtual and Physical Prototyping*, 9(3), pp. 195–201. Available at: <https://doi.org/10.1080/17452759.2014.938993>.
- Zaman, A. (2022). Zero-Waste: A New Sustainability Paradigm for Addressing the Global Waste Problem. In *The Vision Zero Handbook: Theory, Technology and Management for a Zero Casualty Policy* (pp. 1–24). Springer.

ENHANCING ENVIRONMENTAL, SOCIAL, AND GOVERNANCE (ESG) PERFORMANCE THROUGH BUILDING AUTOMATION SYSTEMS (BAS)

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Abstract. The integration of Environmental, Social, and Governance (ESG) principles with Building Automation Systems (BAS) has emerged as a critical strategy for enhancing sustainability in building operations. ESG has emerged as a global framework for assessing corporate sustainability, while BAS facilitates real-time monitoring and control of building systems. Therefore, this study aims to examine the integration of Environmental, Social, and Governance principles with Building Automation Systems to enhance sustainability in building operations in the Sri Lankan context. The research uses a mixed-methods approach, involving a questionnaire survey and semi-structured interviews with professionals in sustainability, facilities management, and BAS engineering. The Relative Importance Index was used to analyse ESG-related issues, while qualitative data from interviews provided insights into strategies for integrating BAS with ESG principles. The findings show that BAS significantly improves environmental sustainability by optimising energy use, reducing operational costs, and improving system efficiency. However, its social and governance contribution is limited due to manual oversight and privacy concerns. Key ESG challenges, such as air pollution and energy inefficiency, were identified, especially in Sri Lanka. Addressing these challenges requires policy reforms, stakeholder engagement, and ethical practices. The study bridges the gap between technological advancements and ESG principles, offering practical recommendations for integrating technology with broader sustainability frameworks.

Keywords. ESG; Building Automation System (BAS), Organisational Performance, Smart Building Technology, Operational Efficiency

1. Introduction

ESG (environment, social and governance), established in 2004, has been widely applied in Europe, America, and other developed countries as a framework incorporating environmental, social, and governance factors in investment decisions and ownership (Li et al., 2021). As a result of the increasing emphasis on sustainable and responsible business practices, there has been a substantial rise in the number of companies that measure and disclose ESG data in recent years (Amir & Serafeim, 2017). According to Fatimah et al. (2023) ESG metrics are crucial in addressing resource depletion and environmental challenges, as evidenced by strategic initiatives like the Sustainable Development Goals and climate action plans. To evaluate sustainability, ESG scores have become widely acknowledged indicators, and researchers and administrators employ them to evaluate the progress of organisations in sustainable development (Clément et al., 2022). Reliable, transparent, and trustworthy sustainable data analysis and reporting are essential for the attainment of ESG objectives, as they provide stakeholders with a quantifiable perspective on a company's ESG performance (Jonsdottir et al., 2022). Further to the author, the primary focus of institutional investors is the quality of ESG data, emphasizing comparability, dependability, and precision. However, the challenges posed by inaccuracies in ESG reporting are significant, as companies frequently encounter difficulty in comprehending the requirements and generating comprehensive reports.

Xiao & Fan (2014) stated that modern buildings utilise advanced technologies like BAS (building automation system) for intelligent real-time monitoring and control, storing records of temperature, flow rate, humidity, pressure, power, control signals, and equipment states in a vast database. BAS enables real-time monitoring and control by integrating a variety of building systems, such as HVAC, lighting, security, and fire safety, into a centralised platform (Himeur et al., 2022). While ESG provides a framework for investment decisions by rating ESG factors, a building automation system (BAS) controls and monitors all systems in real time over the internet (Yang et al., 2020). Despite the clear advantages of BAS, challenges remain in fully utilizing its capabilities for ESG-focused sustainability efforts. Integrating BAS with ESG principles can enhance transparency in sustainability initiatives, improve data accuracy for ESG

reporting, and support companies in achieving environmental sustainability certifications like LEED and BREEAM (Brounen, Marcato, & Op't Veld, 2021). While the existing literature acknowledges the significance of ESG indicators in assessing sustainability and corporate performance and highlights the potential of BAS for real-time monitoring and control, there remains a lack of comprehensive research that effectively integrates ESG principles with BAS capabilities to enhance overall building sustainability. Therefore, this study aims to bridge the gap between technological advancement and societal well-being by examining ESG and BAS capabilities. The paper structure begins with an introduction to the study and followed by a literature review on ESG, BAS, and integration of BAS and ESG. The paper then presents the research methodology and findings, and the final section of the paper presents the conclusion of this research.

2. Literature Review

2.1 BUILDING AUTOMATION SYSTEM (BAS)

Building automation systems are a popular choice in the buildings industry due to its capacity to reduce energy consumption, simplify building operations, and improve customer satisfaction by monitoring and maintaining comfortable requirements (Domingues et al., 2016). Ren et al. (2023) have introduced BAS as a mindset of smart buildings, which facilitates the building's smartness. Additionally, the system necessitated an appropriate connection between system components and external sources, such as the cloud. BASs are deployed in modern buildings, particularly public and commercial buildings such as malls, factories, domestic domains, and enterprise buildings, to monitor and control real-time data. They analyse vast amounts of data that are retained in the system (Domingues et al., 2016; C. Fan et al., 2015).

BAS utilise various sensing methods like CO₂ concentration, temperature, zone airflow, occupancy levels, and daylight levels to maintain comfort and reduce errors and costs (Vandenbogaerde et al., 2023). Sensors, in conjunction with actuators, enable control systems to function, either directly managing sensor information or being controlled by a supervisory layer. Informative sensors aid in mapping essential data for building model calibration, and the design of control and monitoring schemes for detailed building modelling is a research area (Aste et al., 2017)

2.2 ESG FRAMEWORK

An ESG framework is a method that assesses the value of a company by evaluating its performance on non-financial factors, which includes environmental impact, social responsibility, and governance practices (Park et al., 2022). It is imperative for investors to assess corporate behaviour and prospective financial performance using ESG factors. These three factors are crucial for investment analysis and decision-making processes, as they enable the assessment of the sustainability and social impact of business operations (Brounen et al., 2021). According to Park et al. (2022), the ESG index has emerged as a highly significant indicator of a company's non-financial performance, and it has become the new standard to base investment decisions on the ESG index.

Each of the three pillars in the ESG framework serves a distinct yet interconnected function. The environmental pillar assesses a company's endeavours to protect the environment, which includes mitigation of climate change and reduction of carbon emissions, pollution control, management of waste generated during the production process, efficient use of energy and water, and emphasis on diversity and deforestation (Radzi et al., 2023). The social pillar focuses on company's relationships with stakeholders, employees, customers, communities, and suppliers. It encompasses areas such as labour standards, employee well-being, workplace

diversity and inclusion, human rights, and community engagement (Brounen, Marcato, & Op't Veld, 2021). Strong social policies not only enhance a company's public image but also drive innovation and employee productivity. The governance pillar relates to internal practices and policies that drive corporate decisions and accountability. Key areas include board diversity and structure, executive compensation, anti-corruption measures, shareholder rights, and transparency in reporting. Governance is foundational to ethical management and risk mitigation (Radzi et al., 2023).

2.3 ESG-RELATED ISSUES

2.2.1 Environmental Issues

Sri Lanka aims to become a 100% sustainable energy-dependent nation by 2050, aligning its economic strategies with global trends (Koswatte et al., 2024). Despite being a middle-income developing nation, Sri Lanka faces challenges such as land degradation, pollution, inadequate water resource management, diminishing biodiversity, coastal erosion, and poor industrial waste handling. Buildings account for over 40% of the world's energy use, 42% of its CO₂ emissions, and 30% of its freshwater use (Fan & Fang, 2023). To decrease energy and water use, benchmarking energy and water use has become a top priority for governments and relevant agencies. Around 51% of Sri Lanka's energy demand is fulfilled from renewable resources but faces higher energy costs compared to other Asian countries (Koswatte et al., 2024). Small- and medium-sized enterprises (SMEs) continue to face barriers due to a lack of funding, knowledge, technology, and motivation.

Sri Lanka ranked as the 80th worst CO₂ emitter in the world in 2019, with carbon emissions of 20.8 million MtCO₂e. Air pollution in Colombo is a major concern, with Colombo's air quality reaching 169 on the index in December 2022 (Koswatte et al., 2024). Sri Lanka is seventh among the world's worst unmanaged plastic offenders, and waste management in the country has become a severe concern due to rising garbage production and a lack of extensive, well-resourced waste management infrastructure. Over 60% of Sri Lanka's municipal solid waste is organic and biodegradable, but managing hazardous waste is difficult due to a lack of technical expertise (Fernando & Tsuji, 2024).

2.3.2 Social Issues

Sri Lanka's constitution ensures the right to join a trade union, with 2,074 registered trade unions operating in various sectors. However, child labour remains a significant issue, with 43,714 children involved in it (Mudalige, 2023). The country has established the National Policy on Elimination of Child Labour to combat this problem. Work environments in Sri Lanka suffer from issues such as noise, insufficient lighting, and overcrowding, with safety measures often lacking. Sustainability reporting in Sri Lanka has gained less attention than in other countries. Gender-based discrimination and equal rights are also challenged, particularly in the workplace. Women face barriers due to family and social factors, and employers may not be willing to hire them. The International Labour Organisation (ILO) is working to address these issues through social dialogue and developing tools to create a more conducive environment (Dissanayake et al., 2019).

Poverty in Sri Lanka has increased due to economic growth, social protection issues, and the COVID-19 pandemic. The poverty rate reached 14.3% in 2019, with 14.3% of the population living below the national poverty line. Poverty has increased since 2019, reaching 12.7 in 2020 and doubling between 2021 and 2022 (Baffes et al., 2021). To make a more inclusive and prosperous society, there is a need to improve social protection, tackle poverty and inequality, and encourage digital transformation. Traditional methods of supply chain management face

challenges like uncertainty, cost, complexity, and vulnerability. Innovative management processes, such as large-scale smart infrastructure and intelligent automation in SCM (Supply Chain Management), are necessary to address these issues (Abeyrathne & Gunawardana, 2023).

2.3.3 Governance Issues

In order to foster investor confidence and trust, organisations must guarantee transparency in their operations. This encompasses the provision of stakeholders with information that is comprehensive, accurate, and easy to understand. Additionally, this contributes to the improvement of stakeholders' reputations and the mitigation of misunderstandings. Consequently, the aforementioned issues pertain to each of the ESG pillars and their current conditions within an organisation, enumerating areas of concern to mitigate their effects (Sellhorn & Wagner, 2022).

2.4 ACHIEVING ESG THROUGH BAS IMPLEMENTATION

Environmental, Social, and Governance (ESG) goals are increasingly integral to corporate strategies, particularly in the built environment sector. BAS has emerged as a key enabler in achieving these goals by optimizing energy efficiency, enhancing occupant well-being, and supporting transparent governance practices.

On the environmental front, BAS contributes significantly to environmental sustainability by managing HVAC, lighting, and energy systems to reduce carbon emissions and energy consumption (Wang et al., 2012). Smart sensors and predictive analytics embedded within BAS allow for real-time monitoring and adaptive control, resulting in substantial energy savings and compliance with green building standards such as LEED and WELL (Ali et al., 2020).

From a social perspective, BAS enhances indoor environmental quality (IEQ), which influences occupant health, comfort, and productivity. Intelligent lighting and air quality systems can adjust to user preferences and occupancy patterns, promoting well-being (Spengler & Chen, 2000). Moreover, BAS supports inclusivity through adaptive technologies that respond to diverse needs, including accessibility features for people with disabilities.

On the governance front, BAS provides detailed operational data that can be used for ESG reporting and regulatory compliance. This data transparency strengthens stakeholder trust and facilitates data-driven decision-making (Pérez-Lombard et al., 2008). Moreover, the integration of cybersecurity features into BAS platforms ensures the protection of sensitive data, aligning with governance best practices.

Despite these benefits, challenges such as high implementation costs, interoperability issues, and the need for skilled personnel persist (Baharetha et al., 2024). However, advancements in IoT and cloud computing are rapidly addressing these barriers, making BAS a viable and strategic tool for ESG achievement.

3. Methodology

The study was conducted in two phases, focusing on the Sri Lankan context. To integrate ESG and BAS and address existing issues related to ESG factors within Sri Lanka, data were gathered from the ESG and BAS industry practitioners during phase I. Additionally, the perspectives of experts in the ESG and BAS practices were collected in phase II to determine the significance of ESG and to formulate recommendations through BAS. A questionnaire survey was identified as the most appropriate data collection method for Phase I. Quantitative data on existing issues and qualitative data on the opinions of individuals were collected using an online questionnaire. 30 responses were received from the 40 distributed questionnaires and chosen for the analysis. Simple random sampling was chosen as the sampling technique due to its requirement

of a single random selection and a restricted comprehension of the population. The questionnaire predominantly consisted of closed-ended questions and a few Likert scale questions to identify the issues in ESG implementation in Sri Lankan building practices. Moreover, in Phase II of the study, interviews were conducted with experienced expert professionals in Sri Lanka to acquire expert knowledge on ESG and BAS. The literature review identified the matters that served as the foundation for the interviews, which were conducted to gather more comprehensive qualitative information. Eight (08) semi-structured interviews were conducted with experts in ESG practices to determine the most effective strategies for integrating ESG and BAS.

The profiles of the selected experts are provided in Table 1.

Table 1: Profile of the Experts

Expert	Designation	Years of experience in the profession	Years of experience in BAS
E1	ESG group head	16 Years	10 Years
E2	Head of Facilities Management	14 Years	4 Years
E3	Health and Safety Officer	5 Years	2 Years
E4	Head of Facilities Management	10 Years	10 Years
E5	Sustainability Manager	10 Years	2 Years
E6	Operations manager	12 Years	8 Years
E7	Facilities executive	7 Years	1 Years
E8	Project Manager	10 Years	5 Years

The questionnaire survey was analysed using both statistical and manual content analysis, with RII used for the evaluation of issues. Content analysis was used for interview data analysis since most of the data consisted of opinion evidence.

Relative Importance Index (RII) = $\sum w/A \cdot N = (1n1 + 2n2 + 3n3 + 4n4 + 5n5) / 5 \cdot N$; ($0 \leq \text{RII} \leq 1$)

where the symbols indicate:

W: weight was given to each delay factor by the respondent within the range {1, 2, 3, 4}, multiplied by the number of respondents { $n1, n2, n3, n4$ } for each factor.

$n1$ = number of respondents who strongly disagree.

$n2$ = number of respondents who disagree.

$n3$ = number of respondents who neither agree nor disagree.

$n4$ = number of respondents who agree.

$n5$ = number of respondents who strongly agree.

A: highest weight (in this study: 5).

N: overall number of respondents (in this study: 30).

4. Results

4.1 QUESTIONNAIRE SURVEY RESULTS

4.1.1 Profile of the Respondents

The questionnaire was distributed to professionals who are involved in sustainability, facilities management, and BAS engineering, as this survey is intended to identify issues related to ESG factors and BAS integration within organisations. The respondents' profiles are illustrated in Figure 1.

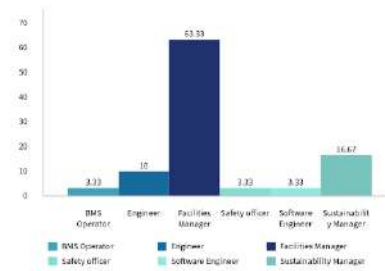


Figure 1: Respondents' profile

Considering the understanding of the respondents regarding the ESG rating, the survey reveals that 40% of respondents have average knowledge about ESG ratings, with 13.3% having very high knowledge, 30% having high knowledge, and 16.7% having low knowledge. The majority of respondents do not have high knowledge on ESG, with over half having average and low knowledge. In the analysis of the ESG performance of the respondents' organisations, the majority of them (76.7%) exhibit a high level of performance in ESG. Additionally, 20% of the organisations exhibit ordinary performance, and 0.3% exhibit very high performance.

4.1.2 ESG Related Issues and Reasons

The study measured ESG-related issues identified through literature review and used a relative importance index (RII) analysis to rank them based on their relative importance. Respondents valued each question based on the level of condition of each factor in their organisation using a five-point Likert scale.

Environmental Issues

Table 2: Environmental issues

Factor	RII	Rank	Reference
Air pollutants	0.587	1	Lucy Pérez et al., 2022
Impact and dependence on ecosystems	0.500	2	Brounen et al., 2021
Impact and dependence on biodiversity	0.467	3	Brounen et al., 2021
GHG emissions	0.460	4	Brounen et al., 2021
Biodiversity and ecosystems; rehabilitation	0.427	5	Lucy Pérez et al., 2022
Energy efficiency	0.340	6	Brounen et al., 2021
Waste management (water, solid, hazardous)	0.313	7	Lucy Pérez et al., 2022
Water usage management	0.307	8	Lucy Pérez et al., 2022
Innovation in environmentally friendly products and services	0.300	9	Brounen et al., 2021
Hazardous-materials management; circularity	0.267	10	Brounen et al., 2021

According to the survey findings, the RII values for environmental factors are within the range of 0.267 to 0.587. The most pressing concern is the discharge of air pollutants, while hazardous waste disposal is the least pressing concern. The majority of organisations have effective hazardous material management systems, which suggests that these factors are not a concern when evaluating RII. As per the respondents, the production process, energy consumption, and

high-intensive machinery are the primary causes of environmental issues in organisations. Building conditions and tenant restrictions are beyond the control of certain organisations, resulting in energy and water waste. Nature can be negatively impacted by the use of harmful materials in apparel, such as cotton and leather, which result in the devastation of habitats and the cutting down of trees. Burning fuels and inefficient fixtures contribute to greenhouse gas emissions during transportation to destination sites. Land development destroys natural habitats, necessitating reforestation initiatives to mitigate the environmental impact. Low energy efficiency is primarily due to the presence of antiquated machinery and fixtures, as well as building envelopes. Organisations frequently furnish waste to CEA-registered outsiders for decomposition and recycling, as the quantity of collected waste, particularly food waste, is a cause for concern. The demand for lighting, heating, and ventilation, as well as the additional consumption of electricity for decorations, all contribute to an increase in energy consumption during peak seasons with an increase in visitors and decorating. Higher energy consumption and greenhouse gas emissions are the consequence of the extended operational hours, increased appliance utilisation, and strain on HVAC systems.

Social Issues

Table 3: Social Issues

Factor	RII	Rank	Reference
Programs for reduce poverty	0.486	1	Lucy Pérez et al., 2022
Discrimination, diversity	0.450	2	Brounen et al., 2021
Forced and compulsory labour	0.407	3	Brounen et al., 2021
Community impacts (How a company affects the well-being and development of the communities in which it operates)	0.340	4	Brounen et al., 2021
Opportunity	0.280	5	Brounen et al., 2021
Equality	0.253	6	Lucy Pérez et al., 2022
Training and education	0.240	7	Lucy Pérez et al., 2022
Customer privacy, satisfaction	0.230	8	Lucy Pérez et al., 2022
Workforce freedom of association	0.200	9	Lucy Pérez et al., 2022
Customer health and safety	0.140	10	Brounen et al., 2021
Workplace health and safety	0.133	11	Brounen et al., 2021
Child labour	0.121	12	Brounen et al., 2021

The survey results indicate that the RII values for social pillar factors range from 0.121 to 0.486. These factors include poverty reduction programs, discrimination and diversity, community impact, opportunity, equality, training and education, customer privacy and satisfaction, workforce freedom of association, customer health and safety, and workplace health and safety related issues. The most critical issue is privacy reduction programs, while the least critical issue is child labour. In relation to the reasons for social issues mentioned, the majority of respondents have indicated that the primary cause of crimes and safety concerns is the failure of employees to adhere to policies and procedures during their work. Additionally, in order to maintain positive social practices, it is essential that management and employees maintain effective communication.

Governance Issues

Table 4: Governance Issues

Factor	RII	Rank	References
Bribery and corruption	0.513	1	Brounen et al., 2021
Incentives	0.287	2	Brounen et al., 2021
Board diversity and structure	0.280	3	Brounen et al., 2021
Stakeholder engagement	0.240	4	Brounen et al., 2021
Supply chain management	0.213	5	
Capital allocations	0.193	6	Lucy Pérez et al., 2022
Codes of conduct and business principles	0.173	7	Brounen et al., 2021
Business ethics, data security	0.167	8	Lucy Pérez et al., 2022
Accountability	0.165	9	Brounen et al., 2021
Fairness of executive pay	0.160	10	Brounen et al., 2021
Transparency and disclosure	0.153	11	Brounen et al., 2021
Shareholder rights	0.140	12	Brounen et al., 2021

The survey results indicated that the RII values for governance factors varied from 0.140 to 0.513. Bribery and corruption were the most critical issues identified, while shareholder rights were the least critical. From the respondents' perspective, the majority of organisations adhere to their governance factors manually, which means that they have acknowledged the possibility of errors such as duplication and reporting.

4.1.3 Building Automation System Contribution to Enhance ESG Performance

The BAS contribution to improving ESG performance is assessed in Figure 2 below based on the respondents' viewpoints. Evaluations were conducted separately for each of the three pillars: Environment, Social, and Governance.

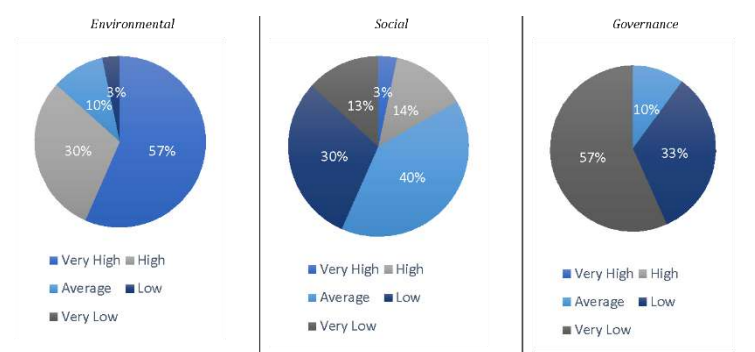


Figure 2: Building Automation System Contribution to Enhance ESG Performance

BAS has been approved by the majority of respondents (57%), with 30% indicating that it has a high contribution to improving environmental performance. The majority of respondents (40%) believed that BAS makes an average contribution to improving social performance while 30% of respondents reported that it makes a low contribution and 13% reported that it is very low. A vast majority of respondents (57%) agreed that BAS makes a very low contribution to improving governance, while 10% stated that it averagely affects the governance performance.

4.2 EXPERT INTERVIEW ANALYSIS

4.2.1 Importance of ESG in the Context of Building Operations

Organisations are increasingly aligning with the Triple Bottom Concept, which focuses on profit, people, and planet. This approach is necessary to address environmental pollution, human rights, resource decay, and compliance with rules and regulations. E2 suggested that

organisations should consider their environmental, social, and governance aspects in order to improve their performance. E3 emphasized the importance of reducing energy usage, waste, and chemicals in their operations. Following ESG principles can help reduce these impacts by implementing energy-saving, less waste, and eco-friendly products, leading to sustainability growth. Governance requirements under this framework can help identify factors that align with each ESG pillar, reducing fraud risks, complying with regulatory compliances, reducing legal disputes, and aligning with sustainability. E3 also highlighted the importance of enhancing brand reputation and trust within stakeholders. Even during crisis times, companies can manage risk and maintain stakeholder trust by facilitating efficient resource management, cost savings, and reducing environmental impacts.

E5 and E6 emphasized the importance of integrating ESG principles into daily operations to examine resource usage, waste generation, and emissions. By monitoring these factors, areas for advancement can be identified and eco-friendly solutions like recycling, leveraging natural light, and recovering energy become feasible. Facility management should shift from resource consumption to exploring reuse possibilities during building construction and maintenance, resulting in a lower environmental footprint. E6 advocated for adopting more energy-efficient technologies, renewable energies, and waste reduction methods to achieve sustainable practices and save costs. Risk management is crucial in this context, as companies can provide proactive solutions for potential risks such as increasing costs due to taxes or high material prices. E7 mentioned that engaging with these factors can attract investors, improve financial performance, and build a strong reputation that attracts customers and talent. Establishing a framework that effectively identifies, assesses, and mitigates risks related to environmental, social, and governance factors helps companies adhere to ESG standards and promote sustainability programs aligned with business objectives.

4.2.2 Strategies to Enhance ESG Factors Through BAS

Environmental Pillar

Experts agreed that BAS can significantly improve environmental factors. E1 stated that they implemented an ESG framework for their organisation, which they followed for around 10 years without using ESG words specifically. After implementing BAS, they saw significant energy savings, with their local factory reducing energy consumption by over 50% compared to an Indian factory with the same capacity. The local factory's performance doubled compared to the Indian factory. E3 also noted that BAS helped to reduce manpower by connecting AC and lighting systems and scheduling them automatically. They also have used BAS to support energy-related tasks, such as meter readings and comparing results. E6 and E8 reported that BAS helped to reduce sudden breakdowns by providing early detection alarms on system errors, allowing staff to take proactive maintenance activities. This led to less breakdowns and efficient system operations, reducing unfrozen costs. In conclusion, BAS implementation positively impacts energy-efficient technologies in facilities, contributing to a more sustainable and efficient environment.

Social Pillar

The BAS system is unable to integrate with the majority of social factors, as per all eight specialists. E1, E2 stated that the company already possess legitimate documents and ongoing data records, and there is no necessity to incorporate these data into the BAS system. E2 clarified further, stating, "A BAS is a controlling and monitoring system. We have installed a motion sensor near the door, and when a person approaches, the sensor sends a signal to the system. We have programmed the system to automatically open the door when the relevant sensors send a signal, and the door open automatically. Also, the system will automatically

activate in accordance with the time signal if the lights are scheduled to be on at 6:00 p.m. But maintaining a database is merely a computerisation procedure. We can enter data into the BAS and access historical data."

Governance Pillar

According to all eight experts most of governance factors cannot integrate with BAS system. E3 further mentioned, "Specially these factors have some kind of privacy level. If we connect with BAS at least BAS operator can achieve to the details. Always we should consider privacy when consider these factors connect with BAS."

Refer Table 5 for the guideline to Enhance ESG performance through BAS.

4.4 DISCUSSION

This study intended to explore strategies for enhancing ESG (Environmental, Social, and Governance) performance through the application of Building Automation Systems (BAS). Empirical findings strongly confirms that BAS significantly contributes to environmental performance, particularly in reducing energy consumption, operational costs, and improving building efficiency aligns closely with the existing literature that highlights BAS as a key enabler of environmental sustainability (Radzi et al., 2023). BAS achieves this by integrating with HVAC, lighting, and energy management systems, facilitating automated control, real-time monitoring, and proactive maintenance. However, a deeper comparative analysis between the literature and empirical results reveals a clear deviation in the system's impact on the social and governance pillars. While literature suggests BAS has the potential to support broader ESG outcomes (Chungath, 2023), practical evidence shows limited influence beyond environmental aspects. Socially, BAS offers indirect benefits such as improving indoor air quality, comfort, and safety, yet it does not address deeper issues like diversity, labour standards, or training elements critical to social sustainability. In the governance realm, although BAS could theoretically promote transparency and accountability through data-driven insights (Brounen, Marcato, & Op 't Veld, 2021), experts and respondents confirm that privacy concerns and system limitations restrict its integration with sensitive governance functions. Most governance practices remain manual, lacking digital oversight through BAS. This discrepancy underscores the need for either enhancing BAS capabilities or incorporating complementary technologies to enable a more holistic ESG implementation in building operations.

While BAS may not directly address all Social and Governance challenges, it can play a significant role in supporting these pillars through enhanced workplace conditions, transparency, and operational efficiency. Some experts have recommended the development of a dedicated database for tracking and automating social and governance factors, which could further strengthen the contribution of BAS in these areas.

5. Conclusion

This study explored the integration of Environmental, Social, and Governance (ESG) principles with Building Automation Systems (BAS) to enhance sustainability in building operations, highlighting BAS's significant role in improving environmental performance through energy efficiency, waste reduction, and operational cost savings. However, its impact on social and governance factors, such as poverty reduction, diversity, and ethical governance, remains limited due to the need for human oversight and privacy concerns. Key ESG-related challenges in Sri Lanka, including air pollution, energy inefficiency, and governance issues like bribery, were identified, emphasizing the need for integrated strategies combining technological innovation with policy reforms. While BAS effectively supports environmental sustainability, addressing

social and governance challenges requires broader stakeholder engagement and ethical practices, underscoring the importance of a holistic approach to achieving ESG goals and fostering sustainable development.

Table 5: Guideline to Enhance ESG performance through BAS

Environmental	Social	Governance
Monitoring • Real-time monitor of power usage (kWh), diesel usage, and gas usage to identify consumption patterns and potential inefficiencies. • Continuously monitor emissions from emission sources like generators, incinerators, and kitchen exhausts using sensors and generating reports for regulatory compliance and improvement tracking. • Check alerts to identify malfunctioning equipment and leaks (gas) for early intervention and maintenance. • Monitoring and analysing energy consumption data for all subsystems in detail, allowing for targeted optimization. • Monitor historical data and gain a clear picture of power consumption and abnormal increases. • Analyse energy consumption by various parameters (system, location, machinery, time) with accurate details and efficiently. • Monitoring air quality in HVAC vents using sensors. • Integrating condensate water recycling with BAS (potentially high cost). • Utilise sensors to monitor water usage and detect leaks in real-time. • Measuring collected waste by type (cardboard, plastic) and entering data into the BAS for trend analysis and identify waste management strategies.	• Feed data collected on things like training, satisfaction feedback and monitor drawbacks and improvements. • Monitor parameters like CO2 level, lighting level, humidity level and control optimal condition. • Program with fire controls, fire alarms.	• Program to generate reports through the system. • can continue a database. • Feed data and keep a database to monitor patterns, trends, variation (for factors like policies, maintenance records, agreement data, supply chain related data)

• Develop a system to identify the composition of regenerated materials in products received from suppliers to inform purchasing decisions. • Creating a database to track monthly chemical usage and identify more sustainable alternatives. Controlling • Integrate occupancy and daylight sensors to automatically adjust HVAC and lighting systems based on real-time conditions. • Automatically increasing fresh air intake when CO2 levels exceed set points. • Setting alarms for exceeding pollutant levels and filter replacements. • Setting irrigation system based on sensor data (soil moisture, timing). • Scheduling HVAC systems and lighting operate based on occupancy and operational needs. • Optimizing equipment usage through scheduling (e.g., schedule on/off times). • Programming maintenance schedules into the BAS system to generate reminders and alerts for overdue tasks. • Prepare water bills and keeping detailed records. • Connect the garbage chute system to the BAS for automated waste segregation and bin replacement alerts. • Facilitate for data collection process of incident reports preparation. • Monitoring and controlling parameters like CO2 and lighting levels. • Program maintenance schedules into the BAS to generate reminders and alerts for overdue tasks,		

ensuring equipment operates efficiently.		

6. References

- Abeyrathne, S. D., & Gunawardana, K. D. (2023). Analysing the Impact of Factors on Challenges and Barriers in Supply Chain Management Implementation in the Sri Lankan Retail Industry During Covid-19. *Journal of Contemporary Perspectives in Accounting and Digitalization*, 6(1), 1–19. <https://doi.org/10.4038/jcpad.v6i1.6>
- Ali, A., Qazi, T., & Noor, S. (2020). Sustainable energy management in smart buildings. *Energy Reports*.
- Amir, A.-Z., & Serafeim, G. ". (2017). Why and how investors use ESG information: evidence from a global survey. In Harvard Business School Working Paper. <http://nrs.harvard.edu/urn-3:HUL.InstRepos:30838135>
- Aste, N., Manfren, M., & Marenzi, G. (2017). Building Automation and Control Systems and performance optimization: A framework for analysis. *Renewable and Sustainable Energy Reviews*, 75, 313–330. <https://doi.org/10.1016/j.rser.2016.10.072>
- Baffes, J., Guenette, J. D., Ha, J., Inami, O., Kabundi, A. N., Kasyanenko, S., Kilic Celik, S., Kindberg-Hanlon, G., Kirby, P. A., Nagle, P. S. O., Okou, C. I. F., Quaglietti, L., Ruch, F. U., Sugawara, N., Vashakmadze, E. T., Vorisek, D. L., Wheeler, C. M., & Yamazaki, T. (2021). *Global Economic Prospects*, June 2021.
- Baharetha, S., Soliman, A. M., Hassanain, M. A., Alshibani, A., & Ezz, M. S. (2024). Assessment of the challenges influencing the adoption of smart building technologies. *Frontiers in Built Environment*, 9. <https://doi.org/10.3389/fbuil.2023.1334005>
- Brounen, D., Marcato, G., & Op't Veld, H. (2021). Pricing ESG equity ratings and underlying data in listed real estate securities. *Sustainability (Switzerland)*, 13(4), 1–20. <https://doi.org/10.3390/su13042037>
- Chungath, J. (2023). Modeling Architecture to manage Energy, Social, and Governance (ESG) data of commercial buildings. Stockholm University.
- Clément, A., Robinot, É., & Trespeuch, L. (2022). Improving ESG scores with sustainability concepts. *Sustainability (Switzerland)*, 14(20). <https://doi.org/10.3390/su142013154>
- Dissanayake, D., Tilt, C., & Qian, W. (2019). Factors influencing sustainability reporting by Sri Lankan companies. *Pacific Accounting Review*, 31(1), 84–109. <https://doi.org/10.1108/PAR-10-2017-0085>
- Domingues, P., Carreira, P., Vieira, R., & Kastner, W. (2016). Building automation systems: concepts and technology review. *Computer Standards & Interfaces*, 45, 1–12. <https://doi.org/10.1016/j.csi.2015.11.005>
- Fan, C., Xiao, F., & Yan, C. (2015). A framework for knowledge discovery in massive building automation data and its application in building diagnostics. *Automation in Construction*, 50, 81–90. <https://doi.org/10.1016/j.autcon.2014.12.006>
- 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. <https://doi.org/10.1007/s10661-023-11515-z>
- Fatimah, Y. A., Kannan, D., Govindan, K., & Hasibuan, Z. A. (2023). Circular economy e-business model portfolio development for e-business applications: Impacts on ESG and sustainability performance. *Journal of Cleaner Production*, 415, 137528. <https://doi.org/10.1016/j.jclepro.2023.137528>
- Fernando, C. J., & Tsuji, M. (2024). Assessment of municipal solid waste management systems of Sri Lanka and Japan in terms of knowledge sharing: a comparative study. *Journal of Material Cycles and Waste Management*, 26(3), 1819–1839. <https://doi.org/10.1007/s10163-024-01927-5>
- Himeur, Y., Elnour, M., Fadli, F., Meskin, N., Petri, I., Rezgui, Y., Bensaali, F., & Amira, A. (2022). AI-big data analytics for building automation and management systems: a survey, actual challenges and future perspectives. *Artificial Intelligence Review*, 56(6), 4929–5021. <https://doi.org/10.1007/s10462-022-10286-2>
- Jonsdottir, B., Sigurjonsson, T. O., Johannsdottir, L., & Wendt, S. (2022). Barriers to using ESG data for investment decisions. *Sustainability*, 14(9), 5157. <https://doi.org/10.3390/su14095157>
- Koswatte, I., Iddawala, J., Kulasekara, R., Ranaweera, P., Dasanayaka, C. H., & Abeykoon, C. (2024). Can Sri Lanka be a net-zero nation by 2050?—Current renewable energy profile, opportunities, challenges,

- and recommendations. *Cleaner Energy Systems*, 8, 100126. <https://doi.org/10.1016/j.cles.2024.100126>
- Li, T.-T., Wang, K., Sueyoshi, T., & Wang, D. D. (2021). ESG: Research Progress and Future Prospects. *Sustainability*, 13(21), 11663. <https://doi.org/10.3390/su132111663>
- Lucy Pérez, Hamid Samandari, Vivian Hunt, Robin Nuttall, & Krysta Biniek. (2022). Does ESG really matter— and why? <https://www.eticanews.it/wp-content/uploads/2022/09/does-esg-really-matter-and-why-vf.pdf>
- Mudalige, N. K. K. (2023). Corresponding Trade Union Laws in Sri Lanka with that of International Standards to Enable Professional Recognition.
- Park, J., Choi, W., & Jung, S.-U. (2022). Exploring Trends in Environmental, Social, and Governance Themes and Their Sentimental Value Over Time. *Frontiers in Psychology*, 13. <https://doi.org/10.3389/fpsyg.2022.890435>
- Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), 394–398. <https://doi.org/10.1016/j.enbuild.2007.03.007>
- Radzi, S. H. M., Hamid, N. A., & Ismail, R. F. (2023). An Overview Of Environmental, Social And Governance (Esg) And Company Performance. In J. Said, D. Daud, N. Erum, N. B. Zakaria, S. Zolkafil, & N. Yahya (Eds.), *European Proceedings of Social and Behavioural Sciences* (pp. 1111–1122). <https://doi.org/10.15405/epsbs.2023.11.90>
- Ren, X., Li, J., He, F., & Lucey, B. (2023). Impact of climate policy uncertainty on traditional energy and green markets: Evidence from time-varying granger tests. *Renewable and Sustainable Energy Reviews*, 173, 113058. <https://doi.org/10.1016/j.rser.2022.113058>
- Sellhorn, T., & Wagner, V. (2022). The Forces that Shape Mandatory ESG Reporting. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4179479>
- Spengler, J. D., & Chen, Q. (2000). Indoor Air Quality Factors In Designing A Healthy Building. *Annual Review of Energy and the Environment*, 25(1), 567–600. <https://doi.org/10.1146/annurev.energy.25.1.567>
- Vandenbogaerde, L., Verbeke, S., & Audenaert, A. (2023). Optimizing building energy consumption in office buildings: A review of building automation and control systems and factors influencing energy savings. *Journal of Building Engineering*, 76, 107233. <https://doi.org/10.1016/j.jobee.2023.107233>
- Wang, S., Yan, C., & Xiao, F. (2012). Quantitative energy performance assessment methods for existing buildings. *Energy and Buildings*, 55, 873–888. <https://doi.org/10.1016/j.enbuild.2012.08.037>
- Xiao, F., & Fan, C. (2014). Data mining in building automation system for improving building operational performance. *Energy and Buildings*, 75, 109–118. <https://doi.org/10.1016/j.enbuild.2014.02.005>
- Yang, S., Wan, M. P., Chen, W., Ng, B. F., & Dubey, S. (2020). Model predictive control with adaptive machine-learning-based model for building energy efficiency and comfort optimization. *Applied Energy*, 271, 115147. <https://doi.org/10.1016/j.apenergy.2020.115147>

BARRIERS IN IMPLEMENTING THE CIRCULAR ECONOMY MODEL IN APPAREL WASTE MANAGEMENT IN SRI LANKA

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Abstract. The apparel industry is one of Sri Lanka's major export-oriented sectors, generating a substantial amount of pre-consumer apparel waste. Currently, landfilling and incineration are the dominant waste management methods, posing significant environmental, social, and economic challenges. This "take, make, use, discard" approach follows the linear economy model. To address its limitations, the Circular Economy (CE) model has gained momentum over the past few decades. However, while some research has explored CE adoption in Sri Lanka's apparel industry, no studies have critically analysed the barriers to its implementation. Given that CE remains a relatively novel concept in the country, addressing these barriers is essential. This study aims to identify the challenges and barriers in implementing the CE model in Sri Lanka's apparel industry. A qualitative research approach was employed, involving four in-depth case studies of large-scale apparel manufacturing organisations. Primary data were collected through twelve semi-structured interviews and validated by four industry experts. Thematic content analysis was conducted manually to analyse the data. The findings identified 39 barriers categorised under seven key pillars as economic, environmental, social, legal, market, organisational and market.

Keywords. Apparel Industry, Barriers, Circular Economy, Pre-Consumer Apparel Waste, Sri Lanka

1. Introduction

Sri Lanka's export earnings from apparel in 2024 reached USD 4.7 billion, recording a year-on-year growth of nearly 5% (Joint Apparel Association Forum Sri Lanka, 2024). According to the Ministry of Industry and Entrepreneurship Development (2021), the Apparel sector's contribution to Gross Domestic Product (GDP) stands at approximately 7%. As an industry-expanding strategy, the apparel sector has developed strong partnerships with famous brands, notably Nike, Victoria's Secret, and Marks & Spencer (Goger, 2013). Nevertheless, the apparel sector contributes significantly to worldwide production and consumption, it is also responsible for generating a considerable amount of waste. The apparel sector in Sri Lanka generates tens of thousands of tons of textile waste annually (Dias, 2024). According to the source of generation, apparel waste can be divided into two categories: post-consumer waste and pre-consumer waste (Tomovska et al., 2016). Pre-consumer apparel waste can be described as waste generated from the manufacturing processes. The apparel supply chain is divided between developed countries and developing countries that have outsourced the apparel production process, which means that the former generates post-consumer waste, while the latter generates more pre-consumer waste (Tomovska et al., 2016). Therefore, Sri Lanka generates high pre-consumer apparel waste as an industrialised country. Gunasekara et al. (2018) also asserted that the management process of apparel waste in Sri Lanka has become a major challenge in modern culture. The primary challenge is not the generation of apparel waste but rather its management and treatment. The apparel sector's present waste management techniques, such as incineration and landfilling, have a tremendous impact on the economy, society, and the environment. This "take, make, use, discard" model is known as the Linear Economy (LE) model. To address the limitations of the LE model, the Circular Economy (CE) model gained momentum during the last few decades.

According to Geng et al. (2012), the model of CE has developed as a viable solution to address these issues and move in the direction of an environmentally friendly strategy. According to the Ellen MacArthur Foundation (2019), CE is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoring, shifts towards the

use of renewable energy, and eliminates the use of toxic chemicals that impede reuse. Further, the CE model aims for the elimination of waste through the effective design of materials, products, systems, and, within its business models. A substantial body of research has focused on CE adoption and implementation in the apparel sector. Considering the apparel sector in Sri Lanka, a few studies published in the last five years explain that CE is a relatively new concept in the country. Mahendrarajah and Thayaparan (2020) conducted a literature review on the applicability of CE in the apparel sector, its benefits, and the challenges of adopting. Edirisinghe et al. (2022) conducted a study to examine the properties of waste, treatment options, and disposal techniques of apparel waste. Furthermore, Edirisinghe et al. (2023) surveyed to examine the production of fabric waste in the apparel manufacturing sector of Sri Lanka. Moreover, Edirisinghe et al. (2024) studied a comprehensive approach to identifying the environmental impact of the product lifecycle in the textile industry, with a specific focus on recognising the potential of CE to mitigate environmental impacts. Regarding CE adoption and implementation of apparel and textile waste, two studies can be found: Sulochani et al. (2020) evaluated best practices in waste and water management in the Sri Lankan textile sector using CE as a theoretical framework, and Jayakodi and Thayaparan (2021) conducted a study introducing an approach for effective pre-consumer apparel waste management practices through the CE model. However, none of these studies have focused on empirically identifying the barriers to implementing CE in pre-consumer apparel waste management. Subsequently, a prevailing research gap was identified as a research avenue to carry out this study in the Sri Lankan context. Identifying barriers to pre-consumer apparel waste management is essential for developing effective strategies to enhance resource efficiency and effective CE implementation apparel sector in Sri Lanka. Further, it helps uncover systemic challenges, enabling policymakers and businesses to design targeted interventions for waste reduction. For industry professionals, understanding these barriers facilitates the adoption of CE practices, improving operational efficiency and compliance with evolving environmental regulations. Therefore, this study aims to critically identify the barriers to implementing the CE model in pre-consumer apparel waste management in Sri Lanka.

2. Literature Review

2.1. APPAREL INDUSTRY AND PRE-CONSUMER APPAREL WASTE GENERATION

Global apparel production is vast, and as a result, a massive amount of apparel materials gets wasted (Swami et al., 2016). The change in the apparel industry with fast fashion and on-time production has led to an increase in the number of fashion seasons and new fashion collections for each season at a low price, which has been identified as the underlined reason for waste generation (Johansson, 2010). The apparel sector in Sri Lanka is also shown to generate an enormous amount of pre-consumer apparel waste (Gunasekara et al., 2018). According to Jordeva et al. (2015), pre-consumer apparel waste can be divided into textile waste, which includes synthetic fibre, cotton fibre, cotton mixtures, and mixed raw content; packing waste, which includes cardboard boxes, containers, bailing, and other waste; and impurities, which include cardboard and paper, buttons and reels, metal components, as well as other types of waste. According to Jayakodi and Thayaparan (2021), fabric and polymer are categorised as textile waste; buttons, metal parts, labels, tags, and trims fall under impurities; cardboard boxes, polythene, and paper are classified as packing waste; and thread cones, fabric cones, broken machinery, and empty chemical cones are identified as other wastes in Sri Lanka. Sarkar et al. (2018) explained that fabric scraps and trimmings, along with defective goods, are produced during the manufacturing process at several stages, such as material cutting and sampling, and along manufacturing. Table 1 indicates the classification of the pre-consumer apparel waste based on the literature findings.

Table 1: Types of Pre-Consumer Apparel Waste

Textile waste	Impurities	Packing waste	Other
Fabric Polymer	Buttons Metal parts Labels Tags and trims	Cardboard boxes Polythene Paper	Thread cones (Plastic and cardboard) Fabric cones (Plastic and cardboard) Broken machinery Empty chemical containers

Larney & Aardt (2010) explained that waste is generated throughout the entire apparel production process. Pre-consumer apparel waste generation poses significant challenges for the apparel sector and increases environmental, social, and financial problems (Sarkar et al., 2018). Additionally, the disposal of apparel waste through landfilling and incineration has gained popularity while also contributing to global warming (Mulla, 2019). Globally, only 20% of apparel waste is accumulated for reuse or recycling (Koszevska, 2018). According to available research, Sri Lanka's main disposal options are landfilling and incineration, with some clothing waste also being reused and recycled (Dissanayake et al., 2018). Although 8,000 to 19,000 tonnes of clothing waste are burned annually in Sri Lanka, only 25% of the material is expected to be recycled or reused (Jayasinghe et al., 2010). The problem has become even more challenging due to the lack of suitable waste management solutions to handle the enormous amounts of pre-consumer apparel waste generated daily (Dissanayake et al., 2018).

2.2. CIRCULAR ECONOMY IN PRE-CONSUMER APPAREL WASTE MANAGEMENT

The LE model is based on the "take, make, use, discard" principle (Sariatli, 2017). This principle serves as an example of how the LE is used in apparel waste management in an effort to maximise short-term earnings and correspond to fast fashion expectations. The LE model's leading illustration of the burden on the environment brought on by high consumption is the fashion industry (Kirchherr, 2018). Landfilling is one approach that eliminates the residual energy of a product after it has been disposed of, and LE is connected to various needless resource losses (Ellen MacArthur Foundation, 2019). Incorporating a waste management system that is environmentally friendly is crucial, according to the author, given the aforementioned shortcomings of the current pre-consumer apparel waste management procedure. Due to the emphasis on preventing waste from ending up in landfills, procedures and embedded adaptability incorporate loops of feedback (Seadon, 2010).

The idea of CE is seen as a solution for balancing goals for environmental conservation and economic growth due to the numerous difficulties and underlying constraints of LE (Lieder & Rashid, 2016). The apparel industry has been recognised as one of the best avenues to implement CE since it represents one of the highest-earning industries in the world, having an estimated market worth of 0.82 trillion euros. However, the industry strongly adheres to the LE model because of its low-cost goods and quick-fashion trends (Barla et al., 2017). Therefore, circularity is designed to serve long-term sustainable development, being the ultimate aim in terms of the environment, the economy, and society. Furthermore, CE has become widely accepted, business model innovation will be just as important as technological advancement in both the Business-to-Customer (B2C) and Business-to-Business (B2B) segments (Rizos et al., 2018). To improve manufacturing performance in terms of sustainability, CE practices and technology are crucial (Šebo et al., 2021). Due to its unexpected results in numerous businesses in Sri Lanka, the zero-waste idea, or the notion of CE, has drawn more attention. Although some CE principles are being applied on an ad hoc basis. For instance, the construction sector in Sri Lanka currently has extremely limited awareness and comprehension of these concepts (Wijewansa et al., 2021). This suggests that the CE is a relatively new concept in Sri Lanka,

and this situation is particularly true for the apparel industry, where there is limited awareness and understanding of its principles.

2.3. INSIGHTS FROM GLOBAL CONTEXT ON BARRIERS IN IMPLEMENTING CIRCULAR ECONOMY PRE-CONSUMER APPAREL WASTE MANAGEMENT

The adoption of CE practices in the apparel sector faces a range of interrelated challenges. A lack of awareness and understanding of CE principles among industry stakeholders is identified as a primary barrier (Ghani & al Hamad, 2024; Zoumpalova et al., 2023). This knowledge gap is further exacerbated by low literacy levels and limited exposure to sustainable business models (Farrukh & Sajjad, 2024). The absence of robust policies, regulatory incentives, and supporting infrastructure also hinders progress (Ghani & al Hamad, 2024; Zoumpalova et al., 2023). Moreover, a lack of communication and collaboration across the value chain limits opportunities for joint innovation and capacity building. Market immaturity, including limited demand for recycled materials and unfamiliarity with circular products, adds another layer of complexity (Ghani & al Hamad, 2024; Sharma et al., 2025). Further resistance to change is often driven by deeply rooted norms, centralised decision-making, and a focus on short-term economic gains over long-term sustainability goals (Farrukh & Sajjad, 2024). Further to the authors, these issues are particularly evident in contexts like Pakistan's textile industry, where manufacturers prioritise profit maximisation and cost-cutting, even when aware of CE benefits. High operational and material costs, combined with technical limitations such as inefficient recycling processes and performance concerns with recycled inputs, further discourage CE adoption (Farrukh & Sajjad, 2024; Ghani & al Hamad, 2024). Financial constraints both internal and macroeconomic are also critical, especially for startups and organisations operating in resource-scarce regions (Zoumpalova et al., 2023). To overcome these barriers, scholars suggest a multifaceted approach including financial support mechanisms, regulatory reforms, knowledge sharing, consumer engagement, and investment in innovation and technology (Farrukh & Sajjad, 2024). Most of the identified barriers to CE implementation are specific to countries such as India, Pakistan, the Czech Republic, and Sweden and largely represent high-level, systemic challenges. However, there is limited understanding of how these barriers manifest in the Sri Lankan context, particularly within the apparel sector's pre-consumer waste management.

3. Methodology

The nature of the research problem determines the choice of an appropriate research approach (Creswell, 2014). The qualitative method places a strong emphasis on interpretation and description, which can lead to the development of new theories or concepts to assess organisational processes (Hancock et al., 2009). Given the qualitative nature of the data required for this study, a qualitative research approach was selected, as it provides deep insights into real-life contexts, preserves the intended meaning, and enables a comprehensive understanding of the research findings, an aspect that is challenging to achieve through quantitative methods. A case study is an empirical investigation that explores a contemporary phenomenon within its real-world context, particularly when the boundaries between the phenomenon and its context are not clearly defined (Yin, 2019). Therefore, the case study approach is suitable for research topics requiring an in-depth understanding of organisational and social processes, allowing for the collection of rich contextual information (Cassell & Symon, 2004). Accordingly, 4 major apparel companies were selected to provide diverse perspectives, enhance the findings, and contribute to a more comprehensive understanding of the subject matter. Three selection criteria were considered when selecting apparel manufacturing facilities as 1) engaged in the export market and collaborating with international brands, 2) employing more than 1000 workers, and 3) having a production capacity exceeding 10,000 items per month. In each case, three semi-structured interviews were conducted with corporate executives and waste management professionals responsible for overseeing waste treatment at the facility with more than 3 years

of experience. The experts were selected for the study using the purposive sampling technique. Additionally, a validity expert form was conducted to validate the findings of the study. Four pioneer experts in the field were selected for this, covering academia and industry, using purposive sampling. Finally, the gathered data was analysed through thematic and manual content analysis.

4. Data Analysis and Discussion

4.1. SEMI-STRUCTURED INTERVIEWS

Table 2: Demographic Details of the Respondents of the Semi-Structured Interviews

Case	Type of Business	Product Type	Respondent Code	Experience	Designation
Case A	Export	Casual wear, Activewear	A 1	7 years	Assistant Manager - Environmental Sustainability
			A 2	3 years	Executive Compliance and Sustainability
			A 3		Assistant - Housekeeping and Waste Management
Case B	Export	Casual wear	B 1	6 years	Senior Manager - Head of Facilities Management
			B 2	4 years	Senior Executive - Facilities Engineering
			B 3		Staff - Waste Management
Case C	Export	Activewear, Lingerie Wear	C 1	11 years	Senior Manager - Corporate Environment Sustainability
			C 2	4 years	Assistant Manager - Waste Handling
			C 3		Assistant - Housekeeping and Waste Management
Case D	Export	Casual wear	D 1	5 years	Senior Manager Corporate Environment Sustainability
			D 2	3 years	Executive Compliance and Sustainability
			D 3		Assistant - Facilities Management

4.1.2 Analysis and discussion

Lack of funding allocation for the automation projects is a crucial barrier that has been stated by B2. For the implementation of CE, it needs a considerable amount of investment, which has a long-term economic return (Liu & Bai, 2014). High cost of recycling is one of the economic barriers which have been faced by all four factories (Ghani & Al Hamad, 2024). D1 has commented that the lack of recycling facilities within the country has been identified as the major reason for this. A1 has commented that through lean manufacturing, a lot of waste generation can be reduced. However, a lack of employee engagement towards the lean manufacturing process is a major barrier that has been identified. Further, he stated that "employees are more concerned about the production process and target completion rather than lean manufacturing aspects". C1 also mentioned that due to a lack of engagement, immense contribution needs to be implemented, and it is an extra burden on employees, confirming with the literature findings (Zoumpalova et al., 2023).

B1 stated that the application of theoretical lean manufacturing tools to the practical situation is lacking or not practical. B2 also confirmed this by explaining that "it can occur conflicts between the operation team and the Business Continuous Improvement (BCI) team, and due to the practicality issues, that occurred within the organisation. Because sometimes the solutions of the BCI team are not practical". Further, B2 commented that the same barrier occurs while implementing planned reduction projects. Generally, the factories have been located all around the country, and some of them have been located in rural areas. This has become a barrier for the CE. The respondent A2 stated that some of the suppliers who fulfil the organisational quality requirements reject the transport of materials to the rural areas due to high transportation costs. Purchasing the materials from only registered suppliers is another barrier. Respondent B2 commented that for some clothing styles, suitable suppliers are recommended by the brands, and the organisation has no authority to select the suppliers from the list, which has already been registered. In such an incident, the organisation selects the suppliers who have a lower price scale without considering sustainability or circularity requirements. Lack of awareness regarding the reusing and recycling opportunities of the waste is another organisational barrier that has been stated by respondents. Respondent B1 stated that the lack of well-established internal policies for reuse and recycling can be identified as a significant barrier towards the implementation of CE.

Most of the respondents commented that emissions have occurred due to the long transportation of the waste material, and transportation is also identified as another environmental barrier. B2 has commented that due to the changes in the properties of the materials, it is hard to reuse some materials. When considering the recycling practices, respondent C2 has commented that it is hard to recycle the blended materials. When comparing the statements of respondent A1 and C1, A1 stated that "blended materials have become a major problem for recycling". As an example, some fabric materials comprised 95% polyester and 5% spandex". C1 also confirmed that "it is hard to recycle the blended materials. Especially dark-coloured and printed materials". When evaluating these two statements, it has been revealed that blended, printed and dark-coloured materials are hard to recycle. Fabric that comprises a variety of fibres and colours will cause challenges in the sorting process and reduce the quality of recycled materials; they are considered limiting factors in textile recycling (Ghani & Al Hamad, 2024; Zoumpalova et al., 2023). Evaluating the statement of C1, it reveals that environmental pollution occurs due to the emissions and fuel usage for the recycled machinery, though recycling is essential towards the CE. The machinery, which is used to treat the waste, consumes more energy and creates pollution (Kumar et al., 2019). In addition to that, most of the respondents commented that the unavailability of advanced technologies regarding apparel waste management is identified as a major barrier. The unavailability of a method that includes all the details of the raw materials, finished goods, and waste items that can track all details is a barrier. Further, B1 argues that such a system can identify the reuse and recycling opportunities of the materials. Use of machinery with outdated technologies for the cutting and sewing processes is identified as another technological barrier. Respondent D2 argues that reduction is not possible through those outdated technologies. Further, respondent A2 commented that "the marker efficiency strategy cannot be efficiently implemented for some styles. Because of that reason, it cannot achieve the reduction targets and generate high wastages". Most of the respondents illustrated that the unavailability of the machinery which recycles the fabric is one of the crucial barriers towards the CE. Due to the lack of fully cost-effective recycling technologies and the existence of cheap fabrics in the market, interest in textile waste recycling is limited (Zamani et al., 2014).

Respondent A1 commented that most of the time, brands are the ones who nominate the suppliers. Therefore, sometimes select the suppliers without considering the sustainability criteria. Further respondents A2, B1, D1, and D2 have commented that lack of local suppliers who fulfil the requirements available in the market. Respondent A2 has further stated that "lack

of local suppliers who fulfil the organisational, legal, and brand level requirements. As an example, most of the suppliers do not fulfil the requirement of EPL and SWML licence, which is issued by the Central Environment Authority (CEA) regarding the waste handling". Most of the design process of a product is done by the brands. Further, they select the materials for a certain design. This has become a crucial barrier for circularity. Respondent A1 has commented that brands have certain restrictions for manufacturers regarding material reductions, which are considered a barrier for CE. The minimum order quantity of the suppliers has become a critical barrier for waste reduction and reuse. C1 has commented that "MOQ of the suppliers has become a huge issue. As an example, for one colour the length of the minimum fabric roll is approximately 10,000m, and for the button 1500-3000 per colour or shape. Most of the time, these fabrics or buttons cannot reuse for another style. Because manufacturers produce their products based on customer requests. These requests can be changed from time to time due to the fast-fashion concept. It is hard to get the materials from the requested amounts". Further, he has elaborated that this has become a huge barrier for the reduction targets as well. Moreover, the respondent commented that "generally, fabric and button manufacturers produce in larger quantities. Because that is the way that they can earn a profit. Because of this, it is hard to reduce the purchasing of materials which are more than required. As an example, most of the thread cone suppliers in foreign countries do the same". D1 has commented that sudden order changes of the customer or brands, and based on the lack of flexibility of the suppliers to change the order from the organisation, have become a major barrier. Most of the respondents from all four cases lack reusing and recycling vendors in the market is also critical, which all four organisations have equally faced.

Lack of employee awareness regarding the different waste management approaches and tools has been identified as a barrier, which has been stated by B1 and D1. Further lack of skills of the machine operators regarding the machine operating method, also highlighted as a barrier. These two barriers can be demonstrated as skill and knowledge level barriers (Sharma et al., 2025; Zoumpalova et al., 2023). Lack of free minds of employees for innovations regarding waste management has been identified as a social barrier for CE. Further to the respondent, "lack of customer willingness towards the recycled products due to high cost, aesthetic appearance and quality has become a social barrier for CE". Kirchherr et al. (2018) identified lack of consumer awareness and interest acts as a major barrier towards the CE implementation. It has been difficult to maintain the strategies of CE due to a lack of demand and low customer acceptance of remanufactured products (Kumar et al., 2019). Respondent B1 has commented that high rules and regulations within the BoI plants have become a major barrier for waste collectors. As an example, their documentation procedure is lengthy. For this reason, most of the vendors deviated from collecting the waste. Further, most of the respondents from all four cases commented that the organisation pays money to obtain the licence for waste management. Charges and taxes specified by the government are another barrier (Altun, 2012). After the analysis of the data, the identified barriers were grouped based on the economic, social and environmental. However, due to the extensivity of the barriers identified, a few more categories were identified as organisational, market, legal and technological. After the classification of the barriers, it was verified that both the barriers and their respective categories were verified by the experts. The summary of the identified barriers with their respective categories is depicted in Figure 1.

4.2 EXPERT VALIDATION FORUM

To validate the analysed data, expert interviews were conducted with four professionals from the waste management field. The interviewees included a chartered sustainability manager, a deputy general manager in compliance and sustainability, and a general sustainability manager, with 8, 14, and 12 years of experience in the apparel industry, respectively. Additionally, a researcher with 20 years of experience in sustainability and CE practices within the apparel

sector was also interviewed. Table 3 illustrates the agreed-upon and revised barriers and barrier categories through the expert validation. The first question asked of the expert group was their opinion on the barrier category name and its adequacy. All the experts agreed with the identified barrier categories, which were generated from the nature of the barriers. Subsequently, it was verified that the barriers under each barrier category were verified, which is depicted in Table 3.

Table 3: Results of the Expert Validation

Barrier Category	Expert Code			
	E1	E2	E3	E4
1. Economic	Agreed	Agreed	Agreed	Agreed
2. Environmental	Agreed	Agreed	Agreed	Agreed
3. Social	Agreed	Agreed	Agreed	Lack of public awareness of recycled materials
4. Organisational			Unavailability of a proper plan to manage the total waste that has been collected within the organisation.	
5. Technological	Agreed	Agreed	Agreed	Lack of technologies within the country to recycle the blended materials.
6. Market	Agreed	Agreed	high cost of the waste management vendors.	Agreed
7. Legal	Lengthy, time-consuming and a lack of continuous monitoring in the environmental license issuing and renewing process.	Cost of the environmental license renewal process.	Lack of rules and regulations on CE.	Lack of national-level research on CE

4.3 SUMMARY OF THE IDENTIFIED BARRIERS



Figure 1: Summary of the Identified Barriers

Figure 1 presents the summarised findings of the study. A total of 44 identified barriers were categorised into seven clusters: environmental, social, economic, market, technological, organisational, and legal. The clustering was carried out by the authors following the semi-structured interviews. These barrier categories and their respective items were then validated through an expert forum, ensuring the accuracy and reliability of the study's final outcomes.

5. Conclusion and Recommendations

Pre-consumer apparel management has emerged as a significant concern, although the apparel sector has been acknowledged as one of the main contributors to the country's economy. Landfilling and incineration have become prominent methods of treating the pre-consumer apparel waste, which has created environmental, economic, and societal concerns. Therefore, the application of the CE model in ensuring the proper handling of pre-consumer apparel waste has great potential. As a relatively new concept to Sri Lanka, barriers to adopting CE in pre-consumer apparel waste management are crucial. Hence, this study was enabled to identify 44 barriers, which include a lack of technological infrastructure, complex legal issues, reluctance to change within organisations, and commercial difficulties. Further identified barriers were

categorised into seven categories as environmental, economic, social, organisational, technological, legal and market-related barriers. Therefore, this lays a background for apparel manufacturing organisations to find suitable strategies to minimise or eliminate the identified barriers for effective CE implementation. Furthermore, policymakers, business professionals, and stakeholders can use the research's findings as helpful insights to create focused plans, policies, and initiatives which tackle the identified barriers. As a limitation of the study, the concept awareness of the experts was identified. Finally, the apparel sector may move toward a CE by working together, encouraging sustainable waste management techniques, and gaining long-term benefits for both the environment and the economy. As a future research avenue, the identification of strategies to eliminate or mitigate is imperative through an empirical study.

6. References

- Altun, S. (2012). Prediction of textile waste profile and recycling opportunities in Turkey. *Fibres & Textiles in Eastern Europe*, 20(5(94)), 16-20.
- Barla, F., Nikolakopoulos, A., & Kokossis, A. (2017). Design of Circular Economy Plants-The Case of the Textile Waste Biorefinery.
- Cassell, C., & Symon, G. (2004). *Essential guide to qualitative methods in organisational research*. London.
- Creswell, J. W. (2014). *Research design: Qualitative, quantitative and mixed method approach*. London: Sage publications Ltd.
- Dissanayake, D., Weerasinghe, D., Wijesinghe, K., & Kalpage, K. (2018). Developing a compression moulded thermal insulation panel using postindustrial textile waste. *Waste Management*, 79, 356-361. doi:10.1016/j.wasman.2018.08.001
- Edirisinghe, L. M., Alwis, A., & Wijayasundara, M. (2023). Uncovering the circular economy potential of industrial waste in Sri Lanka (case study from textile industrial-fabric waste). *E3S Web of Conferences*,
- Edirisinghe, L., de Alwis, A., & Wijayasundara, M. (2024). Sustainable circular practices in the textile product life cycle: A comprehensive approach to environmental impact mitigation. *Environmental Challenges*, 16, 100985.
- Edirisinghe, L., Wijayasundara, M., & De Alwis, A. (2022). Waste generation and characteristics in Sri Lankan textile and apparel sector: case study of the Biyagama industrial export processing zone, Sri Lanka. *Nature Environment and Pollution Technology*, 21(2), 697-702.
- Ellen MacArthur Foundation. (2019). CE butterfly diagram.
- Farrukh, A., & Sajjad, A. (2024). Drivers for and barriers to circular economy transition in the textile industry: A developing economy perspective. *Sustainable Development*, 32(6), 7309-7329.
- Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: An evaluation and critical analysis. *Journal of Cleaner Production*, 23, 216-224. doi:10.1016/j.jclepro.2011.07.005
- Ghani, R., & al Hamad, L. (2024). Exploring and overcoming barriers to implementing circular business model for small businesses in Swedish fashion industry. In.
- Goger, A. (2013). The making of a 'business case' for environmental upgrading: Sri Lanka's eco-factories. *Geoforum*, 47, 73-83. doi:10.1016/j.geoforum.2013.03.006
- Gunasekara, A., Neranja, P., Karunarathne, H., Ravihansi, B., Buddhika, A., Wijekoon, W., . . . Sibera, A. (2018). Evolution of waste management practices: A case study of a leading leading apparel company in Sri Lanka.
- Hancock, B., Ockleford, E., & Windridge, K. (2009). *An introduction to qualitative research*. The NIHR RDS EM / YH.
- Jayakodi, S., & Thayaparan, M. (2021). Application of Circular-Economy Concept to Pre-Consumer Apparel Waste Management in Sri Lanka. *Proceedings of the World Conference on Waste Management*,
- Jayasinghe, I., Basnayake, B., Amarathunga, K., & Dissanayake, P. (2010). Environmental conservation efforts in developing textile waste incorporated cement blocks. *Tropical Agricultural Research*, 21(2), 126-133. doi:10.4038/tar.v21i2.2594

- Johansson, E. (2010). Slow fashion- the answer for a sustainable fashion industry?. (Master's thesis, The Swedish School of Textiles). Retrieved from <https://www.researchgate.net/publication/277120413>
- Joint Apparel Association Forum Sri Lanka. (2024). Textile and apparel exports. Retrieved <https://www.srilankaapparel.com/data-center/yearly-performance/>
- Jordeva, S., Tomovska, E., Trajkovic, D., & Zafirova, K. (2015). Current state of pre-consumer apparel waste management in Macedonia. *Fibres & Textiles in Eastern Europe*, 23(1(109)), 13-16. Retrieved from <https://www.researchgate.net/publication/270278896>
- Kirchherr, J., Piscicelli, L., Bour, R., Smit, E. K., Muller, J., Truijens, A. H., & Hekkert, M. (2018). Barriers to the circular economy: Evidence from the European Union (EU). *Ecological Economics*, 150, 264-272. doi:10.1016/j.ecolecon.2018.04.028
- Koszevska, M. (2018). Circular economy - challenges for the textile and clothing industry. *Autex Research Journal*, 18(4), 337-347. doi:10.1515/aut-2018-0023
- Kumar, V., Sezersan, I., Reyes, J. A., Gonzalez, E. D., & Al-shboul, M. A. (2019). Circular economy in the manufacturing sector: Benefits, opportunities and barriers. *Management Decision*, 57(4), 1-21. doi:10.1108/MD-09-2018-1070
- Larney, M., & Aardt, A. V. (2010). Case study: Apparel industry waste management: a focus on recycling in South Africa. *Waste Management & Research*, 28, 36-43. doi:10.1177/0734242X09338729
- Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, 115, 36-51. doi:10.1016/j.jclepro.2015.12.042
- Mahendrarajah, G., & Thayaparan, M. (2020). Incorporation of circular economy concept to the apparel industry: literature review. <https://doi.org/10.31705/FARU.2020.13>
- Mulla, S. S. (2019, February 3). 3 R's of sustainability in textiles. Retrieved from <https://textilelearner.blogspot.com/2019/02/3-rs-of-sustainability-in-textiles.html>
- Rizos, V., Behrens, A., Drabik, E., Rinaldi, D., & Tuokko, K. (2018). The Role of Business in the Circular Economy: Markets, Processes and Enabling Policies.
- Sariatli, F. (2017). Linear economy versus circular economy: A comparative and analyzer study for optimization of economy for sustainability. *Visegrad Journal on Bioeconomy and Sustainable Development*, 6(1), 31-34. doi:10.1515/vjbsd-2017-0005
- Sarkar, M. M., Das, K. B., Islam, M. A., & Akter, S. (2019). Green supply chain management practices for green apparel supply chain. *International Journal of Scientific & Engineering Research*, 10(1), 1764-1768.
- Seadon, K. J. (2010). Sustainable waste management systems. *Journal of cleaner products*, 18(16-17), 1639-1651. doi:10.1016/j.jclepro.2010.07.009
- Šebo, J., Šebová, M., & Palcic, I. (2021). Implementation of Circular Economy Technologies: An Empirical Study of Slovak and Slovenian Manufacturing Companies. *Sustainability*, 13, 12518. <https://doi.org/10.3390/su132212518>
- Sharma, R., Yadav, V., & Gaur, T. S. (2025). Barriers to adopting circular economy practices in Indian textile industries. *Discover Sustainability*, 6(1), 345.
- Sulochani, R., Jayasinghe, R., Nilmini, A., & Priyadarshana, G. (2020). Transitioning Towards a Circular Textile Economy: Sharing Knowledge and Best Practices from Sri Lanka. *Proceedings of International Forestry and Environment Symposium*,
- Swami, C., Shakya, A., Roy, R., & Sidha, R. (2016). Integrated waste minimization techniques in apparel design: A sustainable perspective (Doctral dissertation). Agra. Retrieved from <http://shodh.inflibnet.ac.in:8080/jspui/bitstream/123456789/4274/1/synopsis.pdf>
- Tomovska, E., Jordeva, S., Trajkovic, D., & Zafirova, K. (2016). Attitudes towards managing post-industrial apparel cuttings waste. *The Journal of the Textile Institute*, 1-8. doi:10.1080/00405000.2016.1160764
- Wijewansa, A. S., Tennakoon, G., Waidyasekara, K., & Ekanayake, B. (2021). Implementation of circular economy principles during pre-construction stage: the case of Sri Lanka. *Built Environment Project and Asset Management*, 11(4), 750-766.
- Yin, R. K. (2019). Case study research design and methods (5th ed.). Thousand Oaks: Sage publications.

- Zamani, B., Peters, G., Rydberg, T., & Svanstrom, M. (2014). A carbon footprint of textile recycling: A case study in sweden. *Journal of Industrial Ecology*, 19(4), 676-687. doi:10.1111/jiec.12208\
- Zoumpalova, T., Jonášová, S. K., & Moldan, B. (2023). Barriers to the circular economy in textile industry: a case study of the Czech Republic. *Waste Forum*.

GLOBAL RESEARCH TREND EVOLUTION IN OCCUPATIONAL HEALTH AND SAFETY OVER THE PAST DECADE

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Abstract. Occupational health and safety (OHS) is crucial for any organisation to create a safe work environment and protect employees' well-being. The field of OHS has evolved significantly over the past decade, with pandemic distractions, evolving labour trends and technological advancements. Thus, this study focuses on investigating the evolution and key trends in scholarly publications related to occupational health and safety. Accordingly, a Scopus-based systematic review was conducted to analyse the journal articles related to this field. As the key outputs of this research, leading countries, authors and journals were identified related to this field. Further, this research reviewed the evolution of research themes and trends over the past decade as a basis for future research. The outcomes of the analysis reveal that the number of publications related to the OHS has increased consistently. Further, the United States was identified as the leading country, while Miyamoto T. was identified as the leading author of the field. According to the Scopus database, "International Journal of Environmental Research and Public Health" was recognised as the prominent journal which has the highest number of publications. Heeding research themes and trends, analysis reveals that the current trends are moving towards an integration between novel technology, such as artificial intelligence, with occupational health and safety in recent years. This study provides a comprehensive understanding of global OHS research trends over the last decade by highlighting the evolution of themes and key contributors in this field.

Keywords. Occupational Health and Safety (OHS), Workplace Health, Workplace Safety, Trends Over Year

1. Introduction

Occupational health and safety (OHS) is increasingly recognized as crucial for organizational performance, worker well-being, and social sustainability (Cottam, 2024; Kavouras et al., 2022). It encompasses the physical, psychological, and social well-being of workers, and core values contributes to promote health across global workplaces (Guillemin & Nicholas, 2022). OHS is crucial for functions of organizations and employee well-being, particularly for workers who face unique vulnerabilities (de Cieri & Lazarova, 2020). Effective OHS implementation requires to build up a positive safety culture, encouraging knowledge transfer across organizations, and promoting learning from incidents and near-misses (Duryan et al., 2020). Even though the implementation of OHS management systems has developed over time, the challenges persist, particularly in developing countries (Johanes et al., 2022).

Although, OHS initiatives significantly reduce absenteeism and healthcare costs for companies, annually, millions of work-related fatalities and accidents still occur (Lu, 2022). The primary purpose of occupational health and safety on avoiding sickness and illness has been shifted to a holistic view of considering the positive impact of work on an individual's health (Guillemin & Nicholas, 2022). Implementation of OHS measures, such as creating safe work environments and reducing work-related accidents and diseases, can significantly impact employee productivity (Hartati et al., 2024). The interventions include workplace inspections, enforcement activities, training, campaigns, and the introduction of technical devices are effective means to improve the working environment. OHS Legislative and regulatory policies and regulations have been contributed to reduce injuries and fatalities (Andersen et al., 2019). International standards, such as ISO 45001, provide guidance for effective OH&S management (Cottam, 2024).

Occupational health and safety (OHS) has evolved significantly over the past few decades. Lindholm et al. (2024) stated that, research areas have shifted from focusing on traditional risks to addressing new and emerging risks related to changing work patterns, workforce

demographics, climate change, new materials, viruses and technological advancements. Risk assessment and management at the organizational level remain central, while individual-level research has expanded from physiological issues to mental health and quality of life (Wang et al., 2020). ISO standards for occupational health and safety (OHS) have evolved significantly in response to industry accidents and health concerns. The introduction of ISO 45001 in 2018 marked a major development, followed by guidance standards addressing psychological health, infectious diseases, and pandemic-related issues (Cottam et al., 2024). Digitalization of work has led to non-routine, complex tasks and job redesign, potentially impacting workers' well-being and inducing work-related stress (Akpa, 2018). Artificial intelligence, robotics and other digital technologies is revolutionizing OHS by offering solutions to responsive approaches to work safety and ergonomics. These improvements will reshape the workplace safety landscape, with the goal of making workers' environments safer and healthier (Koh & Tan, 2024).

According to Akpa (2018), proactive measures and sustainable control strategies are crucial for ensuring safe and healthy workplaces in the future. The COVID-19 pandemic has further highlighted the importance of OHS measures in protecting workers' health and well-being (Lu, 2022). Johanes et al. (2022) revealed that, future research will identify the challenges associated with the deployment of OSHMSs and their causal factors, establishing a foundation to enhance OSHMS acceptance in the workplace. These studies highlight the importance of continued research in OHS to address evolving workplace challenges and leverage new technologies for improved safety outcomes.

Recent reviews have examined the evolution of OHS research from 1930 to 2016, highlighting risk assessment, prevention, and accident analysis as key focus areas (Sánchez et al., 2017). From 1960, there was an obvious trend of increasing number of OHS publications and it reached to the peak in 2018. Numerous studies have explored various aspects of OHS such as the technology implications, mental well-being, and emerging risks (Wang et al., 2020). Febriyani et al. (2023), conducted a bibliometric analysis of OHS literature with related to the dynamic system from 2012–2022. However, the majority of OSH studies has concentrated on micromanagement, with few systematic and detailed literature reviews and evolutionary processes based on an evolutionary perspective (Wang et al., 2020). Also, these studies reveal that there is still room for improvement in understanding the effectiveness of OHS intervention and support for concrete guidance (Vitrano & Micheli, 2024).

Considering this gap of analyzing the evolution of OHS research in recent past years and this space for more improvements, this study will aim to identify the evolution and trends of key publications in the field of occupational health and safety in past ten years. Through identifying OSH research evolution this research contributes to the global OSH discourse and basis for future research.

2. Methodology

Over the last two decades, bibliometric analysis has emerged as a widely used quantitative research methodology for identifying key publications within a particular research field (Zupic & Čater, 2015). Accordingly, a bibliometric analysis of the literature was conducted as the primary research methodology to explore global research patterns in the field of OHS. For the analysis the Scopus database was selected as the sole source for literature retrieval because it is one of the largest and most comprehensive abstract and citation databases of peer-reviewed literature. Accordingly, the systematic review of literature indexed in the Scopus database was conducted, focusing on the publications from 2015 to 2024. This ten-year time frame aligns with the common practice in systematic reviews of limiting literature searches to the past decade, which helps to ensure the inclusion of recent interventions and maintain the relevance (Phokontsi et al., 2020).

To ensure the retrieval of relevant and high-quality publications, a title-based search strategy was developed using a combination of commonly used OHS terms. The search criteria were determined, including "occupational safety", "occupational health", "occupational health and safety", "occupational safety and health", "workplace safety", "workplace health", "workplace safety and health" and "workplace health and safety". The search was conducted using the search string [TITLE ("occupational safety" OR "occupational health" OR "occupational health and safety" OR "occupational safety and health" OR "workplace safety" OR "workplace health" OR "workplace safety and health" OR "workplace health and safety")]. Further, publications were refined using the filters available on Scopus's search tool: (i) DOCUMENT TYPES=(Articles) AND (ii) SOURCE TYPE=(Journals) (iii) LANGUAGE =(English) to recognise the high-quality publications. Accordingly, 3282 journal articles were selected as the basis for bibliometric analysis.

The selected publications were analysed using several bibliometric analysis techniques: the co-occurrence of words and countries, leading countries, authors and journals and the evolution of publications over time in the field of occupational safety and health. Further, Scopus analysis tools and VOS viewer software were used for generating the graphical representations of the analysis.

3. Results

3.1. LEADING COUNTRIES PUBLISHED ON OCCUPATIONAL HEALTH AND SAFETY

A co-authorship analysis was conducted using VOS viewer, with countries as the unit of analysis and the full counting method applied. This approach allowed to examine the international collaboration patterns in occupational health and safety research. In the resulting visual map in Figure 2, larger nodes represent the countries with a higher number of co-authored publications. Considering the largest node of the visual map, United States, indicates their central role in global research collaboration. Other countries with large nodes included the United Kingdom, China, Australia, and Canada. These nodes highlight their contributions and active involvement in the OHS field.

Although, the nodes represent the countries such as South Korea, Israel, Ukraine, Slovenia are linked to the cluster, they are positioned away from the central cluster in VOS viewer visual map in Figure 1. These countries conduct less frequent OHS related studies and having a less collaboration with centrally clustered countries.

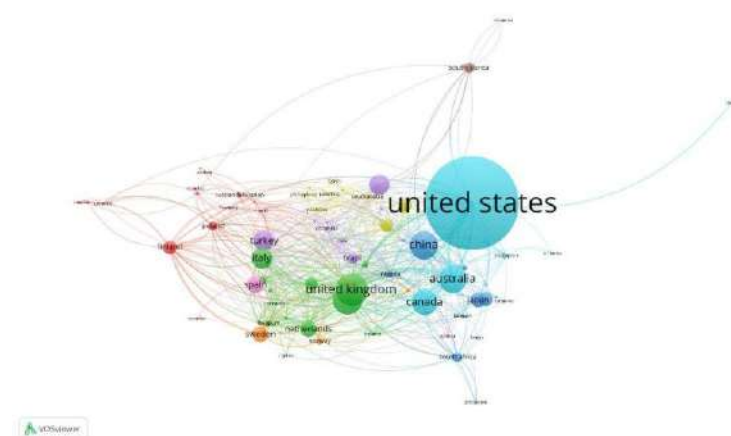


Figure 1: Leading Countries

The bar chart in Figure 2 represents a complementary country wise analysis conducted using Scopus data. In this visualization, countries are displayed along the Y-axis, while the X-axis indicates the number of published documents. This also represents the United States as the country which published the highest number of OHS related publications. Following that, United Kingdom. Germany, China, and Australia presented closely aligned publication counts, reflecting their active research involvement and growing contribution to the domain.

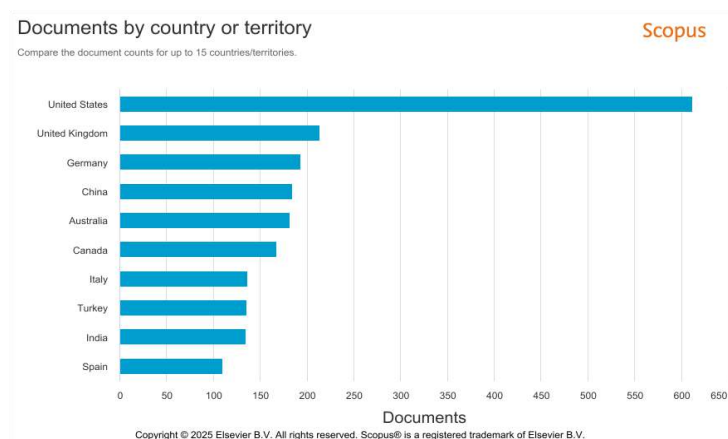


Figure 2: Documents by Countries

3.2. EVOLUTION OF THE NUMBER OF JOURNAL ARTICLES PUBLISHED ON OCCUPATIONAL HEALTH AND SAFETY

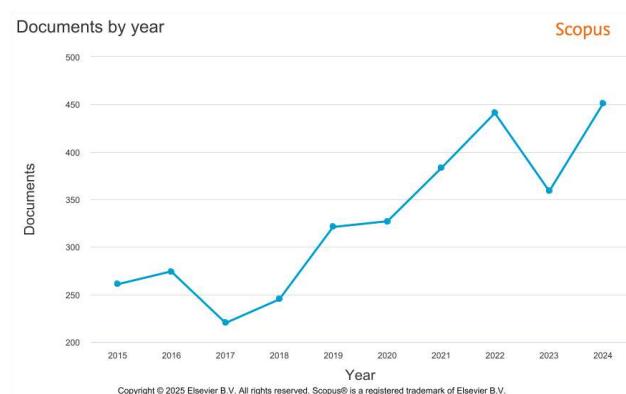


Figure 3: Documents by Years

Figure 3 illustrates the evolution of the number of publications in the field of occupational health and safety from 2015 to 2024. Upon the analysis, the total number of publications within this period is 3282 and the graph reveals an overall upward trajectory of publication fluctuations, which varied from nearly 200 to 500 publications. This indicates a steady growth of publications, reflecting a rising of research interest in OHS research domain. Based on the Scopus database, 261, 274, and 220 publications were identified in 2015, 2016, and 2017 respectively. This illustrates that the number of publications remained relatively stable, with a slight increase in 2016, followed by a decline in 2017. However, again the graph shows a consistent growth in the number of publications from 2018 onwards to 2022. Notably, the graph shows a significant surge in publications from 2020, may be attributed to the global pandemic situations which brought heightened attention to OHS field. Nevertheless, the number of publications related to the field of occupational health and safety decreased to 359 in 2023. Even though this decline was

followed by a strong rebound in 2024, it returned to the previous peak levels with 451 publications.

Overall, the graph indicates an upward trajectory in the number of publications related to the field of occupational health and safety, conveying the sustained scholarly interest in this subject area. Notably, the dramatic escalation in publications within 2020 – 2022 could correlate with the COVID-19 pandemic and its aftermath. In conclusion, this graph shows the occupational health and safety as a dynamically evolving field with the increment of scholarly publications.

3.3. LEADING AUTHORS PUBLISHED ON OCCUPATIONAL HEALTH AND SAFETY

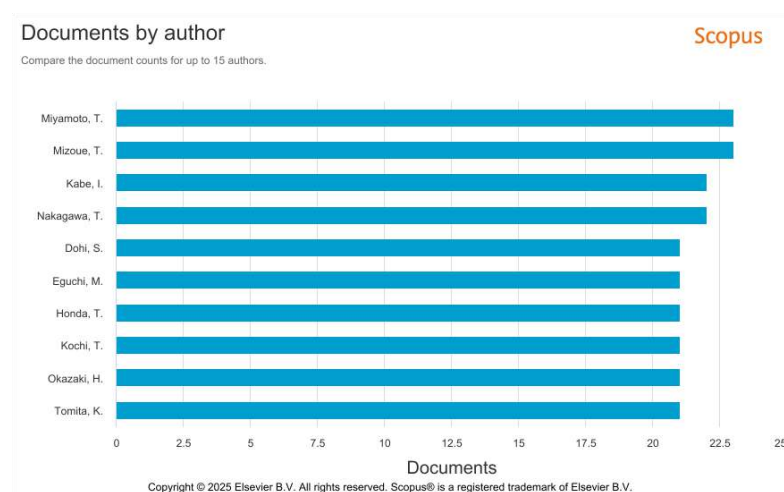


Figure 4: Documents by Authors

Based on the analysis, various researchers have contributed significantly to the field of occupational safety and health across different subject areas. Accordingly, Figure 4 highlights the most influential authors who have extensively published research in the field based on data from Scopus spanning the years 2015 to 2024.

As the graph interprets, the most prolific author in this domain is Miyamoto T. and Mizoue T., who have contributed more than twenty-two (22) publications to Scopus within this period. Following closely, Kabe I., Nakagawa T., Dohi S., Eguchi M., Honda T., Koch T., Okazaki H. and Tomita K have also given a significant contribution towards the field of occupational health and safety with more than twenty (20) publications each. Accordingly, the analysis results elaborate that there is a noticeable concentration of prolific authors who worked on a wide range of subtopics in this research domain. Further, it represents the strong and sustained research focus and long-term commitment to the OHS field. Understanding the leading authors and author networks can provide valuable insights for literature reviews and future research in this field.

3.4. LEADING JOURNALS PUBLISHED ON OCCUPATIONAL HEALTH AND SAFETY

The Figure 5 shows the comparative overview of the prominent journals and their publication trends in the field of occupational safety and health from 2015 to 2024. According to the analysis, BMS Public Health, Safety Science, Journal of Occupational and Environmental Medicine, International Journal of Occupational Safety and Ergonomics, and International Journal of Environmental Research and Public Health are the leading journals in this field. 'International Journal of Environmental Research and Public Health' was the prominent journal that published the highest number of articles related to occupational health and safety. In addition to that, the

'Safety Science' journal also has a relatively high number of publications reflecting a significant contribution to the field of OHS.

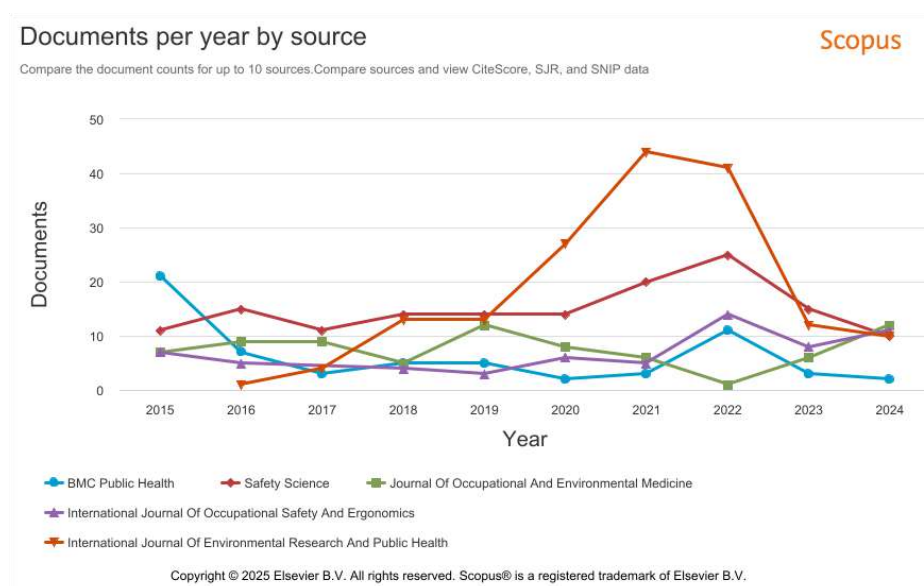


Figure 5: Documents per Year by Source

Heeding the fluctuations of publications, the number of publications has remained relatively stable across all the journals from 2015 to 2018. In the aftermath, a notable uptrend is observed from 2019 onwards, in 'International Journal of Environmental Research and Public Health', 'Safety Science', and 'International Journal of Occupational Safety and Ergonomics'. Accordingly, the 'International Journal of Environmental Research and Public Health' has reached its peak in 2021 with nearly 50 publications, while 'Safety Science', 'International Journal of Occupational Safety and Ergonomics' and 'BMS Public Health' journals have reached their peaks in 2022.

3.5. CO-OCCURRENCE ANALYSIS OF KEYWORDS IN OCCUPATIONAL HEALTH AND SAFETY PUBLICATIONS

Co-occurrence analysis of the key words was conducted using VOS viewer to examine the evolution and emerging trends within the field of occupational health and safety over the past decade. The unit of analysis was selected as the author keywords to identify the frequently co-occurring terms used by authors in OHS articles. By setting the minimum number of key word occurrence to 10, a total of 160 keywords were identified initially for the analysis. However, search strings used during the initial data retrieval process were excluded from the final analysis to ensure relevance and accuracy and final keyword count is considered as 115.

The visual mapping generated through VOS viewer in Figure 6 enables to highlight the dominant research themes and their interrelationships between key topics. Co-occurrence analysis generated 09 thematic clusters in different colors. Frequently appeared keywords are close together in a cluster. The keywords with the highest occurrence are represented by larger nodes, indicating their central importance in the field. Among these, the most frequently occurring keywords included "workplace health promotion", "health promotion", "covid-19" and "risk assessment". In addition, "occupational health services", "construction", "mental health", "risk management" are other key study areas captured with high frequent in the clusters. Table 1 illustrates the keyword clustering results across nine thematic clusters highlighting diverse workplace health and safety concerns.



Cluster1 (20Items)	Cluster 2 (19Items)	Cluster 3 (14Items)	Cluster 4 (13Items)	Cluster 5 (12Items)	Cluster 6 (11Items)	Cluster 7 (9Items)	Cluster 8 (9Items)	Cluster 9 (8Items)
Absenteeism	Accidents	Attitude	Artificial intelligence	Burnout	Climate change	Exercise	Corporate social responsibility	Covid-19
Depression	Construction	Barriers	Audit	Covid-19 pandemic	Exposure	Health education		Employee health
Disability	Construction industry	Compliance	Accident	Effectiveness	Hazards	Health promotion	Leading indicators	Epidemiology
Employment	Construction safety	Education	Healthcare workers	Job satisfaction	Health hazards		Occupational exposure	Mental health
Gender	Construction workers	Healthcare workers	Machine learning	Occupational hazards	Injury	Injury prevention		Occupational & industrial medicine
Occupational disease	Ergonomics	Healthcare	Mining	Occupational hazards	Low back pain	Obesity	Occupational health nursing	Pandemic
Occupational health care	Injuries	Knowledge	Occupational accidents	Participation	Occupational health hazard	Occupational health nursing	Occupational risk	Public health
	Leadership	Psychosocial risks		Productivity			Prevention	
	Legislation							

Occupational health service	Musculoskeletal disorder	Rational emotive occupational coaching	Occupational diseases	Reliability	Personal protective equipment	Occupational injuries	Risk management	Sars-cov-2
Occupational health services	Risk analysis	Regulation	Quality of life	Well-being	Risk factors	Physical activity	Safety management	
Presentism	Risk assessment	Safety culture	Sustainability	Work engagement	Stress	Self-efficacy	Working conditions	
Primary health care	Risk perception	Teachers	Sustainable development	Workplace health promotion	Training			
Process evaluation	Safety climate	Work stress	Workplace violence					
Rehabilitation	Safety performance	Work-related stress						
Return to work	Total worker health							
Screening	Virtual reality							
Sick leave	Exercise							
Sickness								
Absence								
Surveillance								
Work ability								

3.5.1 Cluster 1- Psychosocial Rehabilitation and Return-to-Work Support

This cluster is focused on psychosocial aspects of occupational health in relation to absenteeism, mental health, and disability. Research in this area often linked to return-to-work programs and psychosocial support in post-injury rehabilitation. There is a move towards a more holistic approach, transitioning from risk assessment to proactive management of psychosocial risks and opportunities (Di Tecco et al., 2023).

3.5.2 Cluster 2- Occupational Risk Prevention in Industries

This cluster is focused on accidents, injuries, and construction industry risks, often tied to manual labor sectors where ergonomics and leadership play a role in preventing workplace harm. Also,

this cluster indicate more studies on legislation and safety climate which is required to prevent risks in high-hazard industries that are traditionally prone to workplace harm.

3.5.3 Cluster 3- Safety Education and Organizational Compliance

Keywords in cluster 3 represent the health care education, safety culture, in workplaces and highlight the different barriers for promoting education such as attitudes, work stress, compliance and regulations. Wang et al. (2020) also emphasised that at the organizational level risk assessment and management remain consistent research hotspots, while safety culture, mental health, and quality of life have emerged as core topics in recent years.

3.5.4. Cluster 4- Digital Transformation in Occupational Health and Safety

Technological integration in OHS, including Artificial intelligence, machine learning, and data-driven audits for hazard prediction, showing a growing interest in digital solutions. Studies in this area investigate the use of predictive tools such as machine learning and digital audits to enhance hazard identification and prevention, pointing to a shift toward proactive, tech-driven safety management.

3.5.5. Cluster 5- Covid -19 pandemic and Resilience

This cluster is centred around Covid-19 pandemic and explored burnout, job satisfaction, and work engagement, highlighting the need for psychological resilience among healthcare workers. Considering the resilience, it focuses on productivity, promoting workplace health, well-being and work engagement to meet the health crisis.

3.5.6. Cluster 6 - Environmental Hazards and Protective Strategies

This cluster explored environmental hazards, such as climate change and toxic exposure, relevant to radiology units and nuclear plant safety. These include traditional risks like asbestos and crystalline silica, as well as emerging concerns such as nano plastics and the impact (Laurent, 2024). It also emphasised the risk factors of hazards and usage of personal protective equipment in hazard prevention.

3.5.7. Cluster 7- Workplace Health Promotion and Personal Well-being

Here, the focus is on individual health behaviours and health promotion, covering topics like physical activity, stress, and self-efficacy. Exercise, physical activities, obesity prevention are linked to improved physical and mental well-being, reduced absenteeism, and enhanced job performance.

3.5.8. Cluster 8- Governance and Organizational Responsibility in OHS

This cluster highlighted organizational roles, such as corporate social responsibility, safety policies, prevention and risk management. It suggests that organizational commitment and leadership are vital for fostering sustain-able safety cultures.

3.5.9 Cluster 9- Public Health Preparedness and Occupational Medicine

This cluster addressed epidemiological trends and pandemics, especially public health preparedness and occupational medicine. Together, these clusters present a comprehensive view of how OSH research has evolved to address both traditional risks and emerging global health challenges.

3.6. TRENDS IN KEYWORDS IN OCCUPATIONAL HEALTH AND SAFETY PUBLICATIONS

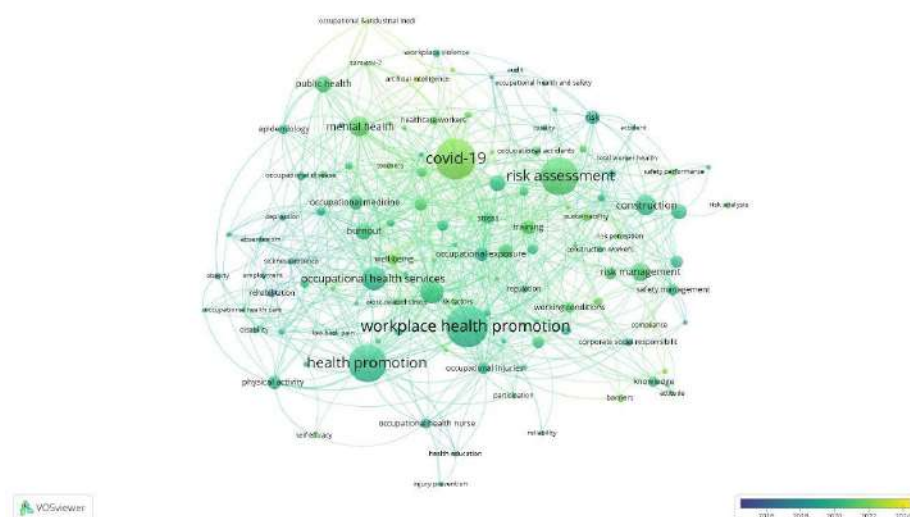


Figure 7: Trends in keywords

The Figure 7 demonstrates the key research themes and their interconnections in the field of occupational health and safety from 2015 to 2024 time period. Here, the colour gradient from blue to yellow indicates the temporal evolution of research trends throughout the time period. Further, node size represents the frequency of keyword occurrence, and the links illustrate the relationships between them.

Accordingly, the graph illustrates that several distinct research clusters and the temporal evolution of their themes. Accordingly, in the initial time phase (2015 – 2018), scholarly focus was laid on the primary occupational safety and health research areas such as “occupational injuries”, “health education”, “disability” and “physical activity. Subsequently, a noticeable shift occurred between 2019 and 2021 towards the psychological aspects of workplace health and safety. Accordingly, the analysis results reveal a significant increase in publications related to “mental health”, “well-being” and “occupational stress” in this time period. Further, these themes are slightly interconnected with various research domains including “occupational health services” and “healthcare workers”. Afterwards, “Covid-19” emerged as an extensively researched domain reflecting its global disruptive influence. Further, this is closely linked with keywords such as “risk assessment”, “healthcare workers”, “occupational exposure” and “public health”.

The graph reflects that research areas have shifted towards areas such as “risk management”, “safety performance”, “construction”, “compliance” and “sustainability” in recent past years (2022-2023). Following this, “artificial intelligence”, “telemedicine”, “corporate social responsibility” and “technological innovation” emerged as the contemporary research areas. This dynamic progression of research themes highlights the adaptability of occupational health and safety to the global needs. Further, it has evolved in response to emerging workplace challenges and societal needs, providing a roadmap for potential future areas of exploration.

4. Conclusion

This study provides a comprehensive overview of the evolution and research trends in the field of Occupational Health and Safety (OHS) over the past decade (2015–2024) through a systematic review and bibliometric analysis using Scopus data and VOSviewer. The findings highlight how OHS research has adapted to global challenges and shifting workplace priorities over the past decade. In the earlier period (2015–2018), research primarily focused on traditional OHS topics such as occupational injuries, health education, physical activity, and

disability. A notable transition occurred between 2019 and 2021, with increasing scholarly focus on mental health, well-being, and occupational stress marking a shift towards psychosocial dimensions of workplace health. The COVID-19 pandemic (2020–2022) then significantly leads to increase the attention towards risk assessment, occupational exposure, healthcare workers' safety, and public health preparedness. The author keyword co-occurrence analysis reveals that, key thematic research areas in workplace health promotion, COVID-19, risk assessment, mental health, and occupational health services. In recent years, new research themes have emerged. including digital transformation in OHS with applications of artificial intelligence, machine learning, corporate social responsibility, sustainability, and technological innovation. These trends signal a growing shift toward data-driven digitalised approaches in safety management.

In country wise contribution to the OHS researches, the United States is identified as the leading contributor, followed by the United Kingdom, China, Australia, and Canada, indicating their lead role in global OHS research. In terms of scholarly contributions, authors such as Miyamoto T. and Mizoue T. identified with over 22 publications each during the review period. The International Journal of Environmental Research and Public Health was identified as the leading journal, with its highest number of publications in 2021. Considering the trend analysis, there is a steady increase in OHS-related publications. A significant surge was observed between 2020 and 2022, likely influenced by the global impact of the COVID-19 pandemic. Although there was a slight drop in 2023, publications have increased again in 2024. This implies the continued interest and relevance in the field. This study encounters certain limitations as it solely based on Scopus-indexed publications and limited to author keywords, which may exclude relevant studies from other databases. Theoretically, this study contributes to the conceptual expansion of OHS by integrating psychosocial, technological, and environmental perspectives. Practically, it offers actionable insights for designing future OHS policies, workforce training, digital safety tools, and organizational interventions aligned with emerging risks and societal expectations. Overall, this study highlights the dynamic growth of OHS research in recent years, identifies key contributors and themes, and provides a foundation for future studies, policy development and improving workplace health and safety worldwide.

5. References

- Akpa, P. N. (2018). PW 0348 Innovative solutions on the effects of emerging risks related to occupational safety and health arising from digitalization of work. *Injury Prevention*, 24, A208–A209. <https://api.semanticscholar.org/CorpusID:81385146>
- Andersen, J. H., Malmros, P., Ebbenhøj, N. E., Flachs, E. M., Bengtsen, E., & Bonde, J. P. (2019). Systematic literature review on the effects of occupational safety and health (OSH) interventions at the workplace. In *Scandinavian Journal of Work, Environment and Health* (Vol. 45, Issue 2, pp. 103–113). Nordic Association of Occupational Safety and Health. <https://doi.org/10.5271/sjweh.3775>
- Cottam, M. (2024). SS09-01 Building global consensus for occupational health and safety (OH&S) management through ISO standardization - Part 1. *Occupational Medicine*, 74. <https://doi.org/10.1093/occmed/kqae023.0092>
- Cottam, M., Humphreys, L., & Swingewood, S. (2024). SPL28 The Contribution of ISO standards to the effective management of Occupational Health and Safety, and how you can contribute to their development. *Occupational Medicine*, 74. <https://doi.org/10.1093/occmed/kqae023.0039>
- de Cieri, H., & Lazarova, M. B. (2020). “Your health and safety is of utmost importance to us”: A review of research on the occupational health and safety of international employees. *Human Resource Management Review*, 100790. <https://api.semanticscholar.org/CorpusID:226342404>
- Di Tecco, C., Persechino, B., & Iavicoli, S. (2023). Psychosocial Risks in the Changing World of Work: Moving from the Risk Assessment Culture to the Management of Opportunities. *La Medicina Del Lavoro*, 114(2), e2023013. <https://doi.org/10.23749/mdl.v114i2.14362>
- Duryan, M., Smyth, H., Roberts, A., Rowlinson, S., & Sherratt, F. (2020). Knowledge Transfer for Occupational Health and Safety: Cultivating Health and Safety Learning Culture in Construction Firms.

- Febiyani, A., Suhardi, B., Laksono, P., & Prastawa, H. (2023). Bibliometric Analysis of Occupational Health and Safety in Relation to Dynamic System. <https://doi.org/10.3233/ATDE230078>
- Guillemin, M., & Nicholas, R. (2022). Core Values at Work — Essential Elements of a Healthy Workplace. *International Journal of Environmental Research and Public Health (IJERPH)*, 19, 12505. <https://doi.org/10.3390/ijerph191912505>
- Hartati, S., Nurdin, I., & Galeria, B. (2024). Implementation of occupational safety and health (OSH) in preventing employee work accidents at the regional disaster management agency (BPDP) Purworejo regency. *CosmoGov*. <https://api.semanticscholar.org/CorpusID:271346306>
- Johanes, M., Mark, M., & Steven, J. (2022). A global review of implementation of occupational safety and health management systems for the period 1970–2020. *International Journal of Occupational Safety and Ergonomics*, 29, 821–836. <https://api.semanticscholar.org/CorpusID:249094933>
- Kavouras, S., Vardopoulos, I., Mitoula, R., Zorpas, A. A., & Kaldis, P. (2022). Occupational Health and Safety Scope Significance in Achieving Sustainability. *Sustainability*, 14(4). <https://doi.org/10.3390/su14042424>
- Koh, D., & Tan, A. (2024). Applications and Impact of Industry 4.0: Technological Innovations in Occupational Safety and Health. *Safety and Health at Work*, 15(4), 379–381. <https://doi.org/https://doi.org/10.1016/j.shaw.2024.09.001>
- Laurent, L. (2024). SPL25 RESEARCH AND OCCUPATIONAL HEALTH ACTIVITIES WITHIN THE PEROSH NETWORK. *Occupational Medicine*, 74(Supplement_1), 0–0. <https://doi.org/10.1093/occmed/kqae023.0036>
- Lindholm, M., Reiman, A., & Tappura, S. (2024). The evolution of new and emerging occupational health and safety risks: A qualitative review. *Work (Reading, Mass.)*, 79, 503–521. <https://api.semanticscholar.org/CorpusID:269564783>
- Lu, J. (2022). Occupational Safety and Health amid the Global Pandemic. *Acta Medica Philippina*, 56(1). <https://doi.org/https://doi.org/10.47895/amp.v56i1.5023>
- Phokontsi, L., Mweetwa, L. L., Mweetwa, L., Tlhoiwe, T., Muya, C. K., Mudawarima, T., Silumesii, L., Chisenge, S., & Phillips, J. (2020). A Systematic Review of the Role of Physiotherapy Interventions in Palliative Care. <https://doi.org/10.20944/preprints202004.0519.v1>
- Sánchez, F. A. S., Peláez, G. I. C., & Alís, J. C. (2017). Occupational safety and health in construction: a review of applications and trends. *Industrial Health*, 55, 210–218. <https://api.semanticscholar.org/CorpusID:203799266>
- Vitrano, G., & Micheli, G. J. L. (2024). Effectiveness of Occupational Safety and Health interventions: a long way to go. In *Frontiers in Public Health* (Vol. 12). Frontiers Media SA. <https://doi.org/10.3389/fpubh.2024.1292692>
- Wang, Y., Chen, H., Liu, B., Yang, M., & Long, Q. (2020). A systematic review on the research progress and evolving trends of occupational health and safety management: A bibliometric analysis of mapping knowledge domains. *Frontiers in Public Health*, 8. <https://doi.org/10.3389/fpubh.2020.00081>
- Zupic, I., & Čater, T. (2015). Bibliometric Methods in Management and Organization. *Organizational Research Methods*, 18(3), 429–472. <https://doi.org/10.1177/1094428114562629>

MANAGING BARRIERS AFFECTING TO IMPLEMENT SUSTAINABLE CONSTRUCTION WOOD WASTE MANAGEMENT IN SRI LANKA

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Abstract. The increasing use of wood in the construction industry in developing countries has led to significant environmental, economic, and health related challenges, thereby highlighting the need for sustainable construction wood waste management. In developing countries, sustainable construction wood waste management cannot be implemented effectively due to different barriers such as financial barriers, technical barriers, knowledge barriers, institutional barriers, and socio-cultural barriers. This study aimed to identify and address the key barriers to implementing sustainable construction wood waste management in Sri Lanka and to propose suitable strategies for overcoming these challenges. The study used a qualitative approach, and the required data was collected through semi-structured interviews. The findings were revealed that three main conventional practices used in Sri Lankan construction industry to manage wood waste such as open dumping, landfilling, and incineration, whereas there are few sustainable practices also used in Sri Lankan construction industry to manage wood waste based on the findings such as recycling, reuse, use as by-product, and use for energy recovering. Overall applicability of sustainable practices to manage construction wood waste is very low rate in Sri Lanka due to existing barriers as financial barriers, technical barriers, knowledge barriers, institutional barriers, and socio-cultural barriers. The study findings revealed five barriers in Sri Lanka under each type of barrier, except socio-cultural barriers. Financial barrier is identified as a major barrier affecting to implementation of sustainable construction wood waste management in Sri Lanka, and it leads to the emergence of other types of barriers. Therefore, this study proposed suitable effective strategies to manage each type of barrier affecting to implementation of sustainable construction wood waste management in Sri Lanka.

Keywords: Wood Waste Management, Sustainability, Construction Industry, Types of Barriers, Effective Strategies

1. Introduction

Nowadays, sustainable practices have become an essential requirement for disposing of construction and demolition waste (Sivashanmugam, et al., 2024). This is because construction and demolition waste contribute to numerous adverse impacts on the environment, such as increased greenhouse gas emissions, high energy consumption, increased public issues and the release of various harmful contaminants into the environment (Chen, et al., 2021). Among different types of construction and demolition waste, wood waste has emerged as a major category that requires sustainable management and disposal due to its adverse impacts on the environment and the high volume generated in the construction industry (Jahan, et al., 2022). Sustainable construction wood waste management offers both environmental and economic benefits, including reduced greenhouse gas emissions, enhanced environmental sustainability, compliance with environmental regulations, improved corporate image, and the potential for electricity generation, so on (Zhu & Feng, 2024).

Nevertheless, the implementation of sustainable practices in construction wood waste management is a significant challenge in developing countries such as Sri Lanka, due to the presence of different barriers (Kozlovská & Spišáková, 2013; Victar & Waidyasekara, 2023). These barriers can be categorised into several categories, such as technical barriers, political or legal barriers, knowledge/ awareness barriers, financial barriers, managerial barriers, and social and cultural barriers (Al-Otaibi, et al., 2022; Kozlovská & Spišáková, 2013). Failure to address these barriers can lead to substantial economic, environmental and public health challenges within the country (Adhikari & Ozarska, 2018).

As a developing country, Sri Lankan construction industry has not given adequate attention to sustainable practices in managing construction wood waste (Victar & Waidyasekara, 2023). Most

existing wood waste management practices are based on conventional methods, which include open dumping, landfilling, and incineration (Bimsara, et al., 2024). These practices have led to increased costs in waste management and greater land area requirements for landfilling. Consequently, professionals involved in managing construction and demolition waste face significant challenges in effectively handling wood waste. The implementation of sustainable construction wood waste management has been identified in global studies as an effective solution to mitigate such issues (Zhu & Feng, 2024). However, in the Sri Lankan context, the adoption of these sustainable practices remains a challenge due to the presence of various barriers. Furthermore, studies, Bimsara, et al., (2024) and Victor and Waidyasekara (2023) carried out in the Sri Lankan context also only focused on other types of construction and demolition wastes, not focused on construction wood waste management. Thus, to manage the barriers to implementing sustainable construction wood waste management, the investigation of suitable strategies will be essential in the Sri Lankan context. Therefore, the aim of this study was to manage barriers to implementing sustainable wood waste management in Sri Lanka by proposing suitable strategies.

2. Literature Review

2.1 OVERVIEW OF CONSTRUCTION WOOD WASTE

Wood waste can be generated from different sources, including municipal, commercial, industrial and construction sectors (Somer & Alkhayat, 2024). Amongst, construction sector is placed in a significant position in generating wood waste as the wood waste has become the second largest component of construction and demolition waste, which contributes approximately 20%-30% of total construction and demolition waste (Jahan, et al., 2022). Usually, construction wood waste refers to wood materials discarded during the construction and demolition of the building (Somer & Alkhayat, 2024). The authors further stated that construction wood waste includes offcuts, sawdust, pallets, packaging, and wood from demolished structures. However, most of the wood waste is mixed with many other construction materials, which makes the separation of them more time consuming and intensive tasks (Kern, et al., 2018).

Improper construction wood waste disposal causes adverse impacts on the environment, economy and human health (Azambuja, et al., 2018). When improperly managed, construction wood waste often ends up in landfills, leading to methane emissions as it decomposes, a potent greenhouse gas that exacerbates climate change (Chen, et al., 2021). Furthermore, improper construction and wood waste management lead to landfill overcrowding and deforestation (Adhikari & Ozarska, 2018). Economically, the inefficient use of wood materials increases construction costs and squanders valuable resources that could be repurposed (Bimsara, et al., 2024). Furthermore, treated or painted wood waste may leach toxic chemicals into soil and water, posing risks to ecosystems and human health (Al-Otaibi, et al., 2022). Hence, addressing these adverse impacts requires the integration of sustainable practices with construction wood waste management.

2.2 INTEGRATION OF SUSTAINABLE PRACTICES WITH CONSTRUCTION WOOD WASTE MANAGEMENT

Integrating sustainable practices into the construction wood waste management is essential for mitigating adverse environmental impacts and improving resource efficiency (Al-Otaibi, et al., 2022). This can be approached through waste reduction, recycling and reuse of wood waste during the construction and demolition process (Azambuja, et al., 2018). Strategies including designing for deconstruction, using modular construction methods, and ensuring accurate material estimation can significantly lower wood waste production (Hossain & Poon, 2018). Additionally, sorting wood waste on-site makes it easier to recycle or repurpose, turning scraps into mulch, bioenergy, or composite wood products (Adhikari & Ozarska, 2018). Utilizing

reclaimed wood in new construction not only reduces the need for new materials but also preserves the embodied energy of previously used wood (Jahan, et al., 2022). Government and organizations can also help by executing effective policies, providing incentives, and creating recycling facilities for construction wood waste management. By adopting these sustainable practices, the construction industry can significantly contribute to environmental conservation, resource management, and the development of a circular economy through sustainable construction wood waste management (Jahan, et al., 2022). However, it is not an easy achievement in developing countries like Sri Lanka due to different types of barriers. Thus, identification of barriers to implement sustainable construction wood waste management is essential to achieve its success.

2.3 BARRIERS TO IMPLEMENTING SUSTAINABLE CONSTRUCTION WOOD WASTE MANAGEMENT

The review of literature indicates that there are five main types of barriers affecting to implementation of sustainable construction wood waste management as follows;

Financial Barriers: When implementing sustainable construction wood waste management, it usually incurs additional financial costs to the project. Furthermore, fear of higher investment costs, longer payback period, client worries about profitability, ignorance of life-cycle cost, and lack of financial resources can be determined as main financial barriers to implementing sustainable construction wood waste management (Agyemang, et al., 2024; Munaro & Tavares, 2023).

Technical Barriers: Review of previous studies indicates a lack of sustainable materials in waste management, a lack of sustainable measurement tools, a lack of demonstration projects, a lack of technical guidance, and a shortage of technical tools and equipment (Al-Otaibi, et al., 2022; Zhu & Feng, 2024).

Knowledge Barriers: Knowledge barriers refer to a lack of professionals with expertise skills, a lack of client awareness, a lack of awareness on benefits, negligence of sustainability and sustainable development, and a lack of education and knowledge on sustainable construction designs (Pandey, 2022; Zhu & Feng, 2024).

Political and Legal Barriers: Political and legal barriers include the absence of adequate support and guidance from government and local authorities, lack of management and leadership, lack of motivation and appreciation process for sustainable wood waste management, lack of policies, rules and regulations on construction wood waste management, and delay in decision making process due to rigid organization structures of relevant authorities (Al-Otaibi, et al., 2022; Olofinnade, et al., 2021).

Socio-cultural Barriers: Social and cultural factors can significantly impact sustainable wood waste management in the construction industry. However, a lack of demand for sustainable products and cultural change resistance are the main socio-cultural barriers in sustainable construction wood waste management (Munaro & Tavares, 2023). Furthermore, the absence of efforts and support from developers and clients also negatively impacts on sustainable construction wood waste management (Victar & Waidyasekara, 2023).

Therefore, these barriers should be managed effectively to implement sustainable wood waste management in the construction industry, especially in developing countries like Sri Lanka. Successful sustainable construction wood waste management would offer numerous environmental, economic, and human health benefits, such as reducing long-term construction costs and time, conserving natural resources, reducing environmental pollution, and supporting the transition to a circular economy in the construction industry.

3. Research Methodology

This study used a qualitative research approach to collect the required data through semi-structured interviews conducted among professionals who are involved in managing construction wood waste in Sri Lanka. Interview participants were selected through purposive sampling based on their expertise, which included over 10 years of experience in construction wood waste management in Sri Lanka, their availability and willingness to participate in face-to-face interviews lasting 70-90 minutes, and their ability to communicate effectively. The interview guideline was prepared based on findings from the literature. Table I presents the details of the interviewees. The collected data were analysed using manual content analysis, as manual coding enhances focus on the data sets, minimises variation in the contextual meanings of data, and strengthens the analytical process.

Table 1: Details of interviewees

Interviewee Code	Designation	Experience (yrs.)	Project Sector
R-01	Chartered Architect	16	Government
R-02	Architect	11	Private
R-03	Chartered Architect	15	Private
R-04	Chief Engineer (Civil)	29	Government
R-05	Site Engineer	19	Government
R-06	Design Manager	20	Private
R-07	Chartered Architect	17	Private
R-08	Civil Engineer	10	Government
R-09	Facilities Engineer	18	Private
R-10	Design Manager	11	Private

4. Research Findings and Discussion

The research findings are discussed under the following four main sections: conventional construction wood waste management practices in Sri Lanka, existing sustainable construction wood waste management practices in Sri Lanka, barriers affecting to implementation of sustainable construction wood waste management in Sri Lanka, and strategies to manage them.

4.1 CONVENTIONAL CONSTRUCTION WOOD WASTE MANAGEMENT PRACTICES IN SRI LANKA

In Sri Lankan construction industry, three main conventional wood waste management practices are used as presented in Table 2;

Table 2: Applicability of conventional wood waste management practices in Sri Lanka

Conventional wood waste management practices	Responses on the applicability of conventional construction wood waste management practices in Sri Lanka									
	R-01	R-02	R-03	R-04	R-05	R-06	R-07	R-08	R-09	R-10
Landfilling	✓			✓	✓	✓		✓	✓	✓
Open dumping	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Incineration		✓		✓					✓	✓

According to findings from semi-structured interviews, landfilling, open dumping, and incineration are conventional practices used in Sri Lanka to manage construction wood waste. Among these practices, open dumping is the most common practice, and it has resulted in an adverse impact on the environment. Apart from the above conventional practices, some of the construction wood waste is managed by selling it for other works or purposes. However, it would not be much applicable in every construction project, as most of the wood waste is mixed with

another construction materials. Adverse impacts of conventional wood waste management practices including greenhouse gas emission, over crowd landfilling requirements, and cost inefficiency, so on lead to find out sustainable ways to manage construction wood waste.

4.2 EXISTING SUSTAINABLE CONSTRUCTION WOOD WASTE MANAGEMENT PRACTICES IN SRI LANKA

As per the interviewees, there are four main sustainable construction wood waste management practices that are exercised by the companies. Table 3 presents the distribution of responses in relation to different types of practices used.

Table 3: Applicability of existing sustainable construction wood waste management practices in Sri Lanka

Existing sustainable construction wood waste management practices	Responses on applicability of existing sustainable construction wood waste management practices in Sri Lanka									
	R-01	R-02	R-03	R-04	R-05	R-06	R-07	R-08	R-09	R-10
Recycling	✓			✓						✓
Reuse	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Use as by-products	✓	✓							✓	✓
Use for energy recovery	✓	✓								

Among existing sustainable construction wood waste management practices, reuse is identified as the most common practice. For example, wood waste from the packing activities of construction materials is reused for temporary construction works at the site. However, recycling, use as a by-product, and use for energy recovery are not frequent construction wood waste management practices in Sri Lanka due to different challenges such as lack of recycling facilities, lack of investment cost, lack of skills and knowledge, and lack of awareness, so on. As a conclusion, there are no adequate existing sustainable construction wood waste management practices in Sri Lankan construction industry, and available practices also are not applicable in Sri Lanka due to different barriers affecting implementation.

4.3 BARRIERS TO IMPLEMENTING SUSTAINABLE CONSTRUCTION WOOD WASTE MANAGEMENT PRACTICES IN SRI LANKA

Barriers to implementing sustainable construction wood waste management practices were determined under five main categories as shown in Table 4.

Table 4: Barriers to implementing sustainable construction wood waste management in Sri Lanka

Types of barriers	Barriers	Responses on the applicability of barriers affecting to implementation of sustainable construction wood waste management in Sri Lanka									
		R-01	R-02	R-03	R-04	R-05	R-06	R-07	R-08	R-09	R-10
Financial	Additional cost to the project	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Fear of higher investment cost	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Longer payback period	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Ignorance of the life cycle cost	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

	Lack of financial resources	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Technical	Lack of sustainable materials in waste management	✓	✓	✓		✓	✓	✓		✓	✓	
	Lack of sustainable measurement tools	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Lack of demonstration projects	✓		✓				✓	✓	✓		
	Lack of technical guidance	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Shortage of technical tools and equipment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Knowledge	Lack of professionals with expertise and skills		✓		✓				✓	✓	✓	
	Lack of client awareness	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Lack of awareness of the benefits		✓	✓			✓		✓	✓	✓	
	Negligence of sustainability and sustainable development	✓	✓						✓	✓	✓	
	Lack of education and knowledge on sustainable construction designs	✓	✓		✓		✓	✓		✓	✓	
Political and legal	Absence of adequate support and guidance from the government and local authorities	✓	✓		✓		✓	✓		✓	✓	
	Lack of management and leadership,		✓	✓	✓					✓	✓	
	Lack of motivation and an appreciation process for sustainable wood waste management	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Lack of policies, rules and regulations on construction wood waste management	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Delay in decision-making process due to the rigid organization structures of the relevant authorities	✓	✓	✓			✓	✓	✓			
Socio-cultural	Lack of demand for sustainable products	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Cultural change resistance	✓	✓		✓	✓		✓			✓	
	Absence of efforts and support from developers and clients	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

According to Table IV, financial barriers are the main barriers to implementing sustainable construction wood waste management practices in Sri Lanka. Literature findings also highlighted that financial barriers become the main challenge when implementing sustainable wood waste management practices in developing countries, especially in the construction industry, due to their dynamic nature. In Sri Lanka, technical feasibility is also to be improved to implement sustainable construction wood waste management. Research findings revealed that a lack of sustainable measurement tools, a lack of technical guidance, and a shortage of tools and equipment are the main technical barriers to implement sustainable construction wood waste management in Sri Lanka. The interviewees stated that those technical barriers mainly occurred as a result of financial barriers and challenges. Knowledge and political and legal barriers are also similarly affecting to implementation of sustainable construction wood waste management in Sri Lanka. Especially, the lack of client awareness in Sri Lanka hinders to achievement of sustainable goals in the construction industry. This may be a result due to lack of education and knowledge on sustainable construction designs and their benefits. Furthermore, Sri Lankan government and other institutions also need to improve their involvement in implementing sustainable construction wood waste management practices. The research findings revealed that existing motivation and appreciation for sustainable practices, policies, rules and regulations, and decision-making processes were not effectively facilitated to implement sustainable construction wood waste management in Sri Lanka. Lack of demand for sustainable products in Sri Lanka and the absence of efforts and support from developers and clients can be determined as the main socio-cultural barriers to implementing sustainable construction wood waste management in Sri Lanka. These barriers may also result from to cost aspects of sustainable practices. Hence, financial barriers are connected with other barriers and require effective strategies to manage all barriers to implement sustainable construction wood waste management in Sri Lanka.

4.4 STRATEGIES TO MANAGE BARRIERS TO IMPLEMENT SUSTAINABLE CONSTRUCTION WOOD WASTE MANAGEMENT IN SRI LANKA

Research findings identified the following strategies, as mentioned in Table 5 to manage barriers to implementing sustainable construction wood waste management in Sri Lanka.

Table 5: Strategies to manage barriers to implement sustainable construction wood waste management in Sri Lanka

Types of barriers	Strategies
Financial barriers	• Allocation of adequate financial resources • Make awareness on financial benefits of sustainable construction wood waste management • Make awareness on payback period • Provide financial funding sources to implement sustainable construction wood waste management • Make decision based on life-cycle cost
Technical barriers	• Adapt new technologies • Conduct professional courses on sustainable wood waste management practices to obtain technical skills • Provide information about demonstration projects in a global context • Use high-tech machinery for wood processing activities in Sri Lankan construction industry by promoting sustainable practices • Provide sustainable measurement tools and other equipment to implement sustainable wood waste management practices
Knowledge barriers	• Conduct a training program on sustainable wood waste management • Make awareness on sustainable construction wood waste management for all project stakeholders

Political and legal barriers	• Establish policies, rules and regulations on sustainable construction wood waste management • Improve government and other authorities' involvement to implement sustainable construction wood waste management • Establish an appreciation and reward process to encourage sustainable construction wood waste management practices
Socio-cultural barriers	• Promote sustainable products in the markets • Encourage to adapt of sustainable designs to construction projects • Improve attitude to promote the source separation of waste • Promote 3R concepts and other sustainable concepts

Except from the above strategies, research findings revealed the following common strategies to implement sustainable construction wood waste management in Sri Lanka effectively.

- Encourage research on sustainable practices used in wood waste management in Sri Lankan construction industry.
- Finalize the design of the construction project with minimum wood waste generation at the construction stage.
- Encourage to planting of trees or arrange the planting of trees proportionately to meet the usage and wastage of wood in Sri Lankan construction industry. It helps offset the environmental impact of deforestation caused by high wood consumption, thereby promoting ecological balance and biodiversity and reducing the overall carbon footprint of the construction sector. Moreover, it ensures the long-term availability of wood resources, promoting a circular approach to resource use.
- Introduce the system to charge fines or penalties from construction projects that do not use sustainable practices in wood waste management in Sri Lankan construction industry.
- Introduce and promote by-products that can be produced by using construction wood waste.

Accordingly, findings were accomplished the aim of this study by proposing above strategies to manage barriers affecting to implement sustainable construction wood waste management in Sri Lanka.

5. Conclusion

Nowadays, the necessity of sustainable construction wood waste management practices in developing countries like Sri Lanka is rapidly increasing due to high usage of wood in the construction industry and their adverse impacts on the environment, economy, and human health. In Sri Lanka, sustainable construction wood waste management is not a familiar concept at present due to different reasons. As a result of that, this study found out three main conventional practices used in Sri Lankan construction industry to manage wood waste, such as open dumping, landfilling, and incineration. Among them, open dumping is frequently used to manage wood waste in Sri Lankan construction industry than other conventional practices. Nevertheless, there are few sustainable practices used in the Sri Lankan construction industry to manage wood waste based on the findings, such as recycling, reuse, use as a by-product, and use for energy recovery. The reason behind the limited applicability of sustainable construction wood waste management practices in Sri Lanka was found to as different types of barriers affecting to implement of sustainable construction wood waste management, including financial barriers, technical barriers, knowledge barriers, political and legal barriers, and socio-cultural barriers. This study revealed five barriers under each type of barrier except socio-cultural

barriers (refer Table IV). Furthermore, financial barriers can be identified as a major barrier to implementing sustainable construction wood waste management in Sri Lanka, and they also lead to the emergence of other types of barriers. Eventually, this study proposed effective strategies to manage each type of barrier to implement sustainable construction wood waste management in Sri Lanka. Furthermore, this study recommended strategies in general to promote and encourage sustainable construction wood waste management in Sri Lanka while accomplishing the aim of the study.

6. References

- Adhikari, S. & Ozarska, B., 2018. Minimizing environmental impacts of timber products through the production process "From sawmill to final products". *Environmental Systems Research*, 7(1), pp. 1-25.
- Agyemang, E., Ofori-Dua, K., Dwumah, P. & Forkuor, J., 2024. Towards responsible resource utilization: A review of sustainable vs. unsustainable reuse of wood waste. *PLOS ONE*, 19(12), p. e0312527.
- Al-Otaibi, A. et al., 2022. Identifying the barriers to sustainable management of construction and demolition waste in developed and developing countries. *Sustainability*, 14(13), p. 7532.
- Azambuja, R., Castro, V., Trianoski, R. & Iwakiri, S., 2018. Recycling wood waste from construction and demolition to produce particleboards. *Maderas. Ciencia y tecnología*, pp. 681-690.
- Bimsara, K., Abenayake, D., Lingasabesan, V. & Shanika, V., 2024. Adopting circular economy practices in major building materials and elements to minimise waste in Sri Lanka. *12th World Construction Symposium - 2024*, pp. 105-118.
- Chen, K. et al., 2021. Critical evaluation of construction and demolition waste and associated environmental impacts: A scientometric analysis. *Journal of Cleaner Production*, 287(1), pp. 125071-125083.
- Hossain, M. & Poon, C., 2018. Comparative LCA of wood waste management strategies generated from building construction activities. *Journal of Cleaner Production*, Volume 177, pp. 387-397.
- Jahan, I., Zhang, G., Bhuiyan, M. & Navaratnam, S., 2022. Circular economy of construction and demolition wood waste—A theoretical framework approach. *Sustainability*, 14(17), pp. 1-26.
- Kern, A., Amor, L., Angulo, S. & Montelongo, A., 2018. Factors influencing temporary wood waste generation in high-rise building construction. *Waste Management*, Volume 78, pp. 446-455.
- Kozlovská, M. & Spišáková, M., 2013. Construction waste generation across construction project life-cycle. *Organization, Technology & Management in Construction: An International Journal*, 5(1), pp. 687-695.
- Munaro, M. & Tavares, S., 2023. A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Cleaner and Responsible Consumption*, Volume 8, p. 100107.
- Olofinnade, O., Manda, I. & Ede, A., 2021. Management of construction & demolition waste: Barriers and strategies to achieving good waste practice for developing countries. *IOP Conference Series: Materials Science and Engineering*, 1036(1), p. 012045.
- Pandey, S., 2022. Wood waste utilization and associated product development from under-utilized low-quality wood and its prospects in Nepal. *SN Applied Sciences*, 4(6), pp. 1-8.
- Sivashanmugam, S., Rodriguez, S. & Rahimian, F., 2024. A bim-integrated semantic framework for construction waste quantification and optimisation. *Automation in Construction*, 168((2024)), pp. 1-26.
- Somer, M. & Alkhayat, O., 2024. A study on wood waste potential in Turkey. *Cleaner Waste Systems*, Volume 8, pp. 100-151.
- Victar, H. & Waidyasekara, K., 2023. Construction and demolition waste management issues in building project life cycle stages: A case of Sri Lanka. *11th World Construction Symposium - 2023*, pp. 392-406.
- Yin, R. (2009). *Case study research: Design and methods* (4th ed.). California: Sage Publications.
- Zhu, S. & Feng, H., 2024. Enhancing circularity of wood waste through deconstruction in building sector. *Journal of Cleaner Production*, Volume 485, p. 144382.

THE IMPACT OF POWER INTERRUPTIONS ON MULTI-STOREY COMMERCIAL BUILDINGS IN SRI LANKA

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Abstract. The recent Sri Lankan economic crisis has led to fuel shortages, affecting power supply in multi-storey commercial buildings. The consequences of power interruption vary by facility type and consumer categories. Thus, comprehensive studies are required to assess the cost of unserved energy. Recently, high-rise commercial buildings have been increasingly studied, due to the shown variations in energy use. Considering this energy usage variation and the requirement of further studies, this study aims to explore the impacts of power interruption on multi-storey commercial buildings in Sri Lanka. Under a qualitative research approach, five multi-storey commercial buildings were selected for the case studies. Document reviews and semi-structured interviews with two respondents in each selected building were executed to data collection, and data were analysed using manual content analysis. The findings revealed that power interruption significantly affects commercial activities, business operations, building systems, maintenance and customer service. Also, the power interruption impacts are varied across the core business activities of the building. As the current solutions, generators and uninterruptible power supply are widely used. Fuel shortage, lack of skilled personnel, and lack of experience in sudden power outages are key barriers to implementing the identified solutions. To overcome the impacts of power interruption, strategies such as remote working, shift scheduling, work prioritisation, limiting the number of operational floors, limited usage of unnecessary systems and equipment, entering into the fuel supplier agreements and conducting routine maintenance to reduce power dependency during outages were suggested.

Keywords. Commercial Building, Electricity, Power Interruptions, Power Supply

1. Introduction

Multi-storey buildings have been rapidly increasing worldwide, due to restricted land availability in popular places and their fundamental role as vital buildings in modern cities and capitals (Amadi & Okafor, 2015). A multi-storey building is a structure with a total height of more than 36 meters or more than 12 floors, with a variety of uses such as residential, administrative, or hotel (Farouk, 2011). The concept of a multi-storey building is generally understood as a structure with multiple floors above ground level. While there is no explicit minimum number of floors defined, research often focuses on buildings with more than four floors (Zohair & Reddy, 2018). Multi-storey buildings appear to be the more environmentally friendly solution to urban density and enable larger urban density than lower buildings and occupy a small area (Weidner et al., 2018). Multi-storey commercial buildings are designed to accommodate a large number of people and businesses, and include amenities such as elevators, escalators, and parking facilities. Multi-storey commercial buildings are common in urban areas where space is limited and the demand for commercial space is high (Levine et al., 2007). However, a closer inspection reveals that multi-storey buildings consume more resources than low-rise buildings due to increased requirements for structure, façade, vertical transit, and foundations (Hall, 2013). Also, multi-storey office buildings reveals that the intensity of electricity and fossil fuel usage has been increased in multi-storey office buildings (Godoy-Shimizu et al., 2018).

The power supply is an important aspect to the multi-storey commercial buildings. For a multi-storey hospital building, continuous power supply is required to run the emergency equipment whereas, multi-storey warehouse buildings require continuous power supply to carry out continuous production in their daily operations. Power distribution has a more concentrated view at the operational level since power interruptions negatively influence key services, business, public life, productivity, resource utilization, and overall customer satisfaction and service level (Al-Aomar et al., 2017). Frequent power outages are also expected to cause direct damage to electrical appliances such as refrigerators, televisions, and other electronics (Cissokho & Seck, 2013). Increased energy consumption, particularly commercial energy like electricity, has

become a symbol of a country's high economic status (Meles, 2020). Frequent power interruptions adversely affect output in productive sectors and discourage new firms from locating or investing in a country (Fakih et al., 2020). The consequences of power outages are depending on whether it is occurring in manufacturing plants, commercial service firms, or households (Suman et al., 2021). Power outages have significant economic and health impacts, particularly in high-rise commercial buildings. These outages can disrupt critical infrastructure, hinder emergency responses, and affect business operations (Mangat & Singh, 2015). The economic impact of electricity interruptions varies across consumer categories such as domestic, industrial and commercial, requiring comprehensive studies to assess the cost of unserved energy (Colambage, 2022). High-rise commercial buildings receiving more attention in recent studies, due to shown variations in energy use and emissions between high-rise and low-rise structures (Bahramian & Yetilmezsoy, 2020). In Sri Lanka, commercial sector consumers consume substantial energy to meet modern client expectations, and revealed that unexpected short outages generally incur higher costs than longer ones, while costs for expected outages increase with duration (Alahakoon et al., 2022; Balasooriya et al., 2023). Thus, it is notable that energy usage varies among different consumer categories with high-rise commercial buildings receiving particular attention. Also, rising costs associated with Sri Lankan commercial buildings emphasise the requirement of further studies on impact of power outages. Therefore, this study aims to examine the impacts of power interruption on multi-storey commercial buildings in Sri Lanka. In Section 1, the literature review explores multi-storey commercial buildings, their operations, the importance of power supply, sources of power, and the causes and impacts of power interruptions on such buildings. Sections 3, 4, 5, and 6 present the methodology, results, discussion, and conclusion, respectively.

2. Literature Review

Due to limited land supply in commercial zones of metropolitan cities multi-storey buildings are rapidly expanding throughout the world (Al-Janabi et al., 2021). Multi-storey commercial buildings have ability to accommodate a large number of businesses in a relatively small footprint (Rodrigues et al., 2019). Commercial buildings are utilized for commercial uses, including offices, shops, restaurants, and other establishments (Zuo, 2015). Multi-storey commercial buildings are significant element of urban landscapes, offering a variety of commercial spaces for enterprises and enhancing the life and energy of metropolitan regions (Jayasinghe et al., 2016). According to Yoo et al. (2013), these buildings require more complex mechanical, electrical, and plumbing systems to provide services to multiple floors.

2.1. OPERATION OF MULTI-STOREY COMMERCIAL BUILDING

The operation of a multi-storey building refers to the processes and activities involved in the day-to-day functioning of the building, such as its maintenance, security, management, and use by occupants (Cahvan et al., 2018). Smith et al. (2013) stated that building services are essential for the smooth operation of a commercial building and are required to ensure the safety, comfort, and functionality of the building for its occupants. In multi-storey buildings, air conditioning systems are equipped with variable speed drives since the cooling load varies throughout the day and season (Lopatin, 2016). Modern multi-storey structures frequently have a large interior space that is not naturally lit by sunlight and must be illuminated by artificial light and the lighting systems are responsible for at least one-third of a building's overall electrical energy costs (Jonas, 2024). Alarms and control units, fire safety control devices, annunciators, power supply, and wiring can all be found in building's fire alarm systems (Nadeem et al., 2012). There are numerous staircases, elevator shafts, pipe shafts, air passageways, cable shafts, and other vertical shafts in multi-storey buildings are caused to quick fire spreads (Liu et al., 2012). The

capacity to construct buildings that are taller and taller depends on the availability of efficient vertical transportation, and current developments in elevator design promise to drastically cut energy usage. The provision of electrical power to commercial buildings is referred to as "power supply," as it is necessary for the building's numerous electrical systems and equipment to function (Hossain et al., 2023).

2.1.1 importance of power supply to a commercial building

Power supplies are utilized in multi-storey commercial structures to provide electricity to different electrical loads under diverse building conditions (Rahman et al., 2018). It is anticipated that a dependable power supply service will improve business performance in terms of availability, quality, and pricing (Arnold et al., 2008). The productivity and welfare of a multi-storey structure are directly impacted by the availability and accessibility of energy supply (Nyanzu & Adarkwah, 2016). Power supply plays a significant role in enhancing the productivity of human capital and almost all corporate operations, particularly those involving industrial facilities (Scott et al., 2014). Power supply availability often plays a crucial role in keeping finished items on hand ahead of demand, which increases consumer satisfaction by ensuring that they are accessible when needed (Moyo, 2012). Commercial buildings use majority of its electricity for lighting (Muhamad et al., 2010). In addition, most energy is used for maintaining comfortable interior environment, including thermal comfort and air quality, as well as household appliances (Kamilaris et al., 2014). Operation of the building services in a commercial building depends on a continuous power supply (Sha & Qi, 2020). A reliable and efficient power supply system is crucial for ensuring the safety and convenience of a commercial building (Basak, 2015).

2.1.2 Sources of power supply for multi-storey commercial buildings in Sri Lanka

The energy demand for commercial buildings in Sri Lanka have increased due to modernized building facilities and current economic practices (Alahakoon et al., 2022). There are several sources of power supply for a multi-storey commercial building, including Grid power, generators, and solar panels. Commercial buildings in Sri Lanka primarily rely on fossil fuels for power supply, with thermal oil and coal and hydroelectricity is second energy source (Fernando et al., 2019). Approximately 160 nations worldwide currently generate electricity using hydropower technology (Kaygusuz, 2016). There is growing interest in diversifying power sources to include more renewable options such as solar and biomass (Nanayakkara et al., 2021). Even though the price is higher than grid electricity, it is vital to use diesel generators in hybrid energy systems of commercial buildings to provide reliable electricity (Kolhe, 2014). Hydropower, wind, solar, and biomass are renewable energy sources that can be used to reduce greenhouse gas emissions and regional air pollutants brought on by the combustion of fossil fuels. The reliability of electricity sources is crucial to the development of future energy systems and environmental sustainability (Müller et al., 2011).

2.1.3 Power interruption in Sri Lankan context

Power interruptions can be divided as planned and unexpected power. Utility companies use planned outages to do maintenance work. Customers are told well ahead of time when an interruption is coming (Colambage, 2022). Power supply in developing countries has been generally characterized by unreliability and inefficiency, resulting adverse impacts on the economic performance of firms (Cissokho & Seck, 2013; Moyo, 2012). Sri Lanka had power shortages due to generating capacity shortfalls and the incapacity of hydropower facilities to fully compensate during periods of major storms (Wijayatunga & Jayalath, 2004). The availability

of electricity from micro hydropower plants that have already been built is difficult to anticipate for a number of reasons, including climatic fluctuations (Hasan & Wyseure, 2018). Since the Russia-Ukraine war has already increased global oil prices, making it more expensive for Sri Lanka to import gasoline for daily necessities, the country is implementing rolling power cuts to save energy (Bobadilla, 2024). All of Sri Lanka's crude oil and refined petroleum products needed for transportation and electricity production must be imported at the current time since the nation has no confirmed fossil fuel resources (Colambage, 2022). Sri Lanka is in the midst of a severe economic crisis as a result of the country's depletion of foreign reserves, which has resulted in food, gasoline, pharmaceutical, cement, and other essential supplies shortages (Sharma, 2022). Long lines of fuel stations are a direct effect of a lack of foreign reserves needed to replenish depleted supplies. The acute scarcity of fuel has forced the closure of many thermal power facilities, causing widespread blackouts throughout the nation (Colambage, 2022). According to Ceylon Electricity Board (2025), entire Sri Lanka faced blackout due to sudden failure in grid and until restore the system, CEB had to limit the electricity generation and disconnect the power according to a schedule.

2.1.4 Impact of Power interruption to the commercial buildings

Power interruptions typically have both direct and indirect effects on the performance of businesses, increasing economic expenses, reducing production quantities, and ultimately lowering sales and productivity (Arnold et al., 2008). Power outages can have a negative impact on corporate operations which ultimately lowers productivity (Bernstein & Hegazy, 1988). Additional costs are incurred to hire or own alternative energy sources such as generators (Yeaple & Golub, 2007). As a result of power outages, expenditures may arise that are both proportional to the length of the outage and to the lost files and programs and idle labor and machinery (de Nooij et al., 2007).

With related to the building operation and maintenance, the machineries and buildings systems are breakdown due to frequent power interruptions. Also, the building performance aspects such as standard lighting levels and indoor air quality are affected due to power interruptions (Meles, 2020). Power interruptions cause to building safety and security related impacts on operations of emergency lighting and access control systems (Sharma, 2022). Due to equipment shutdowns, this will effect on emergency evacuation and increase the risks to the occupants in building (Yasin & Jan, 2021). Customer service and care is getting problematic during the power outage as inability to full fill the requirements of the customer within the time (Ivanov, 2022). To mitigate the impacts of power interruptions, buildings can be adapted with different strategies such as using generators, laying off workers, changing the location of enterprise, obtain insurance policy and reduced shifts (Abeberese et al., 2019). Smart grid technology has potential to enhance grid stability, reduce fossil fuel dependence, and address power interruption challenges in Sri Lanka (Rajapaksha et al., 2024).

3. Methodology

To analyse the impacts of power interruption in Sri Lanka, a comprehensive literature review was conducted focusing on importance of power supply to a commercial building, power interruptions in Sri Lankan context and impact of power interruptions to operations of the commercial buildings. Under qualitative research approach case studies were selected as the research strategy to achieve the aim of the study. Case studies are more suitable for this study, where require to explore real-life specific situation and to gain more holistic understanding (Rahi, 2017). Considering the depth of study, five commercial buildings in the Colombo district were selected through random sampling. Three bank buildings, one software company and one telecommunication building were selected for the case studies. Data collection was conducted using semi-structured interviews and document reviewing. Semi-structured interviews were

conducted with two (02) respondents in managerial level and non-executive level in each selected building. The details of selected case studies and interviewers are listed in Table 1. To obtain the data of building details including building size, number of employees and other special characteristics, document reviewing process were conducted and work schedules and power interruption time, were reviewed under this. The types of documents that were considered for reviewing include work schedules (WS), power interruption schedules (PIS), book of business (BOB) and Impact on cases (IPI). In order to analyse the collected data, manual content analysis was conducted as it allows to accurately identify the information gathered and highlight the crucial viewpoints, characteristics, or conclusions (Hsieh & Shannon, 2005).

Table 1: Selected case studies and respondents' details

Case	Description	Respondent	Description
A	Banking and financing	A1	Facility Manager with 10 years of work experience.
		A2	Senior Maintenance Technician with 08 years of work experience.
B	Software Development	B1	Director of Compliance with 08 years of work experience.
		B2	Maintenance Officer with 06 years of work experience
C	Banking and financing	C1	Maintenance manager with 09 years of work experience.
		C2	Maintenance Supervisor with 08 years of work experience
D	Banking and financing	D1	Senior Maintenance Executive with 10 years of work experience
		D2	Engineering Executive with 08 years of work experience
E	Telecommunication	E1	Electrical Engineer with 15 years of work experience.
		E2	Maintenance supervisor with 06 years of work experience.

4. Results

Data collection was executed under two stages, document reviewing and semi-structured interviews. This section is discussed the analysis of collected data and research findings.

4.1 STAGE 1- DOCUMENT REVIEWING

The commercial characteristics of selected buildings was identified through BOB, given in Table 2. Work schedule data was gathered to identify the impacts of power interruption during work time. According to the reviewed WS, similar type of working patterns was identified in A, C and D. In contrast cases B and E contained different type of data in their WS. Also, those two cases are operated even on the weekend. According to Zohari and Reddy (2018) this study also considered the multi-storey buildings more than four floors.

Table 2, Commercial characteristics of selected buildings

Case	Number of floors	Number of occupants	Primary commercial activity	Working schedule weekdays	Working schedule weekends
A	35	1550	Banking and financing	08.30 - 03.00	Closed
B	06	400	Software development	09.00 - 3.00	09.00 - 1.00
C	07	250-300	Banking and financing	09.00 - 3.00	Closed
D	25	1500	Banking and financing	08.00 - 6.00	Closed
E	10	500	Telecommunication	07.30 - 6.00	07.30 - 6.00

4.1.1 Power interruption period

During the economic crisis period CEB imposed power cuts by dividing the country into several zones and PIS documents provide details about the power cut periods. From March to June 2022, the country experienced a power cut for more than ten hours, and later from July to September, it has reduced to 4 hours. Then during the period of September to December power cuts were reduced to 2.30 hours. This power interruption period was significantly reduced after August 2022, as government was capable to resolve the issue after importing the fuel.

4.1.2 Impact of power interruption

Based on the commercial characteristics of buildings in Table 2, the impact of power interruptions was identified separately for banking and financing buildings. Case A, C and D had consequences in service availability, making it difficult for customers to access their accounts or perform transactions. The ATMs and digital banking platforms are declined. Power interruptions in banks lead to data loss, and improper backup systems cause delays, transaction difficulties, and customer issues. Case C had difficulties in the processing of loans and credit applications. Additionally, power cuts make it more difficult to financial institutions for risk management. However, based on the reviewed documents none of the banking building was identified difficulties in fraud detection as banking facilities are using backup powers in security systems. Power interruption negatively impacted on customer care services by disrupting telephone lines and internet connectivity, preventing customers from contacting the customer care service. Considering case B and E, case B only supported with IPI documents and case E was not maintained any relevant document to obtain the impacts of power interruptions. As a software company, Case B heavily rely on servers and cloud services. Power outages are caused to server breakdowns, resulting in service disruptions and lost revenue. Also, caused data loss or corruption, resulting in costly data recovery efforts and damaging the company's reputation. It was notable that power interruption impact on business continuity, which can result in lost revenue and damage to the company's reputation.

4.2. STAGE 2- SEMI-STRUCTURED INTERVIEWS

The impacts of the power interruption that identified in the literature review were examined related to the selected case studies. Further, the impact on building services by the power interruptions, the solutions for the identified impacts and barriers in implementing proposed solutions were identified in this stage. The impact of power interruptions was identified from each case study as listed in Table 3.

Table 3: Impact on power interruption in commercial buildings in SL

Criteria	Impact of power interruption in commercial buildings in Sri Lanka	A	B	C	D	E
Impact on commercial activities and productivity	Data and inventory losses	✓	✓	✓	✓	✓
	Loss of revenue		✓	✓		
	Employees are unable to undertake their tasks	✓	✓	✓	✓	✓
	Decreases in sales and productivity		✓			✓
	Increases in production costs			✓		
	Firms will lose market opportunities					
	Communication problems	✓	✓	✓		✓
	Machinery breakdowns			✓		✓
	Effects on standard lighting levels	✓				✓

Impact on building system operations and maintenance	Effects on indoor air quality		✓	✓	✓	
	Effects on access control					
	Equipment shutdown and safe evacuation plans	✓				
	Emergency lighting	✓		✓	✓	
	Risk of workers	✓		✓	✓	
Impact on customer service	Inability to full fill the requirements of the customer within the time	✓		✓	✓	
	Getting negative reviews due to poor customer service					✓
	Bad reputation	✓		✓		✓

4.2.1 Impact of power interruptions on commercial activities and productivity

All the respondents highlighted the various factors affecting their commercial activities and productivity. A1, C1, and E1 mentioned that when there is a power loss, computers and other electronic equipment were rendered inoperable, inventory losses occurred and made it difficult to access data. All the respondents stated, power interruption caused decreases in sales and productivity due to disruption in operations. B1 and E2 highlighted that the increase in production costs caused to increase in the overall operating costs. Similarly, E1 mentioned that power outage made interfere with the production process, which reduced the productivity and quality. The site experienced no communication issues with team coordination, but the public addressing system was down due to a power cut. A1 mentioned that, the machinery breakdowns can be rectified quickly with proper vendor communication.

4.2.2 Impact on building system operation and maintenance

Considering the building system operation and maintenance, all most all the respondents mentioned that, long interruptions disrupted the operation of automated lighting systems. C1 stated that the power interruption caused significant damage to the electrical systems and other equipment, leads to expensive repairs and replacement. B1 stated that occasional power interruptions caused damage to lighting equipment, such as bulbs, ballasts, and fixtures. Respondents emphasized the importance of sufficient lighting for safe house-keeping services in a building, as failures can lead to navigation difficulties and increased accident risks.

All the respondents emphasized the importance of HVAC systems for the comfort and safety of building occupants. Power interruption caused poor indoor air quality (IAQ), which made negative health effects. C2 mentioned that workers are exposed to extreme temperatures during the power interruption and malfunctioning of the HVAC system leads to increase the humidity and caused a breeding ground for bacteria and other microorganisms and poor ventilation caused leads to the build-up carbon dioxide. In addition, the air conditioning system will need time to cool the building once power is restored. This results in occupant discomfort and higher energy consumption as the system compensates to restore the desired temperature. Power outages disrupt the operation of water treatment plants, leads to water shortages and automatic fire sprinkler system also will not work. All respondents stated that housekeeping services are carried out with manpower without using electrical equipment for this purpose. Respondents stated that without power system, security services such as intercoms, security cameras, and access control systems were unable to operate and caused risks to employees.

Respondents mentioned that the excess usage of generators caused overheating, shortening lifespan, exhaustion, battery drain, and air filter clogging. In addition, this leads to consume fuel at a high rate, which can lead to fuel exhaustion and cause the generator to shut down. Also, it

was difficult to carry out day to day activities due to the unavailability of fuel during the economic crisis. D2 explained the difficulties of accessing the building to authorized personnel during power interruption, which can delay response time in case of an emergency. The continuous power supply is required to complete maintenance activities in satisfactorily level. It has to be rescheduled due to power failure and delays in the completion of work. In summary, disruptions in building system operations and maintenance were identified, including failures in automated lighting systems, costly repairs to electrical equipment, safety issues due to less illumination, health issues due to poor indoor air quality, discomfort from extreme temperatures, increased generator maintenance, restricted building access, and delays in both emergency response and routine maintenance activities.

4.2.3 Impact on customer service and care

Respondents stated that the interruptions of building services, delays in providing good customer service, and customer complaints reduced building productivity. Power interruptions reduced customer occupancy in the building premises, which led to a decrease sale. According to E1, the disruptions lead to loss of customer confidence, cause to decrease future revenues. Further, A1 specified that the inability to full fill the requirements of the customer within the time led to delays in meeting customer expectations. Additionally, customer dissatisfactions are occurred due to unavailability of essential services such as lights and air conditioning. As a result, customers made negative reviews about the building. Further B2 and E1 stated that during power interruption time businesses were closed temporarily, which caused inconvenience to customers who had planned to visit the building or use the services provided. Additionally, A1 mentioned, any equipment or technology that relies on electricity stops functioning, making it difficult for businesses to conduct transactions or provide services. This also be an inconvenience for customers who are in the middle of a transaction or service. According to A1, as elevators typically stop functioning it is difficult for people to move between floors within the building. This is especially problematic for people with mobility issues or disabilities, as they may not be able to use the stairs and also an inconvenience for people who need to move heavy items or equipment between floors.

4.2.4 Current practices to overcome power interruption impacts

Selected cases are followed up several strategies to minimize the impacts of power interruption. A1 mentioned that, there was some backup strategies applied according to the power cut duration. According to the respondents, generator is the common backup source in all cases. C2 and D2 mentioned that during the period when the power interruption is more than 10 hours, the usage of the generator was extremely high. It leads to the malfunction of generators. C1 stated that, maintaining proper maintenance checklist is possible to overcome this issue. All the respondents highlighted that one common solution for power interruption problems is the use of UPS. Moreover, respondents elaborated that a UPS acts as a backup power source for devices that require a consistent power supply, such as servers and computers. UPS automatically shuts down non-critical systems to conserve battery power, preventing data loss and preventing equipment and machinery damage during a power outage.

Respondents stated that daylighting also helped to reduce the need for artificial lighting during a power interruption, which can save energy and lower costs in the long term. Daylighting improved the visual comfort, productivity, and enhance overall building performance. C1 emphasized implementing solar panels as it is a renewable and clean energy source. This will help to reduce the building's carbon footprint and improve its overall sustainability. D2 deliberately mentioned that, installing solar panels on the commercial building contribute to increase property value, as it demonstrates that the building is energy efficient and sustainable.

C2 specifically mentioned that proper grounding of battery backup can help to prevent damage to machinery caused by voltage spikes caused by power outages. D2 highlighted the requirement of a plan to work in power outages, to minimize the impact and ensure a quick recovery. Therefore, companies allow employees to work remotely in power interruptions. Remote working or telecommunicating helped workers to minimize the disruption caused by power interruptions and allow to continue working. However, E2 stated that both the nature of work from home and remote working are similarly same. Respondents suggested limiting operational floors during power outages in commercial buildings and designating backup power zones to housing essential personnel and equipment, to minimize disruption and allow the building to continue functioning at a reduced capacity. E1 and B2 stated that creating a schedule helped to stay on track, ensuring that tasks were completed on time. It included breaks throughout the day and prioritized tasks requiring more focus and energy. B2 also supported this by stating, prioritizing the work tasks is when the power is out. Additionally, E2 highlighted that technology usage such as using mobile apps and cloud computing helped during power outage, to store documents and manage projects. Also, emphasized the importance of time management during power outages for businesses, as it allows us to continue to operate and deliver services to their customers. In brief, to minimize the impacts of power interruptions, respondents emphasized strategies such as using generators, UPS systems, daylighting, solar panels, remote working, backup power zoning, task prioritization, and leveraging technology for continued operation and sustainability.

4.2.5 Barriers to implement the current practices

All respondents stated that companies heavily rely on fuel to operate the generator during power interruptions. During the economic crisis, the availability of fuel was limited due to the shortage of foreign currency. Other economic challenges, making it difficult for them to secure necessary fuel to power backup generators. E1 and E2 discussed the increased demand for backup generators due to power interruptions and fuel price increases, but also noted the high upfront cost and high upfront investment required for such solutions. A2 stated, the economic crisis impacted the availability of equipment such as backup generators, battery systems, and other power management solutions. A1 stated the technicians did not have the necessary knowledge or expertise to determine which solutions would be the most effective for building in this circumstance. Power interruption solutions can be complex and require specialized knowledge and skills to design, install, and maintain. E2 and E1 discussed the complexity of new technologies, requiring specialized knowledge and skills for installation and maintenance, and the potential for costly hiring of technicians. Also highlighted the challenge of compatibility with existing building systems, significant modifications to electrical infrastructure, and the need for staff training, which can be time-consuming and costly, and may require dedicated employees or external trainers.

4.2.6 Suggestions to overcome the impacts of power interruptions

Case A has a contract with the Indian Oil Company (IOC), ensuring a steady fuel supply even during shortages. Respondents B1, C1, and E2 also have contracts with the Ceylon Petroleum Corporation, but receive fuel on a limited basis. A2 mentioned that, IOC may have been able to purchase fuel when other suppliers were unable to meet their needs. All respondents mentioned that they maintained a daily maintenance checklist to ensure the condition of the backup sources. These checklists include checking the oil level, coolant level, air filter, fuel level, exhaust system, and control panel in daily routine. B2 stated that, to avoid overheating, a daily maintenance checklist is required for the long-life span of generators. A2 mentioned that, technicians working with generators and power systems require a thorough understanding of their operations, quick troubleshooting skills, and efficient repairs to ensure system recovery and quick system uptime.

Other than the identified current practices, respondents provided suggestions that can be implemented in commercial buildings in Sri Lanka. E2 suggested that changing the working shift period when power is available is also a suitable solution to overcome the impact. E1 elaborated on the statement by mentioning that this solution may not always be practical or feasible for all types of work. Additionally, shifting working hours may also have an impact on employee schedules and may require changes to transportation. B1 and B2 suggested that reducing shifts can be one solution to mitigate the impact of power interruptions. By reducing the number of staff during operating hours, the building's energy consumption can be decreased, which in turn reduces the demand for generators during the power interruption. A2 specifically mentioned mobile banking services was carried out as a temporary solution for the power interruption. C1 stated that, as lifts require a significant amount of energy to operate, limited usage during a power interruption can reduce the overall demand for power, and consequently, the fuel consumption of the generator. C2 mentioned it is important to consider the safety of people when limiting the use of lifts during a power interruption. If there is a medical emergency or a situation that requires evacuating people, operable lifts are essential to ensure their safety. D2 suggested to deploy temporary power generators or backup power systems to supply electricity to specific floors or areas, such as emergency lighting, elevators, security systems, and life safety equipment.

5. Discussion

Uninterrupted power supply is an important aspect in terms of improving business performance, productivity, operating industrial machineries, maintaining comfort indoor environment and working office appliances (Sha & Qi, 2020). In selected cases, the importance of power supply was depended on the commercial activities involved in. Sri Lanka faced power shortages due to generating capacity shortfalls and the incapacity of hydropower facilities (Wijayatunga & Jayalath, 2004). The fuel scarcity has forced the closure of thermal power facilities, causing widespread blackouts throughout the nation (Colambage, 2022). Based on document reviewing, it was identified that during the economic crisis period in Sri Lanka, the buildings experienced power outages more than ten hours and this duration was significantly reduced after resolving the issue of fuel importing.

Power interruptions typically have effects on business performance, increasing economic expenses, reducing production quantities, and ultimately lowering sales and productivity (Arnold et al., 2008). Similarly, Semi-structured interviews were provided details on impacts related to business continuity and productivity. The malfunctioning of electronic equipment resulted in inventory losses and data access issues. Internal business communication was less affected. Damage to electrical systems led to costly repairs and replacements. Document reviewing of selected cases shows that power interruption impacts are vary across the core business activities of the building. Banking and financing related companies are facing issues related to ATMs and digital banking, data losses, service availabilities and difficulties in risk management. Software and telecommunication facilities are heavily impacted by issues with server uptime, data integrity, development of testing, cloud services, and business continuity. Literature further discussed the power interruption impacts on safety, security and customer service. Interviews proved this stating; the security systems and access control systems are unable to operate and caused risks to employees. Power interruption caused poor indoor air quality, negative health effects due to carbon dioxide buildup, bacteria and other microorganisms, and exposure to extreme temperatures due to absence of HVAC. People with mobility issues or disabilities are facing issues due to inability of using elevators and escalators.

To overcome the impact of power interruptions there were certain strategies are used (Abeberese et al., 2019). As the current practices, selected cases are adhering to the backup strategies such as using generators, UPS systems and Solar panels as a renewable energy

source. Daylighting reduces artificial lighting during power interruptions, while proper grounding of battery backups and preventive maintenance are necessary to prevent damage to machinery due to voltage spikes. In addition, remote working procedures are implementing in buildings to reduce the number of workers who are working inside the building premises and limit the number of operational floors during an outage. Respondents highlighted the importance of prioritizing the work tasks during the power is out. In selected cases, certain barriers were identified in implementing these strategies. Due to the increased demand for the backup generator, investing on backup solutions is not affordable. Also, during the economic crisis, limited fossil fuel availability is a barrier to operate backup generators. Designing, installing, and maintaining power interruption solutions can be complex and require specialized knowledge, while new technology integration can require costly electrical infrastructure modifications. To power interruption management training staff can take time and resources. To prevent the fuel shortages commercial buildings are tend to get into agreements with fuel suppliers. To ensure the reliability of the backup sources organization conduct the daily maintenance checklist and provide adequate training to the technicians. Other than the current practices, respondents suggested to limit the number of workers inside the building using strategies such as shift working, remote working and work prioritization, to reduce the required backup power load.

6. Conclusion

In conclusion, this study examined the impact of power interruption in multi-storey commercial buildings in Sri Lanka, revealing significant consequences on commercial activities, productivity, building systems and operation and customer service. Findings indicate that power outages significantly affect various commercial sectors differently, with banking and finance industries facing challenges in ATM operations and digital banking, while software and telecommunication companies struggle with server uptime and data integrity. Furthermore, power interruptions disrupt building services such as lighting, heating, cooling, and security systems, leading to reduced tenant satisfaction, financial losses, and health risks due to poor IAQ. To mitigate these impacts, commercial buildings rely on backup power solutions such as generators, UPS systems, solar panels and daylight utilization. Additionally, preventive maintenance of backup systems and proper grounding of battery backups were also identified as critical measures. However, economic constraints, fuel shortages, and technical complexities of new technologies such as smart grids, pose barriers to implementing effective power interruption management solutions. Thus, strategies such as remote working, shift scheduling, and work prioritization have been adopted to reduce power dependency during outages. Additionally, agreements with fuel suppliers and routine maintenance checks ensure the reliability of backup sources. This study contributes to minimize the impact of power interruption on multi-storey commercial buildings in Sri Lanka. Data collection and case studies were conducted within the limitation to multi-storey commercial buildings which have the building structure have more than four floors and located in Colombo, Sri Lanka. As the power impacts are de-pends on the core activities of building, analyse the power interruption impact on other types of consumer categories can be suggested for further studies.

7. References

- Abeberese, A., Ackah, C., & Asuming, P. (2019). Productivity Losses and Firm Responses to Electricity Shortages: Evidence from Ghana. *The World Bank Economic Review*, 35. <https://doi.org/10.1093/wber/lhz027>
- Alahakoon, S. S., Silva, H. A. L. V., & Kulatunga, U. (2022). Factors affecting energy consumption of commercial buildings in Sri Lanka. *15th International Research Conference - FARU 2022*, 248–258. <https://doi.org/10.31705/FARU.2022.28>

- Al-Aomar, R., Al-Mansouri, A., & Al-Laban, M. (2017). *Reducing the interruption of power distribution: A six sigma application*. 226–230. <https://doi.org/10.1109/ICKEA.2017.8169934>
- Al-Janabi, I., Al-Kubaisi, M. A., & Weli, S. S. (2021). *High Rise Buildings: Design, Analysis, and Safety: An Overview*. 8, 1–13. <https://doi.org/10.15377/2409-9821.2021.08.1>
- Amadi, H. N., & Okafor, E. N. C. (2015). *Analysis of Methodologies for the Evaluation of Power Outage Costs; Analysis of Methodologies for the Evaluation of Power Outage Costs*. <https://www.researchgate.net/publication/277166957>
- Arnold, J., Mattoo, A., & Narciso, G. (2008). Services Inputs and Firm Productivity in Sub-Saharan Africa: Evidence from Firm-Level Data. *Journal of African Economies*, 17(4), 578–599. <https://EconPapers.repec.org/RePEc:oup:jafrec:v:17:y:2008:i:4:p:578-599>
- Bahramian, M., & Yetilmezsoy, K. (2020). Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). *Energy and Buildings*, 219, 109917. <https://api.semanticscholar.org/CorpusID:216265137>
- Balasooriya, B. A. D. T., Weerasinghe, W. A. K. W., Abeygunawardane, S. K., & Pindoriya, N. M. (2023). Impact of Interruption Duration on Cost of Unserved Energy: A Survey Based Study for the Commercial Sector in Sri Lanka. *2023 International Conference on System, Computation, Automation and Networking (ICSCAN)*, 1–6. <https://doi.org/10.1109/ICSCAN58655.2023.10395091>
- Basak, R. (2015). *An Article on Electrical Safety*.
- Bernstein, M. A., & Hegazy, Y. (1988). The Economic Costs of Electricity Shortages: A Case Study of Egypt. *The Energy Journal*, 9(2_suppl), 173–188. <https://doi.org/10.5547/ISSN0195-6574-EJ-Vol9-NoSI2-12>
- Bobadilla, S. (2024). *Sri Lanka's Power Grid Reliability: Ripple Effects of the Russia-Ukraine Conflict and Energy Dynamics*.
- Cahvan, V., Lalwani, Y., Mahamuni, M., & Patil, N. (2018). *Planning of Multi-Storey Building Using Advance Tools and Techniques*. <https://doi.org/10.13140/RG.2.2.21386.77769>
- CEB-Annual Report_(2025)_(English). (2025).
- Cissokho, L., & Seck, A. (2013). *Electric Power Outages and the Productivity of Small and Medium Enterprises in Senegal*. www.trustafrica.org/icbeDakar,
- Colambage, D. (2022). Economic Impact of Electricity Interruptions: A Case Study Based on Sri Lanka. *American Journal of Electrical Power and Energy Systems*, 11(1), 1. <https://doi.org/10.11648/j.epe.20221101.11>
- de Nooij, M., Koopmans, C., & Bijvoet, C. (2007). The value of supply security: The costs of power interruptions: Economic input for damage reduction and investment in networks. *Energy Economics*, 29(2), 277–295. <https://doi.org/https://doi.org/10.1016/j.eneco.2006.05.022>
- Fakih, A., Ghazalian, P., & Ghazzawi, N. (2020). The Effects of Power Outages on the Performance of Manufacturing Firms in the MENA Region. *Review of Middle East Economics and Finance*, 16(3). <https://doi.org/10.1515/rmeef-2020-0011>
- Farouk, Dr. A. (2011). *High Rise Buildings and How They Affect Countries Progression*. <https://api.semanticscholar.org/CorpusID:143431030>
- Fernando, W., Gupta, N., Ozveren, C. S., & Kamyab, G. (2019). Renewable energy resources and technologies applicable to Sri Lanka towards a 100% RE future. *8th Renewable Power Generation Conference (RPG 2019)*. <https://api.semanticscholar.org/CorpusID:216796546>
- Godoy-Shimizu, D., Steadman, P., Hamilton, I., Donn, M., Evans, S., Moreno, G. A. M., & Shayesteh, H. (2018). Energy use and height in office buildings. *Building Research & Information*, 46, 845–863. <https://api.semanticscholar.org/CorpusID:115594564>
- Hall, J. R. (2013). *HIGH-RISE BUILDING FIRES*. www.nfpa.org/osds
- Hasan, M. M., & Wyseure, G. (2018). Impact of climate change on hydropower generation in Rio Jubones Basin, Ecuador. *Water Science and Engineering*, 11(2), 157–166. <https://doi.org/https://doi.org/10.1016/j.wse.2018.07.002>
- Hossain, J., Kadir, Aida. F. A., Hanafi, Ainain. N., Shareef, H., Khatib, T., Baharin, Kyairul. A., & Sulaima, Mohamad. F. (2023). A Review on Optimal Energy Management in Commercial Buildings. *Energies*, 16(4). <https://doi.org/10.3390/en16041609>
- Hsieh, H.-F., & Shannon, S. (2005). Three Approaches to Qualitative Content Analysis. *Qualitative Health Research*, 15, 1277–1288. <https://doi.org/10.1177/1049732305276687>
- Ivanov, D. (2022). Blackout and supply chains: Cross-structural ripple effect, performance, resilience and viability impact analysis. *Annals of Operations Research*. <https://doi.org/10.1007/s10479-022-04754-9>
- Jayasinghe, C., Jayathilake, D., & Dissanayake, B. (2016). *Thermal Performance of Composite Walls Made Out Of Recycled Building Waste and Stabilized Rammed Earth*.

- Jonas, T. (2024). Building the intrinsic infrastructure of agroecology: collectivising to deal with the problem of the state. *Agriculture and Human Values*, 41(3), 1223–1237. <https://doi.org/10.1007/s10460-024-10549-4>
- Kamilaris, A., Kalluri, B., Kondepudi, S., & Kwok Wai, T. (2014). A literature survey on measuring energy usage for miscellaneous electric loads in offices and commercial buildings. *Renewable and Sustainable Energy Reviews*, 34, 536–550. <https://doi.org/10.1016/j.rser.2014.03.037>
- Kaygusuz, K. (2016). Hydropower as clean and renewable energy source for electricity generation. *Journal of Engineering Research and Applied Science*, 5(1). <https://www.journaleras.com/index.php/jeras/article/view/52>
- Kolhe, M. L. (2014). Techno-economic analysis of off-grid hybrid renewable energy system for Sri Lanka. *7th International Conference on Information and Automation for Sustainability*, 1–5. <https://api.semanticscholar.org/CorpusID:17200742>
- Levine, M., Blok, K., Yoshino, H., Bertoldi, P., Boardman, B., Brown, M., Joosen, S., Jochem, E., Xu, H., Ürges-Vorsatz, D., Blok, K., Geng, L., Harvey, D., Lang, S., Levermore, G., Mongameli Mehlwana, A., Mirasgedis, S., Novikova, A., Rilling, J., & Yoshino, H. (2007). *Residential and commercial buildings*. France.
- Liu, X., Zhang, H., & Zhu, Q. (2012). Factor Analysis of High-Rise Building Fires Reasons and Fire Protection Measures. *Procedia Engineering*, 45, 643–648. <https://doi.org/10.1016/j.proeng.2012.08.216>
- Lopatin, V. (2016). *Heating, ventilation and air conditioning in buildings Enhancing comfort, safety, and energy efficiency in commercial and residential environments*.
- Mangat, H. S., & Singh, H. (2015). Affect of Disruptive Energy Supply to Different Type of Industrial and Business Players: An Overview of Concepts and Review of Studies from India. *International Journal of Industrial Engineering and Management (IJIEM)*, 6(3), 133–142. www.iim.ftn.uns.ac.rs/ijiem_journal.php
- Meles, T. H. (2020). Impact of power outages on households in developing countries: Evidence from Ethiopia. *Energy Economics*, 91, 104882. <https://doi.org/10.1016/j.eneco.2020.104882>
- Moyo, B. (2012). Do Power Cuts Affect Productivity? A Case Study Of Nigerian Manufacturing Firms. *International Business & Economics Research Journal*, 11. <https://doi.org/10.19030/iber.v11i10.7262>
- Muhamad, W., Mat Zain, M. Y., Wahab, N., Aziz, H., & Kadir, R. (2010). Energy Efficient Lighting System Design for Building. *Intelligent Systems, Modelling and Simulation, International Conference On*, 0, 282–286. <https://doi.org/10.1109/ISMS.2010.59>
- Müller, B., Arlt, W., & Wasserscheid, P. (2011). A new concept for the global distribution of solar energy: energy carrying compounds. *Energy Environ. Sci.*, 4(10), 4322–4331. <https://doi.org/10.1039/C1EE01595H>
- Nadeem, A., Wong, J., Mok, J., & Chan, J. (2012, February). *Performance of Fire Alarms on Building Construction Projects in Hong Kong*.
- Nanayakkara, N. K. V., Perera, B. A. K. S., & Illankoon, I. (2021). On-site renewable energy for industrial buildings in Sri Lanka: a life-cycle cost analysis. *Intelligent Buildings International*, 14, 499–516. <https://api.semanticscholar.org/CorpusID:237894052>
- Nyanzu, F., & Adarkwah, J. (2016). *M P RA Effect of Power Supply on the performance of Small and Medium Size Enterprises: A comparative analysis between SMEs in Tema and the Northern part of Ghana Effect of Power Supply on the performance of Small and Medium Size Enterprises: A comparative analysis between SMEs in Tema and the Northern Part of Ghana*.
- Rahi, S. (2017). Research Design and Methods: A Systematic Review of Research Paradigms, Sampling Issues and Instruments Development. *International Journal of Economics & Management Sciences*, 6. <https://doi.org/10.4172/2162-6359.1000403>
- Rahman, A., Srikumar, V., & Smith, A. D. (2018). Predicting electricity consumption for commercial and residential buildings using deep recurrent neural networks. *Applied Energy*, 212, 372–385. <https://doi.org/10.1016/j.apenergy.2017.12.051>
- Rajapaksha, E. G. L. S., Rathnayake, U., & Karunaratna, A. S. W. (2024). *Feasibility assessment of smart grid technology for the Sri Lankan urban areas*. <https://doi.org/10.31705/WCS.2024.38>
- Rodrigues, E., Fernandes, M., Gomes, A., Gaspar, A., & Costa, J. (2019). Performance-based design of multi-story buildings for a sustainable urban environment: A case study. *Renewable and Sustainable Energy Reviews*, 113, 109243. <https://doi.org/10.1016/j.rser.2019.109243>
- Scott, A., Darko, E., Lemma, A., & Rud, J.-P. (2014). *How does electricity insecurity affect businesses in low and middle income countries?* <http://bit.ly/133tiEa>.

- Sha, H., & Qi, D. (2020). A Review of High-Rise Ventilation for Energy Efficiency and Safety. *Sustainable Cities and Society*, 54, 101971. <https://doi.org/https://doi.org/10.1016/j.scs.2019.101971>
- Sharma, R. (2022). *Sri Lanka Crisis 2022: The Biggest Economic Debacle & Political Turmoil Since 1948 Raagini Sharma (RIEAS Senior Analyst)*. www.rieas.gr
- Smith, G. C., Mumovic, D., & Curtis, L. (2013). Comprehensiveness and usability of tools for assessment of energy saving measures in schools. *Building Services Engineering Research and Technology*, 34(1), 55–71. <https://doi.org/10.1177/0143624412468761>
- Suman, R., Javaid, M., Nandan, D., Bahl, S., & Haleem, A. (2021). Electricity Generation Through Water Supply Pipes in High Rise Buildings. *Journal of Industrial Integration and Management*, 06(04), 449–468. <https://doi.org/10.1142/S2424862220500098>
- Weidner, S., Kelleter, C., Sternberg, P., Haase, W., Geiger, F., Burghardt, T., Honold, C., Wagner, J., Böhm, M., Bischoff, M., Sawodny, O., & Binz, H. (2018). The implementation of adaptive elements into an experimental high-rise building. *Steel Construction*, 11, 109–117. <https://doi.org/10.1002/stco.201810019>
- Wijayatunga, P., & Jayalath, M. S. (2004). Assessment of economic impact of electricity supply interruptions in the Sri Lanka industrial sector. *Energy Conversion and Management*, 45, 235–247. [https://doi.org/10.1016/S0196-8904\(03\)00132-8](https://doi.org/10.1016/S0196-8904(03)00132-8)
- Yasin, R., & Jan, G. (2021). Power outage and proactive service performance: the role of patient incivility and job stress. *International Journal of Productivity and Performance Management*, ahead-of-print. <https://doi.org/10.1108/IJPPM-08-2020-0456>
- Yeaple, S., & Golub, S. (2007). International Productivity Differences, Infrastructure, and Comparative Advantage. *Review of International Economics*, 15, 223–242. <https://doi.org/10.1111/j.1467-9396.2007.00667.x>
- Yoo, E.-H., Lee, C.-R., & Park, K.-H. (2013). Valuing Commercial Spaces in Multistory Buildings Using a Three-level Mixed-effects Modeling Approach. *International Regional Science Review*, 38(4), 413–436. <https://doi.org/10.1177/0160017613505202>
- Zohair, M., & Reddy, K. M. (2018). Analysis and Design of Multistorey Building G+ 4. *International Journal of Advance Research, Ideas, and Innovations in Technology*, 4(1), 43–49.
- Zuo, Y. (2015). *Study on Design of High-Rise Commercial Residential Complex*. <https://doi.org/10.2991/asei-15.2015.79>

THE IMPACT OF LIGHT AND HEAT LEVELS IN THE WORKING ENVIRONMENT ON WORKERS' SAFETY

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Abstract. The quality of the working environment plays a crucial role in workers' health and safety. This study examines the impact of physical workplace conditions, specifically lighting and temperature, on occupational safety in selected factories in Sri Lanka's Western Province. Using a descriptive research design, secondary data were analyzed from environmental monitoring reports and accident registers. The study found a significant negative correlation between light levels and occupational accidents ($r = -0.506$, $p < 0.01$), indicating that improved lighting reduces accident risk. A positive correlation was observed between high temperatures and accidents ($r = 0.367$, $p < 0.01$), suggesting that heat stress contributes to increased incident rates. Among the factories surveyed, 72.7% reported at least one workplace accident. Of the recorded incidents, 75.5% were minor injuries, 20.4% major injuries, and 4.1% fatal. The findings emphasize the necessity of maintaining adequate lighting and thermal conditions to enhance workplace safety. The study recommends stricter enforcement of occupational safety standards and further investigation into other environmental and organizational factors affecting worker health and safety.

Keywords. Occupational Health, Workplace Environment, Safety, Accident Prevention, Environmental Conditions

1. Introduction

The quality of the working environment plays an important role in ensuring workers' health and safety in the workplace. A better physical environment can motivate workers to improve their performance, while cluttered and poorly maintained workplaces are major contributors to accidents and occupational illnesses. Noble (2009) states that greater attention should be given to identifying and addressing working environment conditions, as employees who perceive their environment negatively may suffer from chronic stress. According to Opperman (2002), the working environment includes processes, systems, structures, tools, or conditions in the workplace that can influence individual performance either positively or negatively.

Numerous studies have shown that the physical work environment, including factors such as lighting, temperature, ventilation, and noise can significantly affect workers' job satisfaction, performance, and safety (Sundstrom et al., 1994; Vischer, 2007). In particular, poor lighting has been associated with increased visual fatigue, errors, and workplace accidents (Boyce, 2003), while excessive heat exposure has been shown to reduce concentration and physical performance, thereby increasing accident risks (Parsons, 2014; Ramsey & Bernard, 2000). As a result, employers are increasingly prioritizing the creation of positive and safe working environments, not only to comply with regulatory requirements but also to enhance productivity and employee retention (Zohar, 2000).

1.1. BACKGROUND OF THE STUDY

The working environment is argued to impact immensely on employees' performance either towards negative or the positive outcomes (Chandrasekar 2001). A quality workplace environment leads to reduce the workplace accidents and increase the productivity. A proper workplace environment helps in reducing the number of absenteeism and thus can improve the workers' performance which leads to increased productivity at the workplace (Boles et al.2004).

Governments around the world have recognized the importance of regulating workplace conditions to ensure employee safety, health, and well-being. These regulations aim not only to prevent occupational accidents and illnesses but also to promote fair labor practices and improve employee satisfaction. Research has consistently shown that the physical conditions of the

workplace, including factors such as lighting, temperature, ventilation, and noise can have a substantial impact on workers' job satisfaction, mental health, and performance (Vischer, 2007; Seppanen, Fisk, & Faulkner, 2003). As a result, employers are increasingly focusing on creating conducive work environments to enhance employee motivation and safety outcomes.

The ILO's Decent Work and the 2030 Agenda for sustainable development emphasize that safety and health at work should be ensured by protecting labour rights and promoting safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment. According to the International Labour Organization (ILO), occupational accidents and work-related diseases cause approximately 2.3 million deaths each year, with 6,400 people dying every day due to these causes. Additionally, an estimated 860,000 people are injured on the job daily. The economic cost of these occupational incidents is significant, with an estimated annual loss of US\$2.8 trillion- equivalent to 4 percent of global gross domestic product-resulting from lost working time, production interruptions, treatment costs, and compensation (ILO, 2023). These figures underscore the urgent need for global efforts to promote a culture of prevention that upholds the right to a safe and healthy working environment and ensures that both employers and workers are aware of their responsibilities and rights.

1.2. RESEARCH PROBLEM

Although workplace safety is a critical component of occupational health, many factories in Sri Lanka continue to face challenges related to inadequate physical environmental conditions, particularly poor lighting and excessive heat. These factors are often overlooked in occupational safety assessments, despite growing evidence that they significantly influence workers' well-being, performance, and risk of injury. While general studies exist on working conditions, there is a lack of focused research examining how specific environmental elements such as light and heat levels affect safety outcomes in industrial settings. This gap limits the ability of employers, policymakers, and safety officers to implement evidence-based interventions. Therefore, this study seeks to investigate the extent to which light and heat levels in factory environments impact the safety of workers, aiming to provide data-driven recommendations for improving occupational conditions and reducing workplace accidents.

1.3. RESEARCH OBJECTIVES

This research was guided by the following study objectives. The main objective of this study was to explore the impact of light and heat levels in the working environments on the safety of workers in selected factories in the Western province. The specific Objectives of this study were,

- To identify appropriate methods for measuring light and heat levels in the working environment.
- To evaluate the relationship between lighting and heat levels in the workplace and work-related accidents.
- To assess the current light and heat conditions in selected factories.
- To provide recommendations for improving workplace lighting and thermal conditions to enhance workers' safety.

1.4. RESEARCH QUESTIONS

1. What are the appropriate methods for measuring light and heat levels in the working environment?
2. What are the existing light and heat conditions in the selected factories?

3. Is there a relationship between workplace lighting and heat levels, and work-related accidents?

4. How can improvements in lighting and heat conditions contribute to enhanced worker safety?

This study was designed to examine the impact of light and heat levels in the working environments on safety of the workers in selected industries in Western province.

2. Literature Review

Numerous studies have established that physical environmental factors significantly affect workplace safety and employee performance. Among these, lighting and temperature play critical roles in influencing both the physical and cognitive functioning of workers.

Lighting is a key component of a safe and productive work environment. Adequate illumination helps reduce visual fatigue, improve precision in manual tasks, and prevent accidents caused by poor visibility (Boyce, 2003). Insufficient lighting has been linked to an increased likelihood of slips, trips, and falls, especially in industrial settings where workers must navigate machinery or hazardous materials (Hedge, 2000). Studies also show that poor lighting conditions can impair concentration and increase error rates, which in turn can elevate accident risks (Veitch & Newsham, 2000). The International Labour Organization (ILO, 2010) emphasizes lighting as a fundamental aspect of workplace safety regulations.

In parallel, temperature, particularly heat stress, has been identified as a major occupational hazard. Exposure to high temperatures can cause thermal discomfort, fatigue, dehydration, and reduced mental alertness (Parsons, 2014). These physiological responses may impair motor coordination and decision-making, increasing the likelihood of workplace injuries (Ramsey & Bernard, 2000). Furthermore, prolonged exposure to hot environments is associated with heat-related illnesses, which can affect long-term worker health and increase absenteeism (Kjellstrom et al., 2009). The risk is particularly high in factory environments where machinery and enclosed spaces contribute to elevated temperatures.

Consequently, the physical environment is a tool that can be leveraged both to improve business results (Mohr, 1996) and employee well-being (Huang, Robertson and Chang, 2004). Ensuring adequate facilities are provided to employees is critical to generating greater employee commitment and productivity. The provision of inadequate equipment and adverse working conditions has been shown to affect employee commitment and intention to stay with the organization.

Furthermore, McCoy and Evans (2005) stated that the elements of working environment need to be proper so that the employees would not be stressed while getting their job done. In their article, they also stated that the physical element plays an important role in developing the network and relationship at workplace. Result of the employees' performance can be increased from five to ten per cent depending on the improvement of the physical workplace design at their workplace (Brill, 1992).

An effective work environment management entails making work environment attractive, creative, comfortable, satisfactory and motivating to employees so as to give employees a sense of pride and purpose in what they do. The following are some of the tools used to manage work environment to improve productivity. Noise control, contaminants and hazard control, enhancing friendly and encouraging human environment, job fit, rewards, feedback, work environment modelling, creating qualitative work life concepts and making physical working conditions favourable (Cecunc, 2004; Opperman, 2002; Elywood, 1999).

Although much of the global literature highlights the importance of the environmental factors, few studies have examined the specific correlation between lighting, heat levels, and accident rates in factory settings within the Sri Lankan context. This research seeks to address this gap by offering empirical evidence on how variations in light and heat relate to workplace accidents, thereby contributing region-specific data to the broader field of occupational health and safety.

3. Research Methodology and Design

This section describes the methods that were used to gather the data relevant to the study. It contains the research design, study area, population, sample size and sample technique, sampling procedure and explains the method and procedures for data collection.

3.1. RESEARCH METHODOLOGY

Research design refers to a plan which shows the strategy of an inquiry thought appropriate to the research (Kothari, 2004). For the purpose of this study, descriptive research design was used. Since the data for this study were collected from various sources and the research focused on identifying and evaluating the impacts of the physical environment, specifically light and heat levels in factories, the study was primarily evaluative in nature. The collected data were analysed using descriptive analysis techniques.

3.2. STUDY AREA

The study area for this research was the selected factories those are situated in the western province of Sri Lanka. The target population of this study included the factories and their workers in the selected province.

3.3. SAMPLE SIZE, SAMPLING TECHNIQUE AND DATA COLLECTION METHODS

Twenty-two factories from the Western Province were selected as samples for this study. The convenience sampling method was used as the sampling technique. In this study, secondary data were used for data collection. Secondary data refer to information that has been collected by someone else and already exists. These data were obtained by reviewing various documents, such as inspection reports and environmental monitoring reports of factories, which were sourced from the Occupational Hygiene Division of the Labour Department. And also general registers of factories were analysed to collect data about accidents and dangerous occurrences in factories. These data included the number of reported occupational accidents, types of injuries, and recorded measurements of workplace lighting (in lux) and heat stress (WBGT in degrees Celsius) over a period. Websites of Department of Labour, Industrial Safety Divisions and Annual Labour statistics reports of Department of Labour, which are relevant to the theme of the study, were used for the purpose of gathering information. All secondary data were sourced from documented, officially maintained records to ensure accuracy and reliability.

4. Results and Discussion

The collected data were analysed using descriptive statistics to summarize key variables such as mean light levels, average heat stress, and accident frequencies across the sample. The software used for analyzing the findings included Microsoft Excel 2010 and the Statistical Package for the Social Sciences (SPSS) version 17.0. Pearson correlation analysis was then used to explore the strength and direction of relationships between light levels and accident rates, and separately between heat levels and accident rates. The correlation coefficients provided a basis for interpreting whether higher or lower environmental values were associated with increased or decreased accident frequencies. Where appropriate, graphical representations such as tables and charts were used to visualize the data relationships and enhance understanding. The sample

of 22 factories was taken and their environmental monitoring reports and general registers were analysed for the purpose of collecting data. Below is the analysis of collected data.

4.1. TYPE OF FACTORIES

The sample included a variety of factory types from the selected province. The distribution of these factories by type is shown in Figure 4.1. Among the selected factories, the majority were steel-based factories, accounting for 33%.

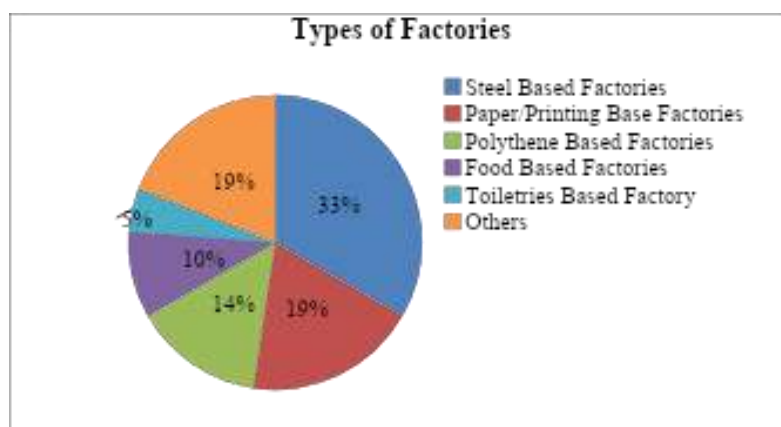


Figure 1: Types of factories

4.2. PHYSICAL WORKING ENVIRONMENT

In this study, the physical working environment was considered a key factor in determining the overall quality of the working environment. It is one of the major contributors to the health and safety of workers. The distribution of factories based on physical working environment characteristics is presented in Table 1.

Table 1: Distribution of factories according to the physical working environment.

Quality of working environment	Number of factories	Percent	Valid Percent	Cumulative Percent
Bad	4	18.2	18.2	18.2
Good	8	36.4	36.4	54.5
Moderate	8	36.4	36.4	90.9
Very Bad	2	9.1	9.1	100.0
Total	22	100.0	100.0	

According to Table 4.1, the majority of the factories have a good or moderate working environment (36.4%). In some factories, the quality of the working environment is very poor (9.1%). None of the factories in the selected sample were classified as having a very good working environment.

4.3. NUMBER OF ACCIDENTS

Table 4.2 explains the number of accidents occurred in the selected factories in particular time period.

Table 2: Number of accidents

Number of accidents	Number of factories	Percent	Valid Percent	Cumulative Percent
0	6	27.3	27.3	27.3
2	8	36.4	36.4	63.6
3	2	9.1	9.1	72.7
4	4	18.2	18.2	90.9
5	1	4.5	4.5	95.5
6	1	4.5	4.5	100.0
Total	22	100.0	100.0	

From the table it was noted that, in 27.3% of selected factories didn't record any accident in particular period and 4.5% of factories recorded more than five accidents.

4.4. NATURE OF ACCIDENTS

According to the severity of accidents, distribution of accidents is shown in Table 3.

Table 3: Distribution of accidents according to the severity

Severity	Number of accidents	Percent	Valid Percent	Cumulative Percent
Fatal	2	4.1	4.1	4.1
Major Injuries	10	20.4	20.4	24.5
Minor Injuries	37	75.5	75.5	100.0
Total	49	100.0	100.0	

According to the Table 3, two accidents are fatal accidents and 75.5% of accidents are recorded as minor injuries.

4.5. RELATIONSHIP BETWEEN LIGHT AND HEAT LEVELS OF WORKING ENVIRONMENT AND ACCIDENTS

Table 4: Relationship between light levels and number of accidents

No. Of accidents	Pearson Correlation	1	Light Level
	Sig. (2-tailed)		.000
	N	55	55
Light	Pearson Correlation	-.506**	1
	Sig. (2-tailed)	.000	
	N	55	55

** . Correlation is significant at the 0.01 level (2-tailed).

The data presented in Table 4 indicate a negative correlation between light levels and the number of occupational accidents. This suggests that lower light levels are associated with a higher frequency of accidents, whereas higher light levels tend to correspond with fewer incidents. This relationship is consistent with existing literature, which highlights that inadequate lighting can impair visibility, reduce hazard recognition, and increase the likelihood of slips, trips, and contact with machinery or objects (Boyce, 2003). Poor illumination may also contribute to visual fatigue, which can compromise workers' alertness and reaction time.

However, while this negative correlation supports the hypothesis that light levels influence workplace safety, it is essential to emphasize that correlation does not imply causation. The observed trend may be influenced by a combination of factors beyond lighting alone. These may include the nature of tasks performed, the design of the work environment, and adherence to safety protocols, shift timing, worker training, psychological stress, and fatigue. For instance, poorly lit environments may also coincide with less supervision or out-dated equipment, further increasing risk.

Therefore, while enhancing lighting conditions appears to be a practical intervention to reduce accidents, a comprehensive approach that addresses multiple environmental and human factors is necessary for meaningful improvements in workplace safety.

Table 5: Relationship between heat levels and number of accidents

		No. Of accidents	Heat Level
No. Of accidents	Pearson Correlation	1	.367**
	Sig. (2-tailed)		.006
	N	55	55
Heat	Pearson Correlation	.367**	1
	Sig. (2-tailed)	.006	
	N	55	55
**. Correlation is significant at the 0.01 level (2-tailed).			

The data presented in Table 5 reveal a positive but weak correlation between the heat level of the working environment and the number of occupational accidents. This indicates that as ambient temperature increases, the number of workplace accidents tends to rise slightly, and conversely, as temperature decreases, accident rates tend to decline marginally. Although the correlation is not strong, the direction of the relationship aligns with existing research suggesting that excessive workplace heat can negatively affect workers' safety and performance.

Heat exposure has been shown to impair concentration, increase fatigue, and reduce physical and cognitive performance, all of which may elevate the risk of accidents, particularly in physically demanding or precision-based tasks (Parsons, 2014; Ramsey & Bernard, 2000). Additionally, thermal discomfort can lead to reduced alertness and slower reaction times, making workers more prone to errors or unsafe behaviours. However, the modest strength of the observed correlation implies that while heat is a contributing factor, it is likely not the sole or primary cause of accidents.

Other factors, such as the nature of the job, duration of exposure, availability of rest breaks, hydration status, ventilation systems, safety training, and behavioural responses may have a stronger influence on accident rates. It is also possible that workers develop adaptive behaviours or coping mechanisms that mitigate some of the risks associated with moderate heat exposure. Therefore, while heat control remains an important occupational safety consideration, it should be addressed alongside a range of physical, organizational, and psychosocial factors to effectively reduce workplace accidents.

5. Conclusion and Recommendations

The findings of this study confirm that physical aspects of the working environment, specifically light and heat levels have a measurable impact on workers' health and safety. The analysis revealed that inadequate lighting and elevated temperatures are associated with increased occupational accidents in factory settings. Therefore, it is evident that improving these environmental conditions is essential for enhancing workplace safety and reducing the incidence of injuries.

Based on the results, it is recommended that factory employers take proactive steps to ensure a safe and high-quality working environment. This includes maintaining optimal lighting conditions and controlling indoor temperatures to minimize risks associated with poor visibility and heat stress. Such improvements will not only support worker health but also contribute to overall productivity and operational efficiency.

This study was limited to selected factories in the Western Province of Sri Lanka, focusing solely on the effects of light and heat levels. While these limitations may narrow the generalizability of the findings, they also present opportunities for future research. Further studies are encouraged to explore additional environmental factors, such as noise, air quality, and ergonomic design and their combined effects on occupational health and safety across diverse industrial sectors and geographic regions.

Although previous research has examined the broader effects of workplace environments on employee well-being and productivity, few studies have investigated the direct correlation between measurable environmental parameters (light and heat levels) and occupational accident rates, particularly in developing country contexts. This study contributes new knowledge by offering quantitative, correlation-based evidence from Sri Lankan factory settings, where such data have been limited. By integrating secondary accident records with on-site environmental measurements, the research provides actionable insights that can inform safety audits and workplace design strategies. Furthermore, it underscores the need for stronger regulatory enforcement and environmental monitoring in occupational health and safety systems, especially in regions where implementation gaps remain.

This context-specific contribution helps fill a gap in the existing literature and highlights the critical role of environmental controls in safeguarding worker health and safety.

6. References

- Babisch, W., Ising, H., Gallacher, J. E., Sweetnam, P. M., & Elwood, P. C. (1999). Traffic noise and cardiovascular risk: The Caerphilly and Speedwell studies, third phase–10-year follow-up. *Archives of Environmental Health: An International Journal*, 54(3), 210–216.
- Boles, M., Pelletier, B., & Lynch, W. (2004). The relationship between health risks and work productivity. *Journal of Occupational and Environmental Medicine*, 46(7), 737–745.
- Boyce, P. R. (2003). *Human factors in lighting*. Crc press.
- Cecunc, E. (2004). *Improving employee productivity in regulating industries*. Academic Pres, New York.
- Chandrasekar, K. (2011). Workplace Environment & Its impact on organizational performance in public sector organizations. *International journal of Enterprise computing and Bussiness systems*.
- Department of Labour (2024). *Department of Labour*. Retrieved June 5, 2024, from Annual Reports: <https://labourdept.gov.lk/annual-reports/>
- Huang, Y. R. (2004). *The role of environmental control on environmental satisfaction, communication, and psychological stress: effect of officenergonomics training*: Environment and Behaviour.
- International Labour Organization. (2019). *Decent work and the 2030 Agenda for sustainable development*. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40europe/%40ro-geneva/%40ilo-lisbon/documents/event/wcms_667247.pdf
- Kjellstrom, T., Holmer, I., & Lemke, B. (2009). Workplace heat stress, health and productivity—an increasing challenge for low and middle-income countries during climate change. *Global health action*, 2(1), 2047.
- Kothari, C. R. (2004). *Research methodology: Methods and techniques*. New Age International.
- McCoy, J. M., & Evans, G. W. (2005). Physical work environment. In *Handbook of work stress* (pp. 219–246). SAGE Publications, Inc..
- Noble, C. (2009). *Business performance and employee wellbeing: A resource-based approach*. University of Nottingham.

- Opperman, C. S. (2002). *Tropical business issues*. Partner Price Water House Coopers. International Business Review.
- Parsons, K. (2014). Human thermal environments: *The effects of hot, moderate, and cold environments on human health, comfort and performance* (3rd ed.). CRC Press.
- Ramsey, J. D., & Bernard, T. E. (2000). Heat stress—the effects of heat on working populations. *Journal of Occupational and Environmental Medicine*, 42(1), 94–100.
- Seppanen, O., Fisk, W. J., & Faulkner, D. (2003). *Cost benefit analysis of the night-time ventilative cooling in office building*.
- Sundstrom, E., Town, J. P., Rice, R. W., Osborn, D. P., & Brill, M. (1994). Office noise, satisfaction, and performance. *Environment and behavior*, 26(2), 195-222.
- Veitch, J. A., & Newsham, G. R. (2000). Preferred luminous conditions in open-plan offices: Research and practice recommendations. *Lighting Research & Technology*, 32(4), 199–212.
- Vischer, J. C. (2007). *The concept of environmental comfort in the performance of the work environment*, 7(1), 21-34.
- Zohar, D. (2000). A group-level model of safety climate: testing the effect of group climate on microaccidents in manufacturing jobs. *Journal of applied psychology*, 85(4), 587.

DECISION-MAKING CRITERIA FOR BOILER MAINTENANCE: AN EMPIRICAL STUDY

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Abstract. Accurate decision-making in boiler maintenance is essential to ensuring efficiency, reliability and cost-effectiveness, especially in low-tech integrated buildings where manual data collection is prevalent. This study identifies key criteria for boiler maintenance decision-making to support structured and data-driven maintenance. A comprehensive literature survey was conducted to identify the key boiler maintenance activities which had been studied by different scholars. In addition to that, a qualitative research approach was adopted, including expert interviews and the Delphi technique, to develop the criteria based on practical understanding. Findings highlight critical factors such as equipment-specific parameters, resource allocation, and operational impact, influencing effective maintenance decisions. The proposed criteria provide a structured basis for improving boiler maintenance practices in low-tech environments. This research contributes to developing a systematic software-based decision-making model that enhances maintenance efficiency, minimizes downtime, and optimizes operational performance.

Keywords. Boiler Maintenance, Decision-Making Criteria, Low-Technology Buildings, Manual Data Collection, Preventive Maintenance, Predictive Maintenance, Delphi Technique

1. Introduction

Building service systems deteriorate with time due to operational usage and environmental factors, which produce system failures that affect safety levels, operational quality and system availability (Alaswad & Xiang, 2017). Traditional methods of maintenance include performing maintenance only after failures which complicates maintenance management activities within organizations (Jonge & Scarf, 2020). In contrast, modern maintenance aims to achieve occupant satisfaction alongside safety and regulatory compliance standards through data-driven decision-making (Mydin, 2015).

Maintenance decision-making heavily depends on data collection of building systems and their maintenance activities. Despite the availability of advanced technologies such as IoT, smart sensors, and BIM, most organizations continue to use manual data collection methods. (Mahlamaki & Nieminen, 2020). Higher implementation costs for sensor networks and analytics platforms (Senthilkumar et al., 2023), institutional resistance to digitization in traditionally manual workflows (Pasi & Muller, 2007), and skill gaps in interpreting IoT-generated data among maintenance staff (Agarwal & Suhane, 2017) have hindered the adaptation of digital technologies in building maintenance.

Boilers are one of the critical building systems in buildings where building heating and hot water or steam facilities are available (Patil et al., 2022). In manual operations and maintenance, boilers are considered a critical component, particularly in low-tech integrated buildings which are defined as facilities that rely on manual or semi-automated systems due to budget constraints or lack of technical infrastructure such as old industrial plants in developing economies (Khalil et al., 2021). Rodrigues et al. (2023) demonstrated how maintenance decisions play a vital role in cost-effective operations, as studies reveal that maintenance costs account for between 2-20% of operating costs in various building sectors. Furthermore, in terms of the health and safety of the building occupants, data-driven decision-making in boiler maintenance provides a secured workplace for the occupants, by predicting associated risk based on the prevailing data (Patil et al., 2022). Existing research highlighted the relevance of reactive maintenance strategies in such environments, where manual inspections and logbooks relied. For instance, Yang et al. (2020) demonstrated the potential of IoT to reduce downtime by 30%

through predictive analytics, but these technologies are rarely applied in resource-constrained settings. Similarly, Triantaphyllou et al. (1997) established frameworks for multi-criteria decision-making but did not address manual data handling limitations. This exacerbates the gap in boilers where maintenance decisions often prioritize short-term cost savings over long-term efficiency. In addition to that, Widyanto (2025) introduced a decision support model for determining fuel in boilers, but a comprehensive study of decision-making in boiler maintenance is still lacking.

Therefore, there is a need to develop a multi-criteria maintenance decision-making model using manually collected data to achieve operational efficiencies. This research aims to identify boiler maintenance decision-making criteria to develop a software-based multi-criteria maintenance decision-making model using manually collected data for low-tech integrated buildings. The objectives include reviewing existing boiler maintenance activities and identifying boiler maintenance criteria. Limiting to oiled fired firetube boilers with capacities ranging from 1000kg/hr. to 1800kg/hr.

2. Literature Review

This review explores existing boiler maintenance activities and identifies the criteria that have been studied by other scholars in the field. Modern industries depend heavily on boilers to generate steam and hot water throughout their operation. Other applications include power production, oil extraction, food processing and heat-based sterilization (Bhatt et al., 2023). Hotels and healthcare facilities depend on boilers because these supply heat and offer both laundry and medical sterilization functions (Favero, 2007). Greenhouse heating and crop processing in agriculture also utilize boilers (Reinoso et al., 2021). Moreover, high-capacity boilers serve district heating systems as well as support domestic water heating and space heating applications according to Bennett et al. (2019).

Boilers are generally classified based on fuel type, design and application. Design types include water tubes, fire tubes, packed, fluidized beds and pulverized fuel boilers (Singh et al., 2018). Boiler maintenance relies on three maintenance approaches including corrective, preventive and predictive methods to extend operational life and improve performance. Preventive maintenance requires regular inspections along with cleaning and stopping system failures (ER-Ratby & Mabrouki, 2018). The combination of analytics in predictive maintenance allows organizations to optimize resource use by monitoring both temperature variations and vibrational signals (Moleda et al., 2020). The procedures of corrective maintenance involve repairing broken device components and fixing leaking areas (Arno et al., 2015).

2.1 KEY MAINTENANCE ACTIVATES IN BOILERS

Maintenance is a set of activities that are organized to keep the operation condition of an asset at its expected level with minimum cost. Those are activities which aim either to prevent failures or rectify existing issues. Therefore maintenance is a combination of financial and engineering activities that are coupled and suitable for the convenience of its users throughout its life cycle by restoring, configuring, commissioning, parameterizing, diagnosing, repairing, managing assets and auditing (Agarwal & Suhane, 2017). Maintenance activities for critical components in boilers are synthesized in Table 1.

Table 1: Key maintenance carried out on boiler key components

Key Component	Key Maintenance Activities	Source
Feed Pump	Replace worn seals to prevent leaks and maintain operating pressure.	(Leishear et al., 2007)
	Replace damaged impellers to maintain efficient water flow.	

	• Realign the motor shaft with pump coupling to reduce vibration and wear. • Lubricate and clean bearings to reduce friction and extend life. • Replace worn or damaged couplings to ensure smooth power transmission.	
Economizer	• Remove soot and ash deposits to restore heat transfer efficiency. • Replace corroded or eroded pipes to prevent leaks. • Apply protective coatings to reduce corrosion caused by acidic flue gases. • Replace loose economizer fittings and supports.	(Arifin & Herlina, 2022)
Feed Water Tank	• Remove sediment and sludge from the bottom of the tank to maintain water quality. • Replace worn or damaged inlet and outlet valves to ensure proper flow control. • Apply anti-corrosion coatings or paints to prevent internal rust. • Replace damaged or deteriorated insulation to maintain consistent water temperatures. • Clear clogged drainpipes to ensure proper drainage.	(Rahmania et al., 2020) (Johnston, 2020)
Heat Exchanger	• Use chemical stripping agents to remove mineral buildup. • Replace cracked heat exchanger tubes. • Reinforce tube sheets to maintain structural integrity. • Clean internal and external surfaces to improve heat transfer.	(Kuchař et al., 2018)
Combustion Chamber	• Remove ash and slag deposits to maintain proper combustion airflow. • Replace or patch cracked reflector linings to effectively contain heat. • Replace defective igniters. • Resurface-worn chamber interior to maintain thermal efficiency. • Cracks in combustion chamber welds.	(Singh et al., 2018)
Burner	• Replace worn or clogged nozzles to maintain efficient fuel spray patterns. • Clean or replace damaged burner electrodes for proper ignition. • Calibrate air dampers to ensure the correct air-fuel mixture. • Tighten or replace burner flanges to prevent instability during operation.	(Sarofim, 2001)
Exhaust Stack	• Apply coatings to protect the stock from high temperatures. • Replace or patch corroded parts. • Clean accumulated soot or carbon deposits to ensure unobstructed airflow. • Replace defective draft regulators to ensure proper exhaust.	(Elkelawy, 2019)
Safety Valve	• Replace worn springs to maintain pressure relief function. • Polish valve seats to ensure a tight seal. • Replace corroded or damaged discs for effective pressure regulation. • Replace worn gaskets to prevent leaks.	
Pressure Gauge	• Replace damaged internal mechanisms for accurate pressure readings. • Clean the measurement ports to ensure unobstructed pressure transmission.	

	• Replace or tighten loose fittings to prevent leakage at measurement connections.	

According to Table 1, 9 key components were identified which require thorough attention in maintenance. Several key maintenance activities were identified under each key component. Among them, the feed pump requires replacing worn seals, replacing damaged impellers, realigning the motor shaft with coupling, lubricating and cleaning bearings, and replacing worn or damaged couplings. The key maintenance activities of the economizer are removing soot and ash deposits, replacing corroded or eroded pipes, applying protective coatings, and replacing loose economizer fittings and supports. Furthermore, the feed water tank requires removing sediment and sludge, replacing worn or damaged inlet and outlet valves, applying anti-corrosion coatings or paints to prevent internal rust, replacing damaged or deteriorated insulation, and clearing clogged drainpipes. The key maintenance activities of heat exchangers are removing mineral buildup, replacing cracked heat exchanger tubes, reinforcing tube sheets, and cleaning internal and external surfaces. The combustion chamber requires removing ash and slag deposits, replacing or patching cracked reflector linings, replacing defective igniters, resurfacing worn chamber interiors and fixing cracks in combustion chamber welds.

In addition, replacing worn or clogged nozzles, cleaning or replacing damaged burner electrodes, calibrating air dampers, and tightening or replacing burner flanges are key maintenance activities of the burner. Exhaust stack requires applying coatings, replacing or patching corroded parts, cleaning accumulated soot or carbon deposits, and replacing defective draft regulators. Key maintenance activities of the safety valve are replacing worn springs, polishing valve seats, replacing corroded or damaged discs, and replacing worn gaskets. Pressure gauge requires replacing damaged internal mechanisms, cleaning the measurement ports, and replacing or tightening loose fittings as key maintenance activities.

2.2 REVIEW OF MAINTENANCE DECISION-MAKING CRITERIA

Several scholars have studied the decision-making criteria related to different aspects of boilers. Widyanto (2025) introduced a decision support model for determining fuel in boilers. Patil et al. (2022) developed an optimized maintenance program for boiler systems using a reliability-centered maintenance approach. Demirel et al. (2021), developed a PROMETHEE decision model to prioritize energy efficiency practices for industrial steam boilers. According to Ahmad & Kamaruddin (2012), condition-based maintenance decision-making involves assessing the current condition of the equipment and conducting maintenance activities based on the findings of the assessment to enhance the performance or restore the standard performance levels. Effective boiler maintenance in resource-limited environments requires structured decision-making frameworks to prioritize actions among competing operational demands. Traditional approaches often rely on reactive strategies but recent research suggests that multi-criteria models can balance various factors. (Disegna, 2018). Estimate equipment-specific parameters used, include the reliability, repairability and total lifecycle of machinery (Hassanain et al., 2015). Resource allocation includes trained labour, spare parts, and financial capacity, which affect maintenance feasibility (Poppe et al., 2017). The operational impact is managed by scheduling maintenance during periods of low demand to minimize disruptions (Bangari et al., 2019). Technological advances such as predictive analytics, IoT, and condition monitoring have transformed maintenance into a proactive task, reducing unplanned downtime and improving reliability (Green et al., 2022).

Triantaphyllou et al. (1997) showed that criteria such as "steam pressure deviation" and "flue gas temperature differences" are very important for fire tube boilers, and when integrated into preventive schedules, they reduce downtime by 25%. Similarly, ResQ's guidelines highlighted

the role of feedwater flow rates (<4 bar) and sediment levels in determining maintenance urgency. This shows weighted decision models for assessing these criteria, including AHP as well as WSM, and demonstrates their importance for low-tech implementations where IoT/BIM integration is limited.

3. Methodology

This section discusses the research methodology used to identify boiler maintenance decision-making criteria for the Sri Lankan context. The Delphi method was used to identify boiler maintenance criteria, which was carried out by iterative expert consensus, and included three rounds of testing. Semi-structured interviews identified 38 initial criteria across boiler components (Table 3). Experts provided open-ended feedback on operational thresholds. Then, assessed agreements on criteria (Criteria retained only if supported by ≥ 4 experts' practical logs). Finally, revised criteria which analysed and summarized were redistributed with experts to obtain feedback (35/38 criteria reached 90% agreement: Table 4).

Interviews with five boiler maintenance experts (Table 2) with extensive experience were conducted using a semi-structured format. After conducting the first interview with an expert, a second interview was structured including the main findings of the first interview. This process was repeated throughout all 5 interviews to collect more insightful findings due to the limitation of the literature in this area. This method enabled in-depth investigation into maintenance decision-making criteria while collecting both theoretical understanding and practical knowledge from the experts. Additional data sources maintenance logs, visual inspection reports, and feedback from technicians on the effectiveness of various maintenance tasks were used for the data collection.

Manual qualitative content analysis is used for data analysis. Systematically coded to identify recurring themes, patterns, and criteria relevant to boiler maintenance. The analysis followed a stepwise process: organizing data, coding for key concepts, grouping codes into broader themes, and synthesizing insights for decision-making. Especially, findings obtained from interviews, log analysis, and literature review were cross-validated to ensure the reliability and robustness of the identified criteria.

Table 2: Profiles of Experts

Expert Name	Organization	Experience Level	Role
E1	Steam engineering company	34 years	Regional Site Manager in boiler maintenance
E2	Hotel	35 years	Chief Engineer specializing in steam engineering.
E3	Hotel	32 years	12 years experience as a shift engineer in boilers
E4	Outsourcing	18 years	Site Executive in boiler maintenance.
E5	Hotel	52 years	Experienced boiler operator (50+ years).

4. Findings and Discussion

While the literature emphasizes theoretical best practices, expert insights are based on practical, experiential knowledge. Appropriate criteria were obtained by majority agreement of the experts or by considering the common suggestions provided. The summary of the expert interviews is shown in Table 3.

Table 3: Findings of expert interviews

Key Component	Key Maintenance Activities	Input Data (From Expert Interviews)	Experts' Opinion on Maintenance Criteria					Suitable Criterion
			E1	E2	E3	E4	E5	
Feed Pump	FPMA 1	Pump Operating Hrs	12,000hrs	10,000hrs	12,000hrs	12,000hrs	-	12,000hrs
	FPMA 2	Feed Water Flow Rate	4 -6 bars	Below 4 bars	Below 4 bars	Below 4 bars	Below 4 bars	Below 4 bars
	FPMA 3	Operating Temp	85-110°C	90°C	90°C	110°C	90°C	Above 90°C
	FPMA 4	Amperage Logs	Increase	Increase	Annually	Increase	Annually	Increase
Economizer	EMA 1	Flue Gas Temp	190-220°C	Above 190 °C	190-200°C	Above 190°C	Above 200°C	Above 190°C
Feed Water Tank	FWTMA 1	Sediment Levels	Annually	Annually	Annually	Annually	Annually	Annually
		Return Hot Water Temp	Below 90°C	Below 85°C	Below 90°C	Below 90°C	Below 90°C	Below 90°C
	FWTMA 2	Return Hot Water Temp	Above 90°C	Above 95°C	Above 90°C	Above 90°C	Above 90°C	Above 90°C
	FWTMA 3	FW Temp	Below 85-90°C	Below 90°C	Below 90°C	Below 80°C	Below 85°C	Below 90°C
	FWTMA 4	FW Flow Rates	Below Operating	Below 4 bars	Below 4 bars	Below Operating	Below Operating	Below Operating
	FWTMA 5	Boiler Water Level	Above Baseline	Above Baseline	Above Baseline	Above Baseline	Above Baseline	Above Baseline
	FWTMA 6	FWT Water Level	Above Baseline	Above Baseline	Above Baseline	Above Baseline	Above Baseline	Above Baseline
Heat Exchanger	HEMA 1	Steam Production Rate	Below Daily Requirement	Below 1800 kg/hr	Below 1200 kg/hr	Below Daily Requirement	Below 1100 kg/hr	Below daily requirement
	HEMA 2	Hydro Test	Water leak	-	-	Water leak	Water leak	Water leak
	HEMA 3	Flue Gas Temp	190-220°C	Above 190 °C	190-200°C	Above 190°C	Above 200°C	Above 190°C
Combustion Chamber	CCMA 1	Steam Pressure	Pressure Drop	Below 9 bars	Below 8 bars	Pressure Drop	Below 9 bars	Below 9 bars
	CCMA 2	Physically	Break Down	Break Down	Break Down	Break Down	Break Down	Break Down
	CCMA 3	Steam Temp	Above 160-170°C	Above 160°C	Above 170°C	Above 160-180°C	Above 170°C	Above 170°C

Burner	BMA 1	Flue Gas Temp	190-220°C	Above 190 °C	190-200°C	Above 190°C	Above 200°C	Above 190°C
		Operating Hrs	2000-3000hrs	2000hrs	1500hrs	2000hrs	-	2000hrs
	BMA 2	Visual	Poor Spark	Poor Spark	Poor Spark	Poor Spark	Poor Spark	Poor Spark
	BMA 3	O ₂ Level at Exhaust	Increase	Increase	Increase	Increase	-	Increase
	BMA 4	Fuel Readings	Overconsumption	-	Overconsumption.	Overconsumption	-	Overconsumption
	BMA 5	Steam Productivity	Below Daily Requirement	Below 1800 kg/hr	Below 1200 kg/hr	Below Daily Requirement	Below 1100 kg/hr	Below daily requirement
		Steam Temp	Below 160-170°C	Below 160°C	Below 170°C	Below 160-180°C	Below 170°C	Below 170°C
	BMA 6	Fuel Readings	Overconsumption	Overconsumption	Overconsumption	Overconsumption	Overconsumption	Overconsumption
	BMA 7	Visual	Poor Spark	Poor Spark	No Spark	Poor Spark	No Spark	Poor Spark
Exhaust Stack	ESMA 1	Flue Gas Temp	Below 190°C	Below 190°C	Below 190°C	Below 190°C	Below 200°C	Below 190°C
	ESMA 2	CO Readings	100 – 200 ppm	200 ppm	300 ppm	100 – 200 ppm	-	Above 200 ppm
Safety Valve	SVMA 1	Valve Popping Pressure	8-10 bars	9 bars	8 bars	8-10 bars	9 bars	Deviation
	SVMA 2	Steam Pressure	Pressure Drop	Below 9 bars	Below 8 bars	Pressure Drop	Below 9 bars	Below 9 bars
	SVMA 3	Steam Leak	Break Down	Break Down	Break Down	Break Down	Break Down	Break Down
	SVMA 4	Steam Leak	Break Down	Break Down	Break Down	Break Down	Break Down	Break Down
Pressure Gauge	PGMA 1	Steam Pressure Readings	Break Down	Break Down	Break Down	Break Down	Break Down	Break Down
	PGMA 2	Steam Pressure Readings	Break Down	Break Down	Break Down	Break Down	Break Down	Break Down
	PGMA 3	Steam Pressure Readings	Break Down	Break Down	Break Down	Break Down	Break Down	Break Down
Boiler Shell	BSMA 1	Blowdown	Break Down	Break Down	Break Down	Break Down	Break Down	Break Down

	BSMA 2	Steam Pressur e	Above 9 bars	Above 9 bars	Above 8 bars	Above 9 bars	Above 9 bars	Above 9 bars

Combining all the findings of the literature review and expert interviews, a decision-making criterion for boiler maintenance was developed. The developed boiler maintenance decision-making criteria are shown I Table 4.

Table 4: Decision-making criteria for boiler maintenance

Key Component	Key Maintenance Activities	Input Data	Criteria
Feed Pump	• Replace worn seals	• Pump Operating Hrs	12,000hrs
	• Replace damaged impellers	• Feed Water Flow Rate	Below 4 bars
	• Lubricate and clean bearings	• Operating Temp	Above 90°C
	• Motor Megger testing	• Ampere Logs	Increase
Economizer	• Remove soot and ash deposits	• Flue Gas Temp	Above 190°C
Feed Water Tank	• Remove sediment and sludge from the bottom	• Return Hot Water Temp	Below 90°C
	• Whole Trap System Clean	• Return Hot Water Temp	Above 90°C
	• Replace damaged or deteriorated insulation	• Feed Water Temp	Below 90°C
	• Clear clogged drainpipes	• Feed Water Flow Rates	Below Operating
	• Water Level Cutoff valve replacement/repair	• Boiler Water Level	Above Baseline
	• Non-return valve replacement/repair	• Feed Water Tank Water Level	Above Baseline
Heat Exchanger	• De-Scaling / remove COCO3.	• Steam Production Rate	Below daily requirement
	• Replace cracked heat exchanger tubes.	• Hydro Test	Water leak
	• Clean internal and external surfaces	• Flue Gas Temp	Above 190°C
Combustion Chamber	• Remove ash and slag deposits	• Steam Pressure	Below 9 bars
	• Rebe tray Repair	• Physically	Break Down
	• Resurface worn chamber interior	• Steam Temp	Above 170°C
Burner	• Replace worn or clogged nozzles	• Flue Gas Temp	Above 190°C
	• Replace defective igniters.	• Visual	Poor Spark
	• Calibrate air dampers	• O ₂ Level at Exhaust	Increase
	• Photocell cleaning	• Fuel Readings	Overconsumption
	• Fuel Pressure Pump filter cleaning	• Steam Productivity	Below daily requirement
	• Solenoid Valve Replace	• Fuel Readings	Overconsumption
	• Atomizer Replace	• Visual	Poor Spark

Exhaust Stack	• Clean accumulated soot or carbon deposits	• Flue Gas Temp	Below 190°C
	• Replace defective draft regulators	• CO Readings	Above 200 ppm
Safety Valve	• Replace worn springs	• Valve Popping Pressure	Deviation
	• Polish valve seats	• Steam Pressure	Below 9 bars
	• Replace corroded or damaged discs	• Steam Leak	Break Down
	• Replace worn gaskets	• Steam Leak	Break Down
Pressure Gauge	• Replace damaged internal mechanisms	• Steam Pressure Readings	Break Down
	• Clean the measurement ports	• Steam Pressure Readings	Break Down
	• Replace or tighten loose fittings	• Steam Pressure Readings	Break Down
Boiler Shell	• Blowdown Valve repair	• Blowdown	Break Down
	• Pressure switches replace	• Steam Pressure	Above 9 bars

These criteria provide guidelines to support preventive and predictive maintenance approaches in resource-constrained settings, reducing downtime and optimizing maintenance plans. This research bridges the gap between theoretical best practices and real-world constraints by providing practical insights from industry experts. However, the study is limited to oil-fired fire tube boilers within a specific capacity range. Future research could explore the integration of emerging technologies such as IoT and AI to overcome the issues in manual data collection. Implementing the proposed criteria in real-world settings will further validate the effectiveness of optimizing maintenance decision-making for low-tech buildings.

5. Conclusion

This research identifies key decision-making criteria for boiler maintenance in low-tech integrated buildings, where manual data collection remains the standard. Effective maintenance decision-making is critical to ensuring operational efficiency, reducing downtime, and optimizing resource allocation. By analysing equipment-specific parameters, resource constraints, and operational impact, this research provides a structured framework to support maintenance planning. Unlike traditional reactive approaches, the proposed criteria emphasize preventive and predictive strategies, enabling maintenance teams to make informed decisions despite technical limitations. The findings highlight the importance of aligning maintenance actions with practical constraints, ensuring that even buildings without advanced monitoring tools can adopt systematic maintenance practices. Ultimately, this research will be used to develop a software-based maintenance decision-making model for low-tech integrated buildings, which will improve maintenance practices.

6. References

- Agarwal, S., & Suhane, A. (2017). Study of Boiler Maintenance for Enhanced Reliability of System A Review. In *Materials Today: Proceedings* (Vol. 4). www.sciencedirect.comwww.materialstoday.com/proceedings
- Ahmad, R., & Kamaruddin, S. (2012). A review of condition-based maintenance decision-making. In *Industrial Engineering* (Vol. 6, Issue 5).
- Alaswad, S., & Xiang, Y. (2017). A review on condition-based maintenance optimization models for stochastically deteriorating system. *Reliability Engineering and System Safety*, 157, 54–63. <https://doi.org/10.1016/j.ress.2016.08.009>

- Arifin, J., & Herlina, F. (2022). *Analisis Sootblower Terhadap Head Transfer Economizer Pada Boiler* (Vol. 6, Issue 1).
- Arno, R., Dowling, N., & Schuerger, R. (2015). Equipment failure characteristics & RCM for optimizing maintenance cost. *IEEE Transactions on Industry Applications*, 2015, 1257–1264. <https://doi.org/10.1109/TIA.2015.2483700>
- Bangari, P., Nangare, K. E., & Al Mazrouei, H. K. (2019). *Improving Equipment Reliability and Availability through Real-time Data*. <https://doi.org/https://doi.org/10.2118/197347-ms>
- Bennett, G., Elwell, C., & Oreszczy, T. (2019). Space heating operation of combination boilers in the UK: The case for addressing real-world boiler performance. *Building Services Engineering Research and Technology*, 40(1), 75–92. <https://doi.org/10.1177/0143624418794552>
- Bhatt, A., Ravi, V., Zhang, Y., Heath, G., Davis, R., & Tan, E. C. D. (2023). Emission factors of industrial boilers burning biomass-derived fuels. *Journal of the Air and Waste Management Association*, 73(4), 241–257. <https://doi.org/10.1080/10962247.2023.2166158>
- Demirel, Y. E., Simsek, E., Ozturk, E., & Kitis, M. (2021). Selection of priority energy efficiency practices for industrial steam boilers by PROMETHEE decision model. *Energy Efficiency*, 14(8), 1–20. <https://doi.org/10.1007/S12053-021-10007-8/METRICS>
- Disegna, E. S. (2018). *Review and Classification Of Industrial Boilers Maintenance, and A Reliability-Centered Maintenance Methodology Proposal for Production Plants*.
- Elkelawy, M. (2019). Boilers and Steam Generation. In *Power Station Engineering and Economics* (pp. 1–85). https://www.researchgate.net/publication/331411946_Boilers_and_Steam_Generation
- ER-Ratby, M., & Mabrouki, M. (2018). Critical Study of the Different Types of Maintenance Used in Industry. *Research Journal of Applied Sciences, Engineering and Technology*, 15(3), 91–97. <https://doi.org/10.19026/rjaset.15.5833>
- Favero, M. S. (2007). Disinfection and sterilization in healthcare facilities. *ACS Symposium Series*, 967, 31–50. <https://doi.org/10.1021/bk-2007-0967.ch002>
- Green, R. N., McNaught, K. R., & Saddington, A. J. (2022). Engineering maintenance decision-making with unsupported judgement under operational constraints. *Safety Science*, 153. <https://doi.org/10.1016/j.ssci.2022.105756>
- Hassanain, M. A., Assaf, S., Al-Hammad, A. M., & Al-Nehmi, A. (2015). A multi-criteria decision making model for outsourcing maintenance services. *Facilities*, 33(3–4), 229–244. <https://doi.org/10.1108/F-01-2013-0003>
- Johnston, B. (2020). Routine Maintenance Prolongs a Storage Tank's Life. *Opflow*, 46(7), 22–24. <https://doi.org/10.1002/opfl.1397>
- Jonge, de B., & Scarf, P. A. (2020). A review on maintenance optimization. In *European Journal of Operational Research* (Vol. 285, Issue 3, pp. 805–824). Elsevier B.V. <https://doi.org/10.1016/j.ejor.2019.09.047>
- Khalil, A. A., Supervisor, T., & Alsayed, M. (2021). *Designing a Device for Industrial Boilers Efficiency Monitoring and Analysis*.
- Kuchař, J., Kreibich, V., Agartanov, V., & Petřík, M. (2018). Maintenance and cleaning of heat exchangers. *Materials Science Forum*, 919, 396–403. <https://doi.org/10.4028/www.scientific.net/MSF.919.396>
- Leishear, R. A., Savannah, W., & Stefanko, D. B. (2007). *Relationship Between Vibrations and Mechanical Seal Life in Centrifugal Pumps*. <http://proceedings.asmedigitalcollection.asme.org/pdfaccess.ashx?url=/data/conferences/ijtc2007/71814/>
- Mahlamaki, K., & Nieminen, M. (2020). Analysis of manual data collection in maintenance context. *Journal of Quality in Maintenance Engineering*, 26(1), 104–119. <https://doi.org/10.1108/JQME-12-2017-0091>
- Moleda, M., Momot, A., & Mrozek, D. (2020). Predictive maintenance of boiler feed water pumps using SCADA data. *Sensors (Switzerland)*, 20(2). <https://doi.org/10.3390/s20020571>
- Mydin, A. O. (2015). Significance of Building Maintenance Management System Towards Sustainable Development: A Review. In *Journal of Engineering Studies and Research* (Vol. 21, Issue 1).
- Pasi, S., & Muller, M. R. (2007). *Investigating the Impact of Boiler Aging In Replacement Decisions*.

- Patil, S. S., Bewoor, A. K., Kumar, R., Ahmadi, M. H., Sharifpur, M., & PraveenKumar, S. (2022). Development of Optimized Maintenance Program for a Steam Boiler System Using Reliability-Centered Maintenance Approach. *Sustainability* 2022, Vol. 14, Page 10073, 14(16), 10073. <https://doi.org/10.3390/SU141610073>
- Poppe, J., Basten, R. J. I., Boute, R. N., & Lambrecht, M. R. (2017). Numerical study of inventory management under various maintenance policies. *Reliability Engineering and System Safety*, 168, 262–273. <https://doi.org/10.1016/j.ress.2017.06.012>
- Rahmania, W., Prasetya, H., & Sholihah, F. (2020). *Maintenance Analysis of Boiler Feed Pump Turbine Using Failure Mode Effect Analysis (FMEA) Methods*. <https://doi.org/10.1109/IES50839.2020.9231886>
- Reinoso, M. J. V., Pinna, H. M. G., Fernandez, M. D., Sanchez Molina, J. A., Lopez Hernandez, J. C., & Acien Fernandez, F. G. (2021). Boiler combustion optimization of vegetal crop residues from greenhouses. *Agronomy*, 11(4). <https://doi.org/10.3390/agronomy11040626>
- Rodrigues, R. C., Sousa, H., & Gondim, I. A. (2023). SMARTS-Based Decision Support Model for CMMS Selection in Integrated Building Maintenance Management. *Buildings*, 13(10). <https://doi.org/10.3390/buildings13102521>
- Sarofim, A. F. (2001). The John Zink Combustion Handbook. *Chemical Engineering*, 108(7), 10. <https://link.gale.com/apps/doc/A76770443/AONE?u=anon~913dbf85&sid=googleScholar&xid=fa10c238>
- Senthilkumar, S., Ayyandurai, P., Dineshwaran, K., Gowtham, V., & Kavin, J. R. (2023). Optimization of boiler operation and maintenance using IOT. *International Journal of Advances in Engineering and Management (IJAEM)*, 5, 1850–1855. <https://doi.org/10.35629/5252-050318501855>
- Singh, A., Sharma, V., Mittal, S., Pandey, G., Mudgal, D., & Gupta, P. (2018). An overview of problems and solutions for components subjected to fireside of boilers. In *International Journal of Industrial Chemistry* (Vol. 9, Issue 1). Springer Berlin Heidelberg. <https://doi.org/10.1007/s40090-017-0133-0>
- Triantaphyllou, E., Kovalerchuk, B., Mann, L., & Knapp, G. M. (1997). Determining the most important criteria in maintenance decision making. In *Journal of Quality in Maintenance Engineering* (Vol. 3, Issue 1, pp. 16–28). <https://doi.org/10.1108/13552519710161517>
- Widyanto, J. (2025). Decision Support Model for Determining Fuel in Boiler Machines. *Journal of Applied Data Sciences*, 6(2), 908–920. <https://doi.org/10.47738/jads.v6i2.520>
- Yang, H. H., Gupta, S. K., Dhital, N. B., Wang, L. C., & Elumalai, S. P. (2020). Comparative investigation of coal- and oil-fired boilers based on emission factors, ozone and secondary organic aerosol formation potentials of VOCs. *Journal of Environmental Sciences (China)*, 92, 245–255. <https://doi.org/10.1016/j.jes.2020.02.024>

A FRAMEWORK FOR EFFECTIVE MANAGEMENT OF JANITORIAL SERVICE CONTRACTS IN SRI LANKAN COMMERCIAL BUILDINGS: A BILATERAL PERSPECTIVE

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Abstract. An outsourcing arrangement starts with a contractual relationship between a client and a service provider, and therefore, the management of janitorial service contracts poses different issues from both client and provider perspectives. However, literature or empirical evidence does not provide a clear picture of such issues or of managing them from this bilateral perspective. Accordingly, this research aims to address the identified research gap by evaluating the current practice of janitorial service contracts and developing a framework for effective management by integrating both these viewpoints. The study adopted a qualitative research approach, conducting five cases selected from commercial buildings in Sri Lanka. According to the research findings, most common issues faced by clients are lack of skilled janitors; breach of trust; disciplinary issues; job switching; lack of technological advancements and poor documentation while the issues faced by service providers are lack of job information, intension of cost reduction; breach of trust; and lack of energetic and young janitors to be employed in clients' sites. As the findings suggested, by adhering to effective contract structures, risk-sharing mechanisms, negotiation strategies, and developing workforce, both clients and service providers will be able to improve the management of their janitorial service contracts.

Keywords. Outsourcing, Janitorial Contracts, Commercial Buildings Janitorial Contract Management, Bilateral Perspective

1. Introduction

Outsourcing refers to the assignment of tasks and operations performed by internal personnel to external service providers (Pang et al., 2021). According to (Zhao et al., 2014), organisations cannot thrive in a competitive landscape by relying only on their own resources, and those outsourcing strategies may serve as a viable approach to confront competition. Further to the authors, outsourcing allows organisations to reduce costs, enhance services, boost staff productivity and morale, and improve the reputation of the organisations. Conflicts and issues may emerge in outsourcing contract practices due to factors such as opportunistic behaviour, quality concerns, delivery timelines, technological advancements, information deficits, and cost-reduction efforts (Lok et al., 2018). Efficient management of contractual practices is essential for addressing these challenges. Outsourcing issues can be prevented or mitigated through effective outsourcing contract processes, and effective techniques must be developed to address challenges associated with service contract procedures (Mawed, 2024; Pang et al., 2021). According to Kenyi and Barasa (2021), a well-defined contractual framework is the foundation for sustaining the relationship between client and service provider when entering into a service contract. Similarly, effective management of contract practices is vital for ensuring that the service provider fulfils the needed services throughout the contract duration (Murthy et al., 2016; Solehah Kadir et al., 2025) while the service provider is supported with a suitable environment for performing their responsibilities (Ifediora et al., 2021).

Janitorial services are among the most often outsourced functions, with the majority of organisations engaging external service providers for these tasks (Toffolutti et al., 2017). Taponen and Kauppi (2020) emphasised the absence of a standardised framework for formulating outsourcing contracts, resulting in ineffective outsourcing practices. In the context of Sri Lanka, although research has been conducted on facilities management outsourcing strategies, risks, and decision-making models (Ikediashi et al., 2012; Lok et al., 2018; Lok & Baldry, 2015; Rajini et al., 2019), a specific framework for the effective management of janitorial service contracts is lacking. Despite the increasing prevalence of outsourcing, the majority of

current research emphasises on the viewpoints of client organisations, frequently ignoring the challenges and barriers faced by service providers. The complexity of outsourcing relationships, which are dependent upon collaboration and alignment between both parties, is not adequately captured by this partial approach. In particular, there is a significant gap in research that simultaneously investigates the outsourcing relationship from the perspectives of both the service receiver and provider, particularly in the context of janitorial services in commercial settings. To address this gap, the objective of this paper is to establish a practical framework for the efficient administration of janitorial service contracts in commercial buildings in Sri Lanka. This framework will incorporate the perspectives of both clients and service providers to guarantee feasible and balanced outsourcing outputs.

The paper begins with an introduction to the study followed by a literature review on concept of outsourcing and outsourcing of support services. The paper then presents the research methodology and findings with the developed framework and the final section of the paper presents the conclusion of this research.

2. Literature Review

2.1 INTRODUCTION TO OUTSOURCING

The notion of outsourcing originates from the American phrase "outside resourcing," which refers to acquiring resources outside (Karakolias, 2024; Troaca & Bodislav, 2012). This concept originated and gained prominence in the 1980s and was first seen as the delegation of non-core tasks via subcontracting or the procurement of products and services from an external partner (outsourcer) for a client (outsourcee) (Bilan et al., 2017). Considering the definition of outsourcing, Ishizaka et al. (2019) analysed the literature from 1994 to 2020 and reached a thorough conclusion: "Outsourcing is a business agreement, either domestic and/or international (known as offshoring), and strategic management initiative for gaining a competitive advantage of a firm by contracting out their existing internal and/or external non-value added functions, and/or value-added functions, and/or core competencies to competent supplier(s) to produce products and/or services efficiently and effectively for the outsourcing firm." (Ishizaka et al., 2019), p. 1)

Outsourcing provides several benefits, making it a smart and economical business choice. It aids in cost reduction, enhances financial stability, and diminishes employee-related expenditures (Charles & Benson Ochieng, 2023). By delegating non-core functions to specialised service providers, outsourcing allows organisations to concentrate on their primary business and improve competencies. It also provides access to vendor knowledge, enhancing service quality, productivity, and operational effectiveness (Mykytyuk et al., 2021; Somjai & Program, 2017; Tayauova, 2012). Moreover, it enhances flexibility, promotes innovation, and facilitates risk transfer to service providers. Organisations benefit from right sizing their workforce, reducing space requirements, and improving customer service, while outsourcing also eliminates the need for major capital investments and facilitates competitive advantage by allowing firms to focus on core business operations (Rajini and Kaluarachchi., 2019; Somjai & Program, 2017).

2.2 OUTSOURCING OF SUPPORT SERVICES

As Kamanga and Ismail (2016) mentioned, outsourcing key services adversely impacts organisational performance, whilst exporting non-essential tasks positively influences corporate performance. Consequently, as noted by Yeboah (2013), businesses predominantly choose outsourcing for non-core operations. Thus, substituting internal services with an external entity to execute one or more operations of the organisation is fundamentally termed as services outsourcing (Taponen & Kauppi, 2020). Organisations outsourcing administrative functions anticipate enhanced efficiency while using less internal resources (Zitkiene & Dude, 2018).

Today, most of the organisations outsource all services that may be executed by other entities, including catering, cleaning, business processes, and information technology (Perunović et al., 2012). The most prevalent outsourced services include supportive services such as electricity, fire detection and protection, air conditioning, drainage, gas supply, waste disposal systems, access and cleaning, maintenance and troubleshooting of building automation systems, vertical transportation systems and lightning protection (Ali et al., 2025; Pahirathan, 2017; Taponen & Kauppi, 2020). Further as Ifediora et al. (2021) indicated, security, laundry, waste disposal, and building fabric maintenance are predominantly outsourced services, while cleaning, catering, furniture, and building service maintenance exhibit an intermediate level of outsourcing. Conversely, energy optimisation, copying, printing, space management, and postal services are the least outsourced services. Janitorial services, which encompass routine cleaning and facility upkeep, are the most common and frequently outsourced to specialized providers to ensure cost efficiency and maintain high standards of hygiene (Solehah Kadir et al., 2025). (Karakolias, 2024) highlighted that this approach allows organizations to focus on their core activities while leveraging the expertise of specialized janitorial service providers to maintain a clean and efficient working environment.

2.3 MANAGEMENT OF SERVICE CONTRACTS

In a service contract context, there will inevitably be conflicts and issues that would arise between the supplier and client. Mainly these issues arise due to the miscommunication of terms of the contracts to the supplier. (Hietanen-Kunwald & Haapio, 2021). Accordingly, these issues arise depending on the nature of the business and the terms included in the contract. When many business and legal terms are involved in a contract, and not adequately communicated, they may lead to arise many issues of service contract management (Zou et al., 2019). A fundamental reason for these issues between the vendor and the client is related to the objectives of each party of the outsourcing contract. As discussed by Andersson et al. (2019), the profit motives of both firms are the same, but they have different perspectives on that. The vendor is trying to maximize the profits from the client and the client is trying to maximize the benefits while reducing the costs. Thus, the conflicts arise.

The management of service contract practices includes not only contract documentation but also many management elements, including relationship management, performance management, knowledge management, and contract management (Kenyi & Barasa, 2021). Especially, the service contracts and their associated elements have a significant role in strengthening the relationship between the parties involved (Zou et al., 2019). A contract is established between two parties when they mutually accept the drafted terms and conditions, whether orally, in writing, or via their presence, and commit to honouring those terms (Klungseth & Blakstad, 2016). Taponen and Kauppi (2020) claimed that the outsourcing process, pertinent to the contextual research, begins when the owner and the service provider reach an agreement and undertake activities to execute the necessary tasks to provide the contracted service. When these contracts are fulfilled and services are performed, the contract is said to be fulfilled. Thus, effective management of contracts involves not only ensuring the fulfillment of services but also proactively overseeing contract elements to enhance collaboration, drive continuous improvement, and achieve long-term value for all parties involved (Bilan et al., 2017).

Klungseth and Blakstad (2016) highlighted janitorial services as secondary yet vital to core business models, integrating processes to enhance organisational effectiveness. Janitorial contracts, distinct from traditional ones, involve three parties: clients, service providers, and janitors, with janitors playing a critical role in service delivery at the client's site, yet employed by the service-providing organisation (Benjamin et al., 2015; Salerno et al., 2012). The rise in outsourcing janitorial services, driven by cost-saving strategies, has increased their importance, especially in large organisations (Knotter, 2017). However, these contracts face unique

challenges, including labour-intensive work, physical injuries, and conflicts between parties (Salerno et al., 2012). High switching costs, health hazards, and unexpected client-related costs further complicate these contracts (Toffolutti et al., 2017; Zhao et al., 2014). Strategies to mitigate issues include joint responsibility, reducing paperwork, and avoiding frequent staff switching (Murthy et al., 2016).

Effective management of service contracts is crucial in ensuring seamless service delivery and maintaining strong relationships between parties involved (Klungseth & Blakstad, 2016). In the case of janitorial service contracts, proper management practices help address challenges such as labour-intensive work, health hazards, and high switching costs (Salerno et al., 2012). By fostering collaboration between clients, service providers, and janitors, organisations can enhance service efficiency while minimising conflicts (Toffolutti et al., 2017). Implementing structured performance monitoring, clear communication, and fair compensation strategies can further improve contract fulfilment. As outsourcing continues to grow, adopting robust management frameworks will be essential in optimising service outcomes and ensuring long-term contract sustainability. These insights highlight the need for effective management frameworks in janitorial service contracts.

2.4 MANAGERIAL CHALLENGES IN SERVICE OUTSOURCING

Although successful outsourcing depends on efficient service contract administration, several managerial issues often arise that might lower operational effectiveness and long-term relationships. A primary concern is the discrepancy in objectives between service providers and clients. While both parties seek financial gains, their perspectives often clash; clients focus on cost reduction, whereas vendors aim to increase profit margins (Andersson et al., 2019). This discrepancy may lead to conflict and distrust, especially when contracts fail to clearly outline methods to resolve conflicts or adjust to operational changes. Static contracts that remain unchanged to accommodate changing business requirements may lead to inefficiencies and disputes (Zou et al., 2019). Lack of communication causes situations to be significantly more challenging since conflicting interpretations of performance standards or service expectations often result in dissatisfaction and disagreements (Hietanen-Kunwald & Haapio, 2021). Further to the authors, maintaining service quality and ensuring accountability has become challenging in the absence of regular and structured communication between the parties.

In terms of operation, outsourcing may lead to issues with knowledge transfer, service continuity, and staff management. The separation of client organisations, service providers, and on-site janitors, for example, might result in discrepancies in responsibility and coordination in cleaning service (Benjamin et al., 2015; Salerno et al., 2012). These challenges are made worse by high staff turnover and uneven training, which results in variable service quality along with additional work for client-side managers in terms of monitoring. Furthermore, companies may lose internal competencies as a result of relying on outside sources, which makes them liable to vendor failures or transitions (Toffolutti et al., 2017). Effective management techniques must include shared responsibility frameworks, adaptive governance mechanisms, and active performance monitoring to handle these issues successfully (Murthy et al., 2016). These methods ensure that outsourcing partnerships stay consistent with long-term organisational goals while preserving adaptability.

3. Methodology

The qualitative approach was adopted as the most suitable research approach, given the nature of the research problem, as this study emphasises understanding the unique dynamics of janitorial service contracts management through in-depth exploration and developing a framework for effective management of janitorial service contracts. Accordingly, five cases were

selected from commercial buildings in Colombo, Sri Lanka, to ensure a relevant and practical understanding of janitorial service outsourcing. These sites were chosen based on the scale of their janitorial operations, the availability and quality of data, the logistical ease of conducting fieldwork, and the willingness of service providers to participate and share insights. Table 1 presents a summary of the selected cases. From each case, the required data were collected from management representatives from both the client and service provider of the janitorial service contract. Accordingly, two interviews from each case were conducted, making it altogether of ten interviews for the study. Data collection was conducted through a semi-structured interview, allowing for flexibility in exploring participants' opinions and experiences, and document review related to the contracts

Table 1: Summary of the selected cases

Case	Nature of the Business carried out in the building
Case A	Office activities related to Software Development
Case B	Office activities related to the accounting service
Case C	Real estate activities related to the Renting the Building
Case D	The rented out to the carry out different office activities
Case E	Office activities to the carry out different Financial Services

Cross-case analysis was employed as the primary technique for data analysis, as it is well-suited for qualitative research. This method enables the identification of patterns, themes, and insights across cases, facilitating the development of conclusions and recommendations for improving janitorial service contract practices.

4. Discussion of Research Findings

Table 2 presents the profiles of the interviewees who participated in the data collection process. To gain a comprehensive understanding of the issues, both clients and service providers from each of the selected cases were interviewed. Person in charge of both clients and the janitorial service outsourced crew from each organisation was interviewed to acquire relevant data.

Table 2: Interviewees Profile

Cases	Respondent	Designation	Experience in the Field
Case A	A-CL	Assistant Administrative Manager	10 years
	A-SP	Accounts Manager	06 years
Case B	B-CL	Administrative Executive	06 years
	B-SP	Head of Business Development	16 years
Case C	C-CL	Facility Manager	25 years
	C-SP	Chief Executive Officer	15 years
Case D	D-CL	Executive Customer Relationship Manager	10 years
	D-SP	Head of Human Resource management	16 years
Case E	E-CL	Civil Engineer	15 years

E-SP	Admin Manager	10 years

4.1 CURRENT PRACTICE OF JANITORIAL SERVICE CONTRACTS IN SRI LANKAN COMMERCIAL BUILDINGS

4.1.1 Drivers for Janitorial Service Outsourcing

The respondents from all five cases shared their perspectives on the drivers for outsourcing janitorial services in Sri Lanka's commercial sector. It was evident that outsourcing is becoming an increasingly popular strategy. Among the key reasons for outsourcing, the scarcity of janitors was highlighted by respondents A-CL and C-CL, while E-CL further emphasised the need for experienced janitors to improve efficiency and performance. Additionally, respondent A-CL mentioned the ease of management as a factor influencing their decision to outsource janitorial services in their building. Respondent C-CL supported this idea from the perspective of reducing material costs, while B-CL viewed it as a form of cost management, which aligns with the same concept. Not only management costs but also the reduction of overall costs was directly stated by respondents A-CL, B-CL, and E-CL as another significant driver for outsourcing. This suggests that cost reduction is a key motive for outsourcing in the commercial sector.

Respondent A-CL also identified the "focus on core business" as a significant factor. Organisations can more effectively allocate resources to their primary activities by outsourcing support services, such as janitorial functions, which is essential for maintaining a competitive edge in the market. Respondent B-CL further highlighted that the decision to outsource janitorial services has been influenced by the growing number of third-party contracts. This trend necessitates that service providers maintain demanding performance standards to remain competitive. The affordability of outsourcing as an alternative was further emphasised by respondent B-CL, who emphasised the challenges associated with administering large spaces. The decision to contract out janitorial services was significantly influenced by the expertise, specialised skills, experience, and capabilities of external providers, which are frequently unavailable internally, as noted by respondents D-CL and E-CL.

4.1.2 Roles and responsibilities of clients and service providers in janitorial service contracts

A janitorial service contract involves multiple stakeholders, primarily the service provider and the client, each with distinct roles and responsibilities. According to respondents A-CL and E-CL, clients are responsible for providing fundamental facilities, adequate storage for equipment and materials, and an appropriate working environment with sufficient infrastructure to ensure janitorial staff can perform their duties efficiently and comfortably. Further, respondent B-CL emphasized the significance of timely payments by the client organisations in fostering a strong, long-term relationship with the service provider. On the service provider's side, respondent A-CL highlighted the necessity of maintaining a structured checklist for scheduled tasks and ensuring the consistent delivery of high-quality services. Respondent D-SP noted that while garbage clearance does not typically fall within their scope of work, service providers occasionally have to undertake additional responsibilities. Respondent B-CL further mentioned that subcontracting supplementary tasks, employing well-trained janitorial personnel, and enhancing cleanliness standards are essential duties. All respondents concurred that service providers must equip janitors with personal protective equipment and provide adequate training on safety, health protocols, and personal hygiene. Moreover, the respondents precisely indicated that internal staff, as occupants of the workspace, have a shared responsibility in maintaining cleanliness, thereby supporting the efficiency of janitorial service providers.

4.2 ISSUES PREVALENT IN JANITORIAL SERVICE CONTRACTS IN SRI LANKA

4.2.1 Issues Faced by Clients in Janitorial Service Contracts

The outsourcing of janitorial services, while beneficial in some aspects, presents several challenges that vary across businesses but share commonalities in their impact. A significant issue highlighted by all five respondents (A-CL, B-CL, C-CL, D-CL, and E-CL) is the lack of skilled janitors, which directly affects the performance of outsourcing practices. Respondents A-CL and D-CL pointed out that insufficient training programs contribute to this problem, while D-CL also identified *"job switching"* as a factor, where skilled janitors are rotated within organisations to fill gaps, worsening the shortage. Another major issue is the shortage of employees for necessary services, which respondents B-CL and D-CL attribute to poor worker engagement brought on by the notion that janitorial work is of low quality. The age of employees provided by service providers was also a concern for B-CL and D-CL, as they did not receive young, energetic labourers, which impacted work efficiency. D-CL emphasized that *"younger staff are more focused and better suited for risky tasks, which could minimize client compensation costs."*

Another pressing issue raised by respondents B-CL and E-CL is the lack of personal protective equipment (PPE) for labourers, which increases the risk of severe injuries and adversely affects clients. E-CL noted that compensation for injuries in their case is currently at a higher level. Trust-related issues were also highlighted, with respondent A-CL describing *"breach of trust as a fatal problem that led to the termination of a previous contract."* Opportunistic behaviours were cited as a potential cause of such breaches, often resulting in expensive legal actions. Efficiency concerns were raised by respondent C-CL, who mentioned that the *"lack of expected efficiency among staff, particularly in the mornings, disrupts core activities."* C-CL also noted the lack of technological adaptation in cleaning methods due to fixed-rate contracts, which discourage modifications or rescheduling of work. Absenteeism was another significant issue, with D-CL and E-CL attributing it to factors such as unattractive salaries, heavy workloads, poor peer and supervisor conditions, and job switching. Respondent A-CL reported additional discipline-related issues, including behavioural problems and a lack of adherence to organisational culture. Instances of theft and inappropriate behaviour were noted, further complicating the outsourcing relationship.

By contrast, A-CL and D-CL identified the challenge of managing and supervising outsourced labourers as a common issue. A-CL also noted that the disparities in work attitudes between outsourced janitors and internal staff could potentially impact the overall organisational environment. In the same vein, E-CL expressed concern about the possibility of a decrease in the level of commitment of internal employees to maintaining hygiene because of cultural disparities between internal and external staff. Furthermore, E-CL emphasised a substantial constraint of fixed-rate contracts: *"service providers can decide to save expenses by using cheaper supplies, which would cause inefficiencies."* C-CL emphasised that the involvement of an external entity in problem-solving may result in increased costs and delays over time, whereas B-CL maintained that the severity of these drawbacks is primarily dependent on the service provider.

4.2.2 Issues Faced by Service Providers in Janitorial Service Contracts

Conflicts in janitorial service contracts often arise due to various reasons, and most of the conflicts are manageable through effective practices. All respondents agreed that issues are inevitable when multiple parties are involved. Interviews with five service providers revealed several key challenges. Three respondents (B-SP, C-SP, and D-SP) identified the lack of clear information from clients as a major issue, leading to hidden costs and misunderstandings. Extra work was another significant problem, with A-SP and E-SP noting that clients often force workers

to perform tasks beyond the agreed scope, frequently without additional payment, as highlighted by B-SP. A-SP also noted that, although the national retirement age ranges from 52 to 60, client organisations often demand janitors under the age of 50, making it difficult to meet staffing requirements within that age limit. *"In my experience, a large portion of the available labour pool consists of experienced workers over 50. When clients insist on hiring only those under 50, it narrows down our options. It becomes a real struggle to find enough janitors to meet demand, especially in areas where younger people aren't interested in taking on janitorial jobs."*

Table 3: Issues identified from cases

	Client (-CL)	Service Provider (-SP)
Case A	- Breach of trust - Lack of trained janitors - Discipline of the janitors (Education level, talking pattern, culture is different)	- Conditions of the clients (requiring an age limit is less than 50 for janitors by the client) - Extra work taken by janitors - Labor turnover
Case B	- Not enough manpower - Lack of PPE usage - Scarcity of youngsters as janitors	Compensation- (the contract includes a minimum number of employees for work if they do not fulfil the requirement deduction of payment.)
Case C	- Janitor absenteeism - Delay of the cleaning work in the morning - Switching (allocate janitors for another absenteeism janitor work as well)	- Try to reduce costs (Since customers constantly cut expenses, high-quality materials are somewhat more costly than low-quality ones.) - Less mutual understanding - Risk transferring (if something goes wrong, clients try to transfer risk to the service provider if it happens due to client errors) - Lack of information (the client may not give all the information related to the job) - Labor turnover
Case D	- Labor shortage (area is large) - Older workforce - Lack of skills	- Cost reduction attempts by clients - Lack of information regarding the job
Case E	- Absenteeism of janitors - Less technological adoption (Although the new technology for cleaning is more efficient than doing it by hand, it is not being used.) - Not maintain a regular checklist - No suitable PPE usage	- Extra work taken from the janitors - If the scope is done with fewer workers deduction is made from the agreed amount

Compensation and service quality were also critical concerns. C-SP and D-SP explained that clients often push for lower payments, forcing service providers to use cheaper materials and compromise on performance. D-SP emphasized that absenteeism among janitors creates compensation issues, as contracts typically require a minimum number of workers daily. Failure to meet this requirement results in payment deductions, even if task switching is used to manage cleaning needs. This imposes a heavy pressure on service providers to maintain that minimum headcount at all times, as it can be difficult due to factors beyond the provider's control, such as sudden absences, high turnover, or difficulties in hiring. A-SP added that the scarcity of trained janitors and a young labour force further complicates meeting client demands. Labor turnover emerged as a serious issue, with skilled workers leaving due to high workloads or excessive extra work demanded by clients. A-SP and C-SP cited labour turnover as a significant challenge in maintaining service quality. Additionally, B-SP highlighted the lack of mutual understanding between clients and service providers, with clients often focusing on service providers' errors, hindering good relationships.

In Sri Lanka, organisations present unique challenges, such as lengthy approval processes for contract renewals. B-SP noted that working with commercial buildings often results in unpaid increments during renewal periods. Risk transfer was another concern, with C-SP stating that clients frequently attempt to shift risks to service providers, even when the responsibility lies with the client. These issues collectively highlight the complexities of janitorial service contract management. The summary of the issues identified from cases, through both client and service provider, has been presented in Table 3.

4.3 STRATEGIES TO OVERCOME THE IDENTIFIED ISSUES AND RECOMMENDATIONS FOR EFFECTIVE MANAGEMENT OF JANITORIAL SERVICE CONTRACTS

To address the common issue of labour absenteeism, several organisations have implemented a salary deduction strategy. All the clients have formalised this approach by including it in their contracts, ensuring that service providers face financial penalties if they fail to provide the agreed number of labourers. Additionally, these organisations have engaged in negotiations with service providers and workers to address related issues. For instance, A-CL emphasises the importance of discipline, while C-CL focuses on preventive measures through discussions with service providers. Training for workers, particularly in skill development, is also a key aspect of these negotiations. Respondent D-CL highlights the importance of good management practices as a solution to various issues, including absenteeism, disciplinary problems, work delays, and the lack of personal protective equipment (PPE) usage. E-CL, on the other hand, employs random checks of work performed against checklists to ensure proper documentation and has identified time management as a critical strategy under the umbrella of good management practices. These measures aim to improve efficiency and address existing challenges.

Negotiation emerges as the most preferred strategy among organisations to mitigate identified issues. Most organisations advocate for negotiations with both service providers and janitors, alongside comprehensive training programs for employees before they begin work. A-CL specifically emphasizes the inclusion of discipline-related training, particularly regarding drug use during working hours. To address absenteeism, organisations recommend motivating workers with attractive payment structures and developing backup plans for contracts. However, several barriers hinder the resolution of these issues. Respondents from B-CL and D-CL identify the lack of participation from younger janitors as a significant challenge, with B-CL noting that labourers over 50 years old are more prevalent in the sector. Additionally, the overall shortage of people willing to work in this field poses a further obstacle to overcoming these problems. These barriers highlight the need for broader systemic changes to attract and retain a younger workforce

To address common issues like a lack of job-related information, B-SP gathers comprehensive job details, helping mitigate problems to some extent. Flexible contracts are emphasized as a key strategy to address insufficient information, extra work, compensation, and clients' cost reduction demands. Respondent C-SP formalizes this by including such conditions in contracts, while C-SP, D-SP, and E-SP highlight effective management practices as a mechanism to address challenges. Negotiation is another critical measure. Respondents negotiate with clients to address skill gaps, often requesting special training for workers. C-SP proactively negotiates with service providers to prevent future issues, while D-SP conducts on-site janitor training to overcome skill shortages. B-SP has signed earlier contracts with government clients to address these challenges and seeks further job-related information. They also emphasise specifying extra work in contracts to avoid overburdening janitors.

Negotiation is widely recommended as a primary solution. D-SP and E-SP advocate for regular meetings to discuss and resolve janitorial service contract issues proactively. C-SP emphasizes strong client relationships and flexible contracts, noting trust as a foundation for mitigating problems. A-SP suggests improving training program quality, while B-SP proposes advanced solutions like maintaining a sophisticated contract tracker, implementing the "Happy Toilet Concept," conducting client awareness programs, and defining responsibilities for janitors, users, and designers. The "Happy Toilet Concept," a new initiative in Singapore, aims to enhance customer satisfaction with washroom conditions, and awareness programs by the World Toilet Organization promote established standards. However, as constraints faced by service providers, E-SP notes workers may resist multiple tasks, potentially leading to labour turnover if forced. B-SP and D-SP highlight financial challenges in providing paid training and workers' reluctance to participate in unpaid programs. C-SP points out the difficulty of negotiating flexible contracts, as clients often prioritize their interests. A-SP and B-SP mention the challenge of changing workers' mindsets to resolve issues effectively.

Respondents emphasize the importance of properly structuring a contract document with all required terms and conditions to effectively manage the contract and minimize future disputes. Respondents highlighted key issues and solutions to be addressed in contracts. A major issue is the lack of labour and employee absenteeism. Respondents suggested including backup plans for absenteeism (C-CL) and minimum salary ranges to discourage turnover (D-CL). B-CL recommended specifying worker age to address the lack of younger workers, while A-CL emphasized adding worker discipline clauses to avoid problematic situations. Health and safety were also highlighted, with B-CL advocating for worker safety clauses and E-CL suggesting PPE specifications to protect both workers and clients from liability. Service providers also proposed contract improvements. E-SP suggested including payment terms for additional work, while D-SP stressed the need for comprehensive job details in contracts. C-SP recommended risk-sharing methods, and B-SP emphasized specifying details like the number of washrooms, square footage, and fixtures to prevent issues. A-SP proposed including minimum experience requirements to ensure janitors' skills and knowledge.

In summary, well-structured contracts with clear terms, backup plans, salary ranges, age and experience requirements, health and safety provisions, and detailed job specifications are essential for successful outsourcing arrangements.

4.4 FRAMEWORK FOR EFFECTIVE MANAGEMENT OF JANITORIAL SERVICE CONTRACTS

Based on the findings of the study, a framework was developed for the effective management of janitorial service contracts, as shown in Figure 1. It outlines the effective management of janitorial service contracts by highlighting the drivers and benefits of outsourcing, key roles and responsibilities, common challenges, and strategic solutions. While outsourcing janitorial services offers advantages such as cost savings, improved quality, and access to specialists, it

also presents challenges like supplier dependency and cultural differences. The contract defines the responsibilities of both service providers and clients, ensuring quality standards, timely payments, and a safe work environment. Common issues include a shortage of skilled janitors, labour turnover, and lack of contract clarity. To address these, effective management strategies like proper compensation, negotiation, strong management, and flexible contracts are recommended. The framework links each identified issue to a corresponding strategy by referencing the issue number under the relevant proposed solution.

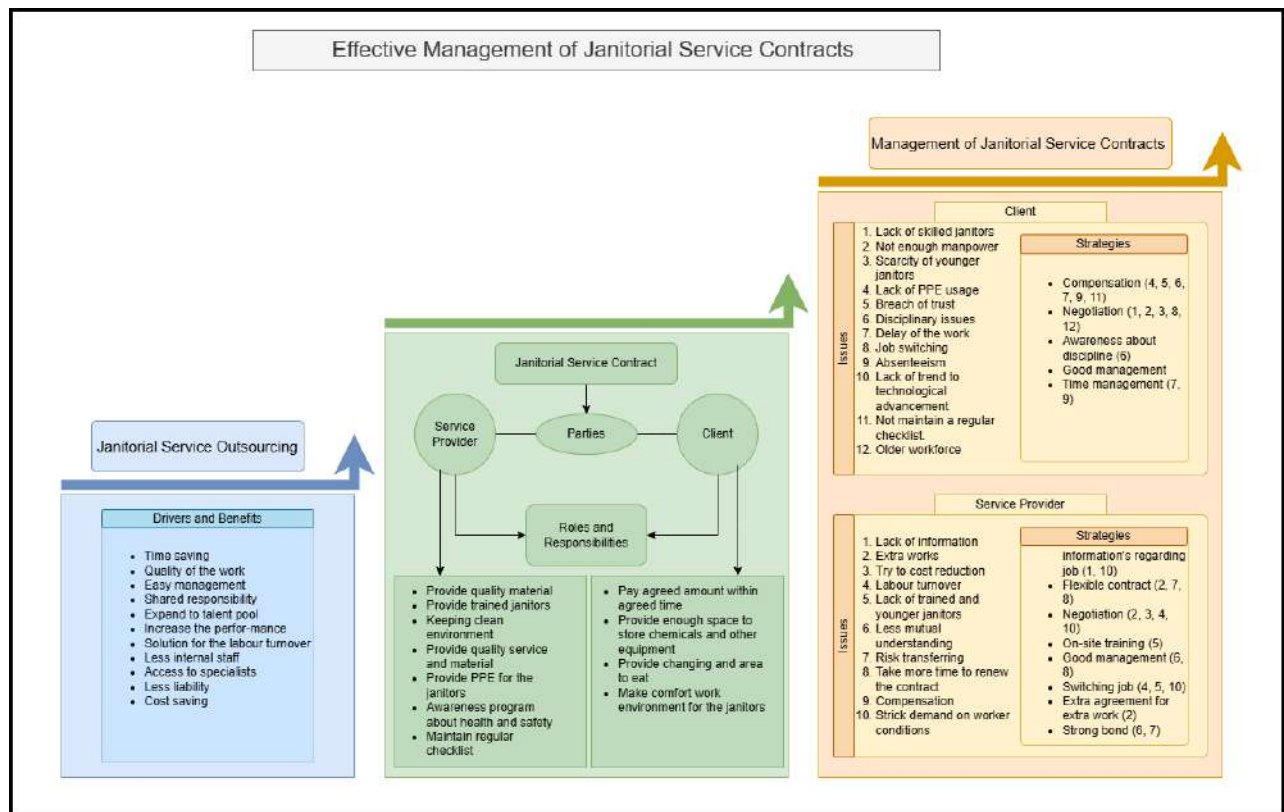


Figure 1: Framework for effective management of janitorial service contracts

5. Conclusions

This study reveals the complexities of managing janitorial service contracts in Sri Lankan commercial buildings, integrating a bilateral perspective, highlighting key challenges such as a lack of skilled labour, unreliable service delivery, and contractual ambiguities. Poorly defined contract terms often lead to inefficiencies, with clients facing absenteeism and quality concerns, while service providers struggle with hidden costs and unrealistic expectations. Effective contract structures, risk-sharing mechanisms, and performance-based agreements are crucial for mitigating these challenges. Communication and negotiation play a significant role in resolving contract-related issues, with strategies such as regular discussions, structured training programs, and performance monitoring helping to improve service efficiency. However, financial constraints, resistance to change, and a lack of mutual trust hinder their effectiveness. Attracting young workers through better employment conditions and leveraging cleaning technologies can further enhance janitorial service management.

To address these issues, this research provides a framework for improving janitorial service contract management in Sri Lanka, emphasizing the need for structured contracts, effective negotiations, and continuous monitoring. Proactive contract management, regulatory compliance, and workforce development are essential for enhancing service quality and fostering

long-term client-provider relationships. Future research could explore the impact of emerging cleaning technologies and digital contract management systems in optimizing janitorial outsourcing. Additionally, a quantitative analysis of cost-effectiveness and long-term benefits could further refine outsourcing strategies. Implementing structured frameworks will help mitigate risks, enhance service standards, and support sustainable outsourcing practices in the janitorial sector

6. References

- Ali, A. J., Verma, M., & Hamdan, R. (2025). Theoretical Insights into the Impacts of Government Outsourcing on Service Quality, Employees, and Cost Savings. In A. Hamdan (Ed.), *Achieving Sustainable Business through AI, Technology Education and Computer Science. Studies in Big Data* (Vol. 158, pp. 577–583). Springer, Cham. https://doi.org/10.1007/978-3-031-70855-8_49
- Andersson, F., Jordahl, H., & Josephson, J. (2019). Outsourcing Public Services: Contractibility, Cost, and Quality. *CESifo Economic Studies*, 65(4), 349–372. <https://doi.org/10.1093/cesifo/ifz009>
- Benjamin, O., Nisim, S., & Segev, G. (2015). Corporate Social Responsibility as Shaped by Managers' Role Dissonance: Cleaning Services Procurement in Israel. *Journal of Business Ethics*, 130(1), 209–221. <https://doi.org/10.1007/s10551-014-2213-9>
- Bilan, Y., Nitsenko, V., Ushkarenko, I., Chmut, A., & Sharapa, O. (2017). Outsourcing in International Economic Relations. *Montenegrin Journal of Economics*, 13(3), 175–185. <https://doi.org/10.14254/1800-5845/2017.13-3.14>
- Charles, M., & Benson Ochieng, S. (2023). Strategic Outsourcing and Firm Performance: A Review of Literature. *International Journal of Social Science and Humanities Research (IJSSHR) ISSN 2959-7056 (o); 2959-7048 (p)*, 1(1), 20–29. <https://doi.org/10.61108/ijsshr.v1i1.5>
- Hietanen-Kunwald, P., & Haapio, H. (2021). Effective dispute prevention and resolution through proactive contract design. *Journal of Strategic Contracting and Negotiation*, 5(1–2), 3–23. <https://doi.org/10.1177/20555636211016878>
- Ifediora, C. O., Ndive, P. C., & Efobi, D. J. (2021). Outsourcing and In-house Facilities Management Practices: Advantages and disadvantages. *International Journal of Innovative Science and Research Technology*, 6(4), 338–344.
- Ikediashi, D. I., Ogunlana, S. O., Boateng, P., & Okwuashi, O. (2012). Analysis of risks associated with facilities management outsourcing. *Journal of Facilities Management*, 10(4), 301–316. <https://doi.org/10.1108/14725961211265756>
- Ishizaka, A., Bhattacharya, A., Gunasekaran, A., Dekkers, R., & Pereira, V. (2019). Outsourcing and offshoring decision making. *International Journal of Production Research*, 57(13), 4187–4193. <https://doi.org/10.1080/00207543.2019.1603698>
- Kamanga, F. N., & Ismail, S. N. (2016). EFFECTS OF OUTSOURCING ON ORGANIZATION PERFORMANCE IN MANUFACTURING SECTOR IN KENYA: A CASE OF DEL MONTE KENYA LIMITED. *European Journal of Logistics, Purchasing and Supply Chain Management*, 4(3), 32–58.
- Karakolias, S. (2024). Outsourcing Non-Core Services in Healthcare: A Cost-Benefit Analysis. *International Journal of Scientific Research and Management (IJSRM)*, 12(10), 1177–1195. <https://doi.org/10.18535/ijssrm/v12i10.mp01>
- Kenyi, Mr. J. A., & Barasa, Dr. P. W. (2021). Influence Of Contract Management Practices On Service Delivery In The Public Sector: A Case Study Of Uganda Civil Aviation Authority. *International Journal of Scientific and Research Publications (IJSRP)*, 11(10), 161–175. <https://doi.org/10.29322/IJSRP.11.10.2021.p11820>
- Klungseth, N. J., & Blakstad, S. H. (2016). Organising in-house cleaning services in public FM. *Facilities*, 34(13/14), 828–854. <https://doi.org/10.1108/F-03-2014-0024>
- Knotter, A. (2017). Justice for Janitors Goes Dutch. Precarious Labour and Trade Union Response in the Cleaning Industry (1988–2012): A Transnational History. *International Review of Social History*, 62(1), 1–35. <https://doi.org/10.1017/S0020859016000651>
- Lok, K. L., & Baldry, D. (2015). Facilities management outsourcing relationships in the higher education institutes. *Facilities*, 33(13/14), 819–848. <https://doi.org/10.1108/F-05-2014-0043>

- Lok, K. L., Opoku, A., & Baldry, D. (2018). Design of Sustainable Outsourcing Services for Facilities Management: Critical Success Factors. *Sustainability*, 10(7), 2292. <https://doi.org/10.3390/su10072292>
- Mawed, M. (2024). Insight into facilities management market in the UAE: trends, drivers, and threats. *Smart and Sustainable Built Environment*. <https://doi.org/10.1108/SASBE-08-2023-0218>
- Murthy, C., Padhi, S. S., Gupta, N., & Kapil, K. (2016). An empirical investigation of the antecedents of value co-creation in B2B IT services outsourcing. *Business Process Management Journal*, 22(3), 484–506. <https://doi.org/10.1108/BPMJ-05-2015-0064>
- Mykytyuk, P., Semenets-Orlova, I., Blishchuk, K., Skoryk, H., Pidlisna, T., & Trebyk, L. (2021). Outsourcing as a tool of strategic planning in public administration. *Studies of Applied Economics*, 39(3). <https://doi.org/10.25115/eea.v39i3.4718>
- Pahirathan, A. (2017). A Literature Review on Outsourcing of Services in Universities. *IOSR Journal of Business and Management*, 19(2), 47–56.
- Pang, Y., Zhang, S., & Xin Jiang, A. (2021). Outsourcing: Overview and Trends. In *Outsourcing and Offshoring*. IntechOpen. <https://doi.org/10.5772/intechopen.98333>
- Perunović, Z., Mefford, R., & Christoffersen, M. (2012). Impact of information technology on vendor objectives, capabilities, and competences in contract electronic manufacturing. *International Journal of Production Economics*, 139(1), 207–219. <https://doi.org/10.1016/j.ijpe.2012.04.009>
- Rajini, D., Kaluarachchi, K., & Kaluarachchi, K. A. S. P. (2019). Understanding Outsourcing from the Client's Perspective: Revisiting the Existing Literature. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 3547–3558. <https://www.researchgate.net/publication/349484817>
- Salerno, S., Kolman, V., Livigni, L., Magrini, A., Bosco, M. G., & Talamanca, I. F. (2012). Women's working conditions in hospital cleaning: a case study. *Work*, 41, 4315–4319. <https://doi.org/10.3233/WOR-2012-0726-4315>
- Solehah Kadir, S., Uzairiah Mohd Tobi, S., & Haryati Jasimin, T. (2025). Overview of facilities management outsourcing services in Malaysia's private hospitals. *IOP Conference Series: Earth and Environmental Science*, 1467(1), 012015. <https://doi.org/10.1088/1755-1315/1467/1/012015>
- Somjai, S., & Program, G. (2017). Advantages and disadvantages of outsourcing. In *The Business and Management Review* (Vol. 9).
- Taponen, S., & Kauppi, K. (2020). Service outsourcing decisions – a process framework. *Journal of Global Operations and Strategic Sourcing*, 13(2), 171–194. <https://doi.org/10.1108/JGOSS-02-2019-0012>
- Tayauova, G. (2012). Advantages and disadvantages of outsourcing: analysis of outsourcing practices of Kazakhstan banks. *Procedia - Social and Behavioral Sciences*, 41, 188–195. <https://doi.org/10.1016/j.sbspro.2012.04.023>
- Toffolutti, V., Reeves, A., McKee, M., & Stuckler, D. (2017). Outsourcing cleaning services increases MRSA incidence: Evidence from 126 english acute trusts. *Social Science & Medicine*, 174, 64–69. <https://doi.org/10.1016/j.socscimed.2016.12.015>
- Troaca, V.-A., & Bodislav, D.-A. (2012). Outsourcing. The Concept. *Theoretical and Applied Economics*, 19(6), 51–58.
- Yeboah, A. (2013). The Relationship Between Outsourcing And Organizational Performance . *European Journal of Business and Management*, 5(2).
- Zhao, X., Xue, L., & Zhang, F. (2014). Outsourcing Competition and Information Sharing with Asymmetrically Informed Suppliers. *Production and Operations Management*, 23(10), 1706–1718. <https://doi.org/10.1111/poms.12097>
- Zitkiene, R., & Dude, U. (2018). The impact of outsourcing implementation on service companies. *Entrepreneurship and Sustainability Issues*, 6(1), 342–355. [https://doi.org/10.9770/jesi.2018.6.1\(21\)](https://doi.org/10.9770/jesi.2018.6.1(21))
- Zou, W., Brax, S. A., Vuori, M., & Rajala, R. (2019). The influences of contract structure, contracting process, and service complexity on supplier performance. *International Journal of Operations & Production Management*, 39(4), 525–549. <https://doi.org/10.1108/IJOPM-12-2016-0756>

EFFECTIVENESS OF FACILITIES MANAGEMENT PERFORMANCE DURING OCCUPANCY PHASE OF CONDOMINIUM BUILDINGS IN SRI LANKA

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Abstract. When a condominium is built and transferred the ownership, there is usually a performance gap between actual and expected performance. User satisfaction with facilities and well-maintained services is a key indicator of performance in condominium buildings in the occupancy phase. However, assessing the effectiveness of facilities management performance during this phase of condominiums remains questionable, due to unclear frameworks for stakeholder involvement, lack of effective participation, and challenges in data management. Also, organisational effectiveness has challenges due to FM outsourcing practices in Sri Lanka. Therefore, recent studies highlighted the requirement of assessing the FM performance across different timelines to identify inefficiencies and opportunities for improvement. Thus, this study aims to determine the effectiveness of facilities management performance during the occupancy phase of condominium buildings in Sri Lanka. Under a quantitative research approach, study was utilized an online questionnaire survey for primary data collection. To evaluate FM service delivery, three aspects of effectiveness were considered, namely schedule compliance, availability, and quality and expectation. The findings reveal strong adherence to schedule compliance, with preventive maintenance, cleanliness, security, energy management, and sustainability receiving high ratings. However, service availability issues were noted in several areas. Polarised views on access control, sustainability, and cleanliness highlight varying resident experiences, emphasising the need for targeted improvements.

Keywords. Condominium, Facilities, Facilities Management, Performance, Performance Measurement

1. Introduction

The Facilities Management (FM) discipline emerged in the 1970s due to the coexistence of rapidly growing complexity in the workplace and the understanding of the connectedness between occupants' behaviours and building design (Bascoul et al., 2018). Facilities management encompasses multiple disciplines in built environment including building services, energy management, water conservation, handling building management system and occupational health and safety management (Pilanawithana & Sandanayake, 2017). International Facilities Management Association (IFMA) (2022), specified 11 specific roles of facilities manager, including finance and business, operations and maintenance, project management, facility information management and technology management, performance and quality, leadership and strategies, communications, occupancy and human factors, real state, risk management and sustainability.

FM in condominiums, covers operation and maintenance, building services such as security, housekeeping, cleaning, pest control, and general services such as furnishing and procurement (Riratanaphong & Limjaroensuk, 2020). The rising price of land and change in the new generation's attitudes and lifestyle had caused demand multi-unit residential buildings (Che-Ani et al., 2010). Also, there is a significant demand for condominiums in the Colombo metropolitan area because of the higher population density and limited supply of land (De Silva et al., 2015). Considering the condominium buildings, user satisfaction with facilities and maintenance services is a key indicator of performance, with residents generally satisfied when services are well-managed (Che-Ghani et al., 2023). Accordingly, facilities management plays a variety of roles in the performance of an organization including control of resources, operating, supply chain management, and change management, but not limited to (Amaratunga & Baldry, 2003). Since FM is crucial for coordinating buildings and building systems, equipment, and other physical assets to achieve organizational long-term goals, higher concern has to be given to the Performance Measurement (PM) of FM (Amaratunga et al., 2000). Benchmarking, a balanced scorecard approach, post- occupancy evaluation, and Key Performance Indicator (KPI) metrics

come under major PM practices in FM (Lavy et al., 2014). Regrettably, the majority of the high-rise residential complexes discovered were poorly managed, thereby abandoning the sustainable agenda in housing management (Nazali Mohd Noor & Pitt, 2009). According to de Silva and Ranasinghe (2010), repair and replacement costs was 41.6% and cleaning costs was 18.5% of total maintenance costs of condominiums. By developing comprehensive performance measurement systems, facilities managers can make better decisions to improve facility effectiveness and efficiency (Amaratunga et al., 2000). According to Fatayer et al. (2019), when a facility is built and ownership is transferred, there is usually a performance gap between actual and expected performance.

There is a growing need to measure FM performance to integrate business and facilities domains effectively (Kulatunga et al., 2007). Thus, researchers explored various approaches to develop and implement FM performance frameworks in developing countries (Amos et al., 2021). Amos et al. (2021) concluded that measuring performance act as a key to ensuring ideal service delivery and is also an essential tool for the effective implementation of FM strategy. It is evident that the researchers have focused on performance measurement and tools in the existing studies.

However, recent research highlights several gaps in assessing the effectiveness of facilities management (FM) performance in buildings, including condominiums. These gaps encompass unclear frameworks for stakeholder involvement, lack of effective participation, and challenges in data management (Ensafi & Thabet, n.d.; Sedhom et al., 2023). The COVID-19 pandemic has further emphasized the importance of assessing FM performance across different timelines to identify inefficiencies and opportunities for improvement (Lynn J. Lopez et al., 2023). It is notable that, the effectiveness of FM performance during the occupancy phase of condominiums remains questionable, with factors like aesthetic appearance and client satisfaction influencing project success (Rajapaksha & Ranasinghe, 2021). Also, the adoption of FM outsourcing in Sri Lanka offers benefits and same time faces challenges in organizational efficiency (Fayasa et al., 2020). Considering these gaps in existing studies and remaining questions, this study aims to determine the effectiveness of facilities management performance during the occupancy phase of condominium buildings in Sri Lanka

2. Literature Review

Residential real estate in Sri Lanka contains various types of properties including single houses, storied houses, annexes, twin houses, lined houses, and condominiums. Among them, condominiums are currently gaining popularity, especially in Colombo metropolitan areas (Prathapasinghe et al., 2018). In Sri Lanka types of condominiums can be categorized as luxury, upper-middle and middle income, and Lower-middle income (Udayangani et al., 2017).

2.1. Facilities management Operations In condominiums

According to Apartment Ownership Law, No.11 of 1973 condominium property comprise a land with a building or buildings. It also allows the owners of all registered condominium units to control, manage, maintain or administer the common elements of the condominium property within themselves. Making decisions about the management of the property falls under the condominium's Management Corporation (Udayangani et al., 2017). According to Lai (2012), FM in condominium buildings focused on areas including general management, cleaning, repair and maintenance and landscape and leisure. Also, in condominium project, FM in charge in common properties, building services, residential services, and community services (Riratanaphong & Limjaroensuk, 2020). Building Information Modeling (BIM) is increasingly utilized for efficient condominium facility management, helping to solve data inconsistency issues and streamline processes (Tochaiwat et al., 2022). Facilities manager needs to have certain competencies to carry out the various roles in each of stages of the building life cycle, which are the strategic definition stage, preparation, and brief stage, concept design stage, developed design stage,

technical design stage, construction stage, handover and close out stage, and in use stage (Pilanawithana & Sandanayake, 2017). Riratanaphong & Limjaroensuk (2020), argued that compared to FM in other building types, multi-unit residential FM takes a distinct approach.

2.1 PERFORMANCE MEASUREMENTS IN FACILITIES MANAGEMENT

Performance measurement in facilities management (FM) has evolved to become a critical tool for organizational success. It involves assessing FM performance in terms of quality, cost, and effectiveness, integrating both business and facilities domains (Kulatunga et al., 2005). Organizations with effective performance management systems in place can achieve cost savings of up to 30%. Also, performance measurements through establishment of KPIs allows the senior management to make important strategic decisions (Richard et al., 2009).

The effectiveness of facilities management performance is highly influenced by Key facilities management variables. In condominiums, occupant interactions with building systems, plays a vital role in energy performance and sustainability, often leading a gap between estimated and actual energy consumption (Ebuy et al., 2023). In addition, Cleanliness and general maintenance are among the key service quality dimensions that influence resident satisfaction (Ramli et al., 2021). Also, Security and access control are crucial components of intelligent buildings, affecting occupant satisfaction (Amusan et al., 2021). In condominiums, occupant satisfaction with facility services varies among age groups, influenced by physical environment characteristics and service arrangements (Riratanaphong & Limjaroensuk, 2020). For uninterruptible power supply maintenance is vital, with factors extracted based on industry standards and expert knowledge (Zakeri & Shahabi, 2023). Thus, it is notable that energy management, sustainability, maintenance, cleanliness, security, access control, uninterrupted utility supply are crucial factors in effectiveness of FM performance.

2.2 THE FACTORS THAT DETERMINE THE EFFECTIVENESS OF FM PERFORMANCE

. Neely (1999) defined, performance measurement is "the process of quantifying the effectiveness and efficiency of an action. When evaluating and analysing the performance of organizations, the terms effectiveness and efficiency are crucial. (Mouzas, 2006). The effectiveness is determined by how well it delivers services and how much it helps the building's occupants, who have to have a clear understanding of the caliber of the services it offers (C.W. Ho & Liusman, 2016).

Considering quality and expectation Riratanaphong and Limjaroensuk (2020) reported that client satisfaction is the key performance measurement in real estate. In a condominium building, residents expect effective FM services because they pay monthly (Che-Ani et al., 2010). Therefore, Stakeholder expectations and service quality are crucial in FM, with a need for improved expectation management (Rahman Jumat et al., 2012). Schedule compliance, a key logistic objective in production systems, can be improved by adjusting control variables like safety time and lateness distribution and impacting the effectiveness of facility services (Schmidt et al., 2014). It involves ensuring proper performance by landlords and tenants in leased facilities, including tenant satisfaction, proper maintenance of spaces and adherence to guidelines (Scott-Napier, 2024). The Global Process Effectiveness metric, which incorporates schedule adherence, has been proposed to enhance traditional performance indicators like Overall Equipment Effectiveness (Oliveira et al., 2019). Availability, as a measure of FM effectiveness, relates to the accessibility and readiness of services and facilities. Physical environment characteristics, such as the location and design of common areas, impact occupant satisfaction with facility services (Riratanaphong & Limjaroensuk, 2020). For utility-scale photovoltaic power plants, "Effective Availability" measures energy-based performance, considering factors affecting plant output (Hunt et al., 2015). It is notable that, quality and

expectation, schedule compliance and availability can be identified as the key aspects of determining effectiveness in facilities management performance.

Further, a method for assessing their effectiveness is necessary as the quality-of-service delivery in property management companies are differ (C.W. Ho & Liusman, 2016). Performance measurement in FM is a way to gauge how well FM can recognize the needs of the users and its capacity to put in place appropriate solutions to meet those demands and increase their productivity (Koleoso et al., 2013).

2.3 FM PERFORMANCE MEASUREMENT TOOLS

Various performance measurement tools have been developed for performance measurement in FM such as Post Occupancy Evaluation (POE), Building in Use (BIU), Service Quality (SERVQUAL), Service Performance (SERVPREF), Key performance Indicator model (KPIM), Balanced Score Card (BSC) (Koleoso et al., 2013).

The SERVQUAL model is based on the perception gap between the service quality obtained and the service quality expected (Krishnamurthy et al., 2010). SERVQUAL evaluates two components of service quality. Customers' expectations are measured using 22 measures, while perceptions are evaluated using 22 measures. The five aspects of tangibility, reliability, responsiveness, assurance, and empathy are separated into 22 items for this scale (Abdelkrim & Salim, 2015). BSC is a tool for measuring and evaluating organizational performance and a management tool that facilitates effective strategic management (Tochaiwat et al., 2022). The many forms of performance indicators can be divided into what BSC practitioners refer to as "four perspectives", namely, financial, customer, business perspective and learning and growth (Amaratunga et al., 2002). Key performance indicator model, also referred to as the management by variance tool, contributes primarily to the creation of a model of key performance indicators (Koleoso et al., 2013). The performance indicator is a tool the measurement of work outcomes that aids the team or organization's members in moving forward together and ensure that team members concentrate their efforts on the critical elements of organizational success (Tochaiwat et al., 2022). In addition, several additional types can be used to gauge how well facilities management is performing in terms of cost management, efficiency, and effectiveness.

3. Methodology

A comprehensive literature review was conducted to understand the emergence of condominiums in Sri Lanka, the role of FM in condominiums, and finally the available tools for assessing the FM process. To achieve the research aim, it was required to analyse the perception of occupants and property managers and quantify the factors to obtain a result. Accordingly, quantitative research approach is suitable for quantifying and analysing factors to obtain results (Apuke, 2017). As the data collection technique study was utilized an online questionnaire survey. The questionnaire was titled as "Assessing the Effectiveness of Facilities Management in Condominiums". The sampling technique selected for the selection of participants in this study is purposive sampling. Purposive sampling is an appropriate method for selecting participants in a condominium because it allows to specifically target the respondents. Participants were selected from the condominium units which are aged at least one year after occupancy. Questionnaire survey was distributed among 65 potential respondents and 33 responds were received. The questionnaire was designed using the Likert scale. Respondents responded considering their level of satisfaction which is scaled from 1-4 and schedule compliance, availability, and quality & expectation fulfilment are the aspects of Effectiveness considered. To analyse the data general descriptive analysis was executed to provide a summary of trends shown in responses.

4. Results

Total response rate was identified as 51% (33/ (65-0) *100%) The questionnaire was designed using defined Likert scale as follows.

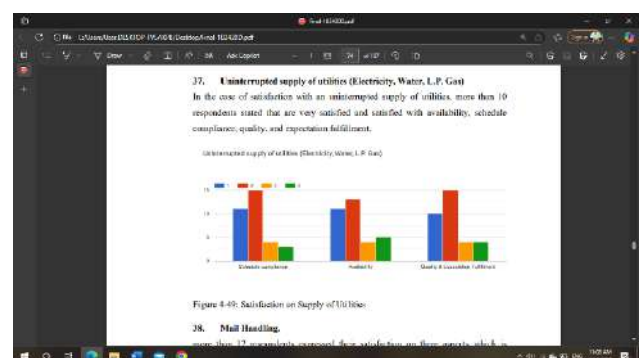
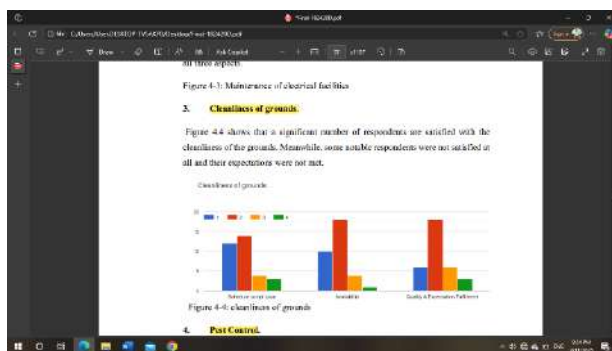
- Score 1- Very Satisfied / Exceeded expectation
- Score 2- Satisfied / Matched expectation
- Score 3- Dissatisfied / Less than expected
- Score 4- Very Dissatisfied / Much less than expected

4.1. Evaluation of occupant's perception of FM service delivery in condominium

Based on literature; to evaluate FM service delivery, 3 aspects of effectiveness were considered namely schedule compliance, availability, and quality and expectation. Also, considering the criticality of the FM services including energy management and sustainability, maintenance, cleaning, uninterrupted utility supply, security and access control and civil- work-related complaints handling was selected to evaluate effectiveness of facilities management performance. The survey results are shown in Figure 1, Figure 2, Figure 3, Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8. Each figure contains responses ratings on different FM services under three evaluating criteria namely, schedule compliance, availability, and quality and expectation.

Considering the schedule compliance, survey results indicate that preventive maintenance, ground cleanliness activities, operation of security facilities, energy management and sustainability implementation received high ratings from the respondents, suggesting strong adherence to the schedule compliance in FM service delivery. Regarding the availability of these FM services, the majority of respondents were either highly satisfied or satisfied with the available services. However, a significant proportion of respondents reported that access control, civil works, energy management services were unavailable. Notably, for these services, a similar number of respondents rated them as highly available and as dissatisfied, indicating various perception and experience with their availability. Although more than 15 respondents were satisfied with availability of access control, only a few were very satisfied, which is a signal for improvement. Similarly, cleanliness, energy management areas also indicated very few respondents who were very satisfied.

Considering the quality and expectations, respondents are suggested that, the supply of utilities including electricity, water and LP gas was in satisfactory level. Similarly, the quality of security services of the condominium buildings was also high. However, considering the access control, energy management and sustainability, civil works and ground cleanliness received considerably similar higher scores and lower scores. It was identified that the respondents have polarized perceptions based on their experience on this service quality. Access card failures in critical areas for improvement were determined based on the number of unsatisfied respondents.



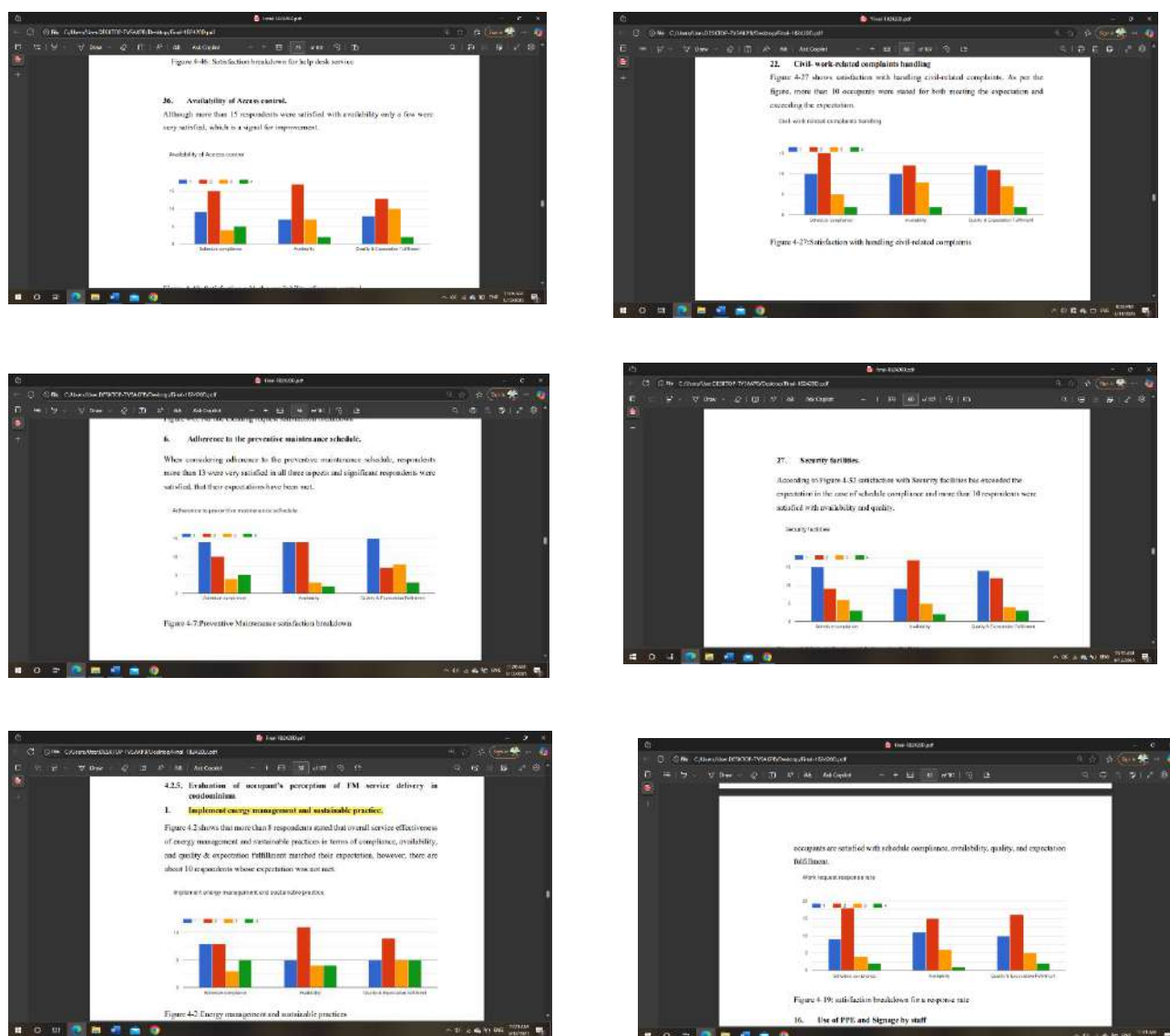


Figure 1: Occupant's Perception of FM Service Deliver

5. Discussion

Facilities management operations in condominium focused on areas including general management, cleaning, repair and maintenance, building services, residential services, and community services (Lai, 2012; Riratanaphong & Limjaroensuk, 2020). Effectiveness of FM performance highly influenced by areas such as energy management, sustainability, maintenance, cleanliness, security, access control and uninterrupted utility supply (Amusan et al., 2021; Ebuy et al., 2023; Ramli et al., 2021; Zakeri & Shahabi, 2023). Participants also revealed that these areas are highly impacted for the effectiveness of the FM performance. To determine the effectiveness of these areas three key aspects were considered; quality and expectation, schedule compliance and availability (Rahman Jumat et al., 2012; Riratanaphong & Limjaroensuk, 2020; Scott-Napier, 2024). Table 1 indicates the effectiveness of performance of each FM areas as per rated by participants.

Table 1: Effectiveness of FM performance

Areas of Facilities Management	Schedule compliance	Availability	Quality and expectation
Energy management and sustainability	High adherence	Medium availability	Satisfied
Maintenance	High adherence	Highly available	Very satisfied
Cleanliness of ground	High adherence	Highly available	Satisfied
Uninterrupted utility supply	Medium adherence	Highly available	Very satisfied
Security	High adherence	Highly available	Very satisfied
Access control	Medium adherence	Medium availability	Satisfied
Civil works	Medium adherence	Medium availability	Satisfied

6. Conclusion

The research aims to determine the effectiveness of FM during the occupancy phase of condominium buildings in Sri Lanka. A comprehensive literature has been carried out about the condominium, their operation, the role of FM in condominiums, parameters of FM, PM in FM, and tools to measure performance. There is much understanding among researchers about the importance of FM in both manufacturing and service organizations. But the performance of FM and evaluation of FM in condominiums and their effectiveness in particular in residential buildings is still undeveloped. Questionnaire surveys were carried out to understand the occupants' satisfaction level with the performance of FM using a Likert scale. Effectiveness was examined under 08 factors. Also, the level of satisfaction was analysed by incorporating aspects of effectiveness such as availability, schedule compliance, and quality and expectation fulfilment. It is evidenced that residents were not fully satisfied with the FM performance in their respective condominiums. It was evident that, there is a strong adherence to schedule compliances. Preventive maintenance, ground cleanliness, security facility operations, energy management, and sustainability implementation were rated highly, indicating effective FM service delivery. While most FM services were generally available, security, civil works, and energy management had notable availability issues, with some respondents finding them highly accessible while others reported unavailability. There were polarized perceptions of service quality in areas such as access control, energy management, sustainability, civil works, and ground cleanliness, highlighting varying user experiences. Thus, recommendations can be provided to enhance overall FM service quality, improvements should focus on service availability, resolving access control issues, and addressing disparities in user experiences, particularly in civil works, energy management, and cleanliness. This study enables to explore further on the effectiveness of facilities management in addressing the specific needs and concerns of different types occupants and further research can be carried out to assess the effectiveness of facilities management in design phase of condominium buildings.

7. References

- 11 Core Competencies Of Facility Management. . (2022).
- Abdelkrim, Y. B., & Salim, B. (2015). *Assessment of the service quality in the preparatory school of economics through Servperf model*. 10, 127–136.
- Amaratunga, D., & Baldry, D. (2003). A conceptual framework to measure facilities management performance. *Property Management*, 21(2), 171–189. <https://doi.org/10.1108/02637470310478909>
- Amaratunga, D., Baldry, D., & Sarshar, M. (2000). Assessment of facilities management performance – what next? *Facilities*, 18(1/2), 66–75. <https://doi.org/10.1108/02632770010312187>
- Amaratunga, D., Haigh, R., Sarshar, M., & Baldry, D. (2002). Application of the balanced score-card concept to develop a conceptual framework to measure facilities management performance within NHS

- facilities. *International Journal of Health Care Quality Assurance*, 15(4), 141–151. <https://doi.org/10.1108/09526860210431805>
- Amos, D., Au-Yong, C. P., & Musa, Z. N. (2021). *Measurement of Facilities Management Performance in Ghana's Public Hospitals*. Springer Singapore. <https://doi.org/10.1007/978-981-33-4332-0>
- Amusan, L., Moses, E., & Rapheal, O. (2021). *Exploratory Approach to Performance of Smart Components of Intelligent [Smart] Buildings* (pp. 215–224). https://doi.org/10.1007/978-3-030-58282-1_35
- Apuke, O. D. (2017). Quantitative Research Methods: A Synopsis Approach. *Kuwait Chapter of Arabian Journal of Business and Management Review*, 6(11), 40–47. <https://doi.org/10.12816/0040336>
- Bascoul, A. M., Tommelein, I. D., Tillmann, P., & Muxen, S. (2018). *Towards Facility Management Participation in Design: A UCSF Case Study*. 505–515. <https://doi.org/10.24928/2018/0209>
- Che-Ani, A., Mohd Tawil, N., Sairi, A., Goh, N., Mohd Tahir, M., & Surat, M. (2010). Facility management indicators for high-rise residential property in Malaysia. *WSEAS Transactions on Environment and Development*, 6, 267–276.
- Che-Ghani, N. Z., Myeda, N. E., & Ali, A. S. (2023). Efficient operation and maintenance (O&M) framework in managing stratified residential properties. *Journal of Facilities Management*, 21(4), 609–634. <https://doi.org/10.1108/JFM-10-2021-0124>
- C.W. Ho, D., & Liusman, E. (2016). Measuring the performance of property management companies in high-rise flats. *Facilities*, 34(3/4), 161–176. <https://doi.org/10.1108/F-06-2014-0056>
- de Silva, N., & Ranasinghe, M. (2010). Maintainability risks of condominiums in Sri Lanka. *Journal of Financial Management of Property and Construction*, 15(1), 41–60. <https://doi.org/10.1108/13664381011027971>
- De Silva, N., Sampath, D. B. D., & De Silva, C. R. (2015). Maintainability of Condominiums Constructed for Low-Income Families in Sri Lanka. *Built-Environment Sri Lanka*, 11(2), 25–39. <https://doi.org/10.4038/besl.v11i2.7608>
- Ebuy, H. T., Bril El Haouzi, H., Benelmir, R., & Pannequin, R. (2023). Occupant Behavior Impact on Building Sustainability Performance: A Literature Review. *Sustainability*, 15(3), 2440. <https://doi.org/10.3390/su15032440>
- Ensafi, M., & Thabet, W. (n.d.). *Challenges and Gaps in Facility Maintenance Practices*. 237–227. <https://doi.org/10.29007/1h2j>
- Fatayer, F. A., Hassanain, M. A., Abdallah, A., & Al-Hammad, A.-M. (2019). Investigation of facilities management practices for providing feedback during the design development and review stages. *International Journal of Building Pathology and Adaptation*, 37(5), 597–614. <https://doi.org/10.1108/IJBPA-05-2018-0040>
- Fayasa, A. F., De Silva, N., Kumaraswamy, M., & Lai, H. K. J. (2020). Exploring challenges and drivers of facilities management outsourcing in Sri Lanka. *Conference Proceedings - FARU 2020*, 237–244. <https://doi.org/10.31705/FARU.2020.27>
- Hunt, K., Blekicki, A., & Callery, R. (2015). Availability of utility-scale photovoltaic power plants. *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, 1–3. <https://doi.org/10.1109/PVSC.2015.7355976>
- Koleoso, H., Omirin, M., Adewunmi, Y., & Babawale, G. (2013). Applicability of existing performance evaluation tools and concepts to the nigerian facilities management practice. *International Journal of Strategic Property Management*, 17(4), 361–376. <https://doi.org/10.3846/1648715X.2013.861367>
- Krishnamurthy, R., B, D. T. M., SivaKumar, Mr. A. K., & Sellamuthu, Dr. P. (2010). Influence of service quality on customer satisfaction: application of servqual model. *International Journal of Business and Management*, 5(4). <https://doi.org/10.5539/ijbm.v5n4p117>
- Kulatunga, U., Amaratunga, D., & Haigh, R. (2007). Performance measurement in the construction research and development. *International Journal of Productivity and Performance Management*, 56(8), 673–688. <https://doi.org/10.1108/17410400710832994>
- Kulatunga, U., Amaratunga, R. D. G., Haigh, R., & Baldry, D. (2005). *Performance measurement applications in facilities management: An investigation into the future directions*. <https://api.semanticscholar.org/CorpusID:14260716>
- Lai, J. H. K. (2012). Analytical assessment and comparison of facilities management services for residential estates. *International Journal of Strategic Property Management*, 16(3), 236–253. <https://doi.org/10.3846/1648715X.2012.682183>
- Lavy, S., Garcia, J. A., Scinto, P., & Dixit, M. K. (2014). Key performance indicators for facility performance assessment: simulation of core indicators. *Construction Management and Economics*, 32(12), 1183–1204. <https://doi.org/10.1080/01446193.2014.970208>

- Lynn J. Lopez, C., A. Sario, J., & Z. Matias, E. (2023). Assessment of Facilities Management Performance in Selected Real Estate Business: Basis for Crafting a Policy Framework. *International Journal of Social Science, Education, Communication and Economics (SINOMICS JOURNAL)*, 1(6), 893–906. <https://doi.org/10.54443/sj.v1i6.101>
- Mouzas, S. (2006). Efficiency versus effectiveness in business networks. *Journal of Business Research*, 59(10–11), 1124–1132. <https://doi.org/10.1016/j.jbusres.2006.09.018>
- Nazali Mohd Noor, M., & Pitt, M. (2009). A critical review on innovation in facilities management service delivery. *Facilities*, 27(5/6), 211–228. <https://doi.org/10.1108/02632770910944943>
- Neely, A. (1999). The performance measurement revolution: why now and what next? *International Journal of Operations & Production Management*, 19(2), 205–228. <https://doi.org/10.1108/01443579910247437>
- Oliveira, R., Taki, S. A., Sousa, S., & Salimi, M. A. (2019). Global Process Effectiveness: When Overall Equipment Effectiveness Meets Adherence to Schedule. *Procedia Manufacturing*, 38, 1615–1622. <https://doi.org/10.1016/j.promfg.2020.01.123>
- 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>
- Prathapasinghe, D., Perera, M., & Ariyawansa, R. (2018). *Evolution of Condominium Market in Sri Lanka: A Review and Predict*.
- Rahman Jumat, A., Coffey, V., & Skitmore, M. (2012). Stakeholder service delivery expectations of military facilities management. *Built Environment Project and Asset Management*, 2(2), 146–166. <https://doi.org/10.1108/20441241211280891>
- Rajapaksha, S. K., & Ranasinghe, G. P. (2021). Development of an Approach to Assess the Success and Failures Influence in Middle Income Housing Projects: Case Study of Jalthara, Bambalapitiya and Dehiwala. *Asian Review of Social Sciences*, 10(2), 1–10.
- Ramli, A. M. A., Harun, A. N., Haron, N. A., & Mohd Nawi, M. N. (2021). Systematic Review on the Attributes of Resident Satisfaction Measurement in the Facility Management Context. *Journal of Advanced Research in Business and Management Studies*, 21(1), 27–39. <https://doi.org/10.37934/arbms.21.1.2739>
- Richard, P. J., Devinney, T. M., Yip, G. S., & Johnson, G. (2009). Measuring Organizational Performance: Towards Methodological Best Practice. *Journal of Management*, 35(3), 718–804. <https://doi.org/10.1177/0149206308330560>
- Riratanaphong, C., & Limjaroensuk, S. (2020). Occupant satisfaction on facility services: case studies of six multi-generational condominiums. *Facilities*, 39(5/6), 286–304. <https://doi.org/10.1108/F-11-2019-0123>
- Schmidt, M., Bertsch, S., & Nyhuis, P. (2014). Schedule compliance operating curves and their application in designing the supply chain of a metal producer. *Production Planning & Control*, 25(2), 123–133. <https://doi.org/10.1080/09537287.2013.782947>
- Scott-Napier, W. (2024). Funding and implementing a lease compliance programme. *Corporate Real Estate Journal*, 13(3), 217. <https://doi.org/10.69554/YSNE2758>
- Sedhom, I., Khodeir, L. M., & Fathy, F. (2023). Investigating current practices for achieving effective participation of stakeholders in Facilities Management. *Ain Shams Engineering Journal*, 14(6), 102099. <https://doi.org/10.1016/j.asej.2022.102099>
- Tochaiwat, K., Suwanchaiskul, A., Vichayapan, P., & Arpornwicharnop, K. (2022). A Study on the Building Information Modeling for Residential Condominium Facility Management. *Journal of Hunan University Natural Sciences*, 49(7), 44–55. <https://doi.org/10.55463/issn.1674-2974.49.7.6>
- Udayangani, K. D. M. S., Disarathna, V., & Wimalasena, N. N. (2017). Gaps in existing apartment ownership law of Sri Lanka. In Y. G. Sandanayake, T. Ramachandra, & S. Gunatilake (Eds.), *What’s new and what’s next in the built environment sustainability agenda?* Ceylon Institute of Builders.
- Zakeri, A., & Shahabi, A. (2023). Prioritizing Management Solutions to Optimize Uninterruptible Power Supply (UPS) Maintenance and Repair Units. *Industrial Innovations: Requirements and Strategies*, 1(3), 285–301. <https://doi.org/10.61186/jii.1.3.285>

PRIORITISATION OF MITIGATION STRATEGIES TO OVERCOME THE HEALTH AND SAFETY RISKS ASSOCIATED WITH E-WASTE RECYCLING WORKERS IN SRI LANKA

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Abstract. E-waste poses a significant challenge in Sri Lanka, as in many other nations, due to its high concentration of hazardous materials and its health and environmental effects. This study aims to identify the health and safety risks and develop effective mitigation strategies. A comprehensive literature review was conducted to identify the e-waste recycling process and health and safety risks associated with e-waste recycling. A mixed-methods research approach was adopted in three phases. First, expert interviews were conducted with managerial-level personnel in e-waste recycling plants to assess the local relevance of health and safety risks identified in the literature. Second, a questionnaire survey was carried out to evaluate the probability and impact of these risks. Third, a second round of expert interviews was held with health and safety professionals to identify feasible mitigation strategies to overcome the health and safety risks. The identified mitigation strategies were prioritised using the Risk Priority Number (RPN), calculated by multiplying severity and occurrence scores. The study identified several mitigation strategies, including providing employee training, providing safe work procedures, installing a local exhaust system, installing a proper filtration system, providing lifting equipment, and regular maintenance of machines etc. According to the prioritisation, providing safe work procedures was prioritised as the most effective mitigation strategy. The study contributes actionable insights for enhancing occupational health and safety in Sri Lanka's e-waste recycling sector.

Keywords. E-Waste, E-Waste Recycling, Hazardous Materials, Health And Safety Risks; Occupational Health And Safety

1. Introduction

Any electrical and electronic product that has been discarded is considered electronic waste (E-waste) (Kumar et al., 2017). The development of information technology and the increase in the obsolescence rate of electronic and electrical products result in higher e-waste generation (Attia et al., 2021; Goel, 2017). However, the e-waste includes different materials and hazardous substances including metals such as Mercury, Lead, Cadmium, Selenium, Arsenic, Gold, Silver, Tin (LY, NHT; GIAO, 2025) and Halogenated compounds (Kiddee et al., 2013), and other substances such as toner dust and radio-active substances (Ministry of Health, Nutrition & Indigenous Medicine Sri Lanka, 2023). Consequently, e-waste is commonly classified as hazardous waste, and improper management of e-waste can result in substantial risks to both human and environmental health (Tsydenova & Bengtsson, 2011). Since many toxic substances can be found in e-waste, the process of recycling differs from other kinds of waste (Ahirwar & Tripathi, 2021). Moreover, Decharat & Kiddee,(2020), revealed that the chemical components of e-waste can be harmful to people's health, particularly for individuals who are involved in recycling. Further, Arain & Neitzel, (2019) also revealed that the recycling process of e-waste results in the release of several harmful chemicals, a significant number of which pose risks to both human and environmental health. According to Perkins et al., (2014), humans may be susceptible to several forms of exposure to hazardous compounds, such as skin contact, inhalation of tiny particles, and ingestion of contaminated dust, especially with inadequate protection techniques. The process of recycling e-waste has an impact on the health of workers and their physical well-being (Acquah et al., 2021). The release of various toxins during the recycling of e-waste poses a significant risk to human health, leading to adverse effects such as skin diseases, impaired brain development in children, damage to the nervous system, kidney dysfunction, respiratory issues, disruption of the endocrine system, negative outcomes during pregnancy and childbirth, and the perpetuation of poor health burdens from mother to child (Ohajinwa et al., 2017). Further, e-waste exposure has been reported to have other adverse health effects as well, such as DNA damage, decreased lung functioning, changes in thyroid

function, adverse neonatal outcomes, changes in temperament and behavior, and a myriad of chronic disease risks, including cancer (Issah et al., 2022). Moreover, workers who engage in the recycling process of e-waste may also be exposed to high levels of physical agents like noise while dismantling and shredding electronic components, which is a well-known cause of hearing loss as well as increased heart rate (Burns et al., 2016) lower back pain (Roffey et al., 2010) negative impact on spinal components (Acquah et al., 2021) muscle soreness and weariness (Garcia et al., 2015).

Ministry of Health, Nutrition & Indigenous Medicine Sri Lanka, (2023) revealed that developed countries have an e-waste growth rate of 1% to 5% annually, but in developing countries typically ranges from 10% to 25%. Therefore, e-waste will become an emerging issue for Sri Lanka, also as same as for other Asian countries in the future (Priyashantha et al., 2022). According to Priyashantha et al., (2022), e-waste poses a significant challenge in Sri Lanka, as in many other nations, due to its high concentration of hazardous materials, leading to detrimental health and environmental effects. There are numerous studies has been carried out to address the e-waste management in Sri Lanka and the challenges related to the e-waste management in Sri Lanka. However, there is no study has been carried out in Sri Lanka yet to address the health and safety risks related to e-waste recycling workers. Consequently, there is a pressing need to explore the health and safety risks that are specific to e-waste recycling plant workers in Sri Lanka. This has so far prevailed as a worthy researchable area, and accordingly, the research question developed as "What are the health and safety risks faced by e-waste recycling plant workers, and how can effective mitigation strategies be developed to address these risks?"

2. Literature Review

2.1 E-WASTE RECYCLING PROCESS

Recycling is a useful technique used for managing the growing amounts of e-waste (Ahirwar & Tripathi, 2021). According to Alahakoon & Gunarathne, (2022) there are two major steps in e-waste recycling, namely, pre-processing and end-processing. Further it mentioned that the preprocessing typically involves manually disassembling electronic equipment, clearing out potentially dangerous elements, and sorting different streams and including disassembling items, mechanical shredding. The end processing step is the final stage in the e-waste recycling chain, where the metal and non-metal components of the trash are further processed (Alahakoon & Gunarathne, 2022).

Disassembling complex electronic equipment serves two primary purposes: salvaging valuable components for profitable recycling and separating hazardous materials for proper disposal (A. Lucier & J. Gareau, 2020). Following the disassembly phase, the subsequent step in the pre-treatment process of e-waste often involves size reduction using shredders (Khanna et al., 2020). These shredders are employed to break down the e-waste into smaller, more manageable pieces, facilitating further processing and material recovery (Chatterjee & Kumar, 2009). Further, Kaya, (2016) mentioned that magnetic separation is commonly used to extract ferrous metals from the shredded material. Eddy-current separation is another technique employed to separate non-ferrous metals, such as aluminum, from the shredded material (Liu et al., 2023). The pyrometallurgical processes and hydrometallurgical techniques are used to the recycling of printed circuit boards (PCBs) (Wang et al., 2017). Toner sweeping is another important step that can be identified in e-waste recycling, which associated with laser printers, photocopiers, and other imaging equipment that utilize toner cartridges (Borthakur & Sinha, 2013). This process involves the recovery of toner powder from used printer cartridges or imaging equipment (Parthasarathy, 2021).

2.2 HEALTH AND SAFETY RISKS ASSOCIATED WITH E-WASTE RECYCLING PLANT WORKERS

Recycling e-waste can result in exposure, either directly or indirectly, to a range of hazardous compounds that are present in e-waste or that are created and released by improper recycling procedures (Perkins et al., 2014)). The emission of toxic components and their derivatives into the environment is dependent on the method used for processing and recycling (Ahirwar & Tripathi, 2021).

Disassembly stages pose risks of accidental releases and spillages of hazardous substances, such as mercury and CRTs (Tsydenova & Bengtsson, 2011). Mechanical treatment methods, such as shredding and separation, generate dust from components being shredded, which may pose inhalation and dermal exposure hazards and environmental contamination risks (Vats & Singh, 2014). Burning plastic often at high temperatures is a common method of getting rid of computer casings or extracting metal from electronic chips and other parts; therefore, heavy metals like lead, cadmium, and mercury are released during incineration (Frazzoli et al., 2010). Moreover, occupational injuries can arise due to the operation of machines or equipment during the mechanized processing of e-waste using shredders or compactors (Fischer et al., 2020). E-waste recycling involves long durations of sitting, standing, walking, and sitting in a low squatting posture, with frequent and heavy manual material handling (MMH) in non-neutral postures such as lifting, carrying, pushing pulling (Acquah et al., 2021). The process of recycling can result in chemical, physical, ergonomic, and psychosocial hazards for workers. Workers in this industry are also likely to have significant exposure to noise, particularly in formal settings, as well as ergonomic hazards due to repetitive motions and awkward postures (Decharat & Kiddee, 2020). Noise sources of the e-waste recycling include mechanical noise from cutting, shredding, equipment, glass dumping, manual breaking, and vibration of conveyor belts also generates noise (Gong et al., 2020). As discussed above, the key health and safety risks identified from various studies have been summarised in Table 1.

Table 1: Health and Safety Risks associated with e-waste recycling

E-waste process	Health and Safety Risks	References											
		A	B	C	D	E	F	G	H	I	J	K	L
Collection and dismantling	Respiratory issues by inhaling dust containing various compounds during dismantling activities.	X	X	X		X		X	X	X	X		
	Musculoskeletal disorders from lifting		X			X							
	Cuts and injuries from sharp objects		X				X						
Shredding	Respiratory problems from fine particulate dust	X		X		X		X	X		X		
	Hearing loss from prolonged noise exposure.		X		X	X	X						X
	Injury from machine operations						X						
Pryo-metallurgical process	Inhalation issues from the dust and fumes of the shredded material and the melting process, containing various compounds such as heavy	X		X		X		X	X				X

	metals and volatile organic compounds.												
	Exposure to carcinogens	X		X		X				X			
	Burns from the high temperatures.	X					X						
Hydrometallurgical process	Chemical poisoning from acid fumes containing various hazardous compounds such as acids and solvents.	X				X							
	Chemical burns from acid and alkalis	X					X						
	Respiratory issues from dust and fumes and some metal additives such as hydrochloride acids, styrene	X		X		X		X	X				
	Chronic respiratory issues from toxic fumes of various compounds from solder and PC board components such as lead, volatile organic compounds, and Polybrominated Flame Retardants.	X		X				X					X
	Injury from improper handling of heated materials	X					X						
Toner sweeping	Respiratory issues from toner dust including carbon black.	X											
	Musculoskeletal disorders from repetitive motion.				X							X	
Acid extraction	Chemical poisoning from acidic fumes containing various hazardous compounds.	X											
	Chemical burns from acid exposure.	X					X						
	Eye damage from acid vapor						X						
A-(Cayumil et al., 2016), B-(California Department of Public Health, 2012), C-(Lau et al., 2014), D-(Okeme & Arrandale, 2019), E-(Fischer et al., 2020), F-(A. Lucier & J. Gareau, 2020), G-(López et al., 2022), H-(Gravel et al., 2023), I-(Singh et al., 2018), J-(Yohannessen et al., 2019), K-(Acquah et al., 2021), L-(Gong et al., 2020)													

3. Research Methodology

This study aims to identify the health and safety risks associated with e-waste recycling plant workers and provide mitigation strategies to overcome these risks. Accordingly, the research question can be developed as “What are the health and safety risks faced by e-waste recycling plant workers, and how can effective mitigation strategies be developed to address these risks?” A comprehensive literature review was conducted to identify the e-waste recycling process and

health and safety risks. A mixed research approach was used for this study. Firstly, expert interviews were conducted with five professionals to assess the relevance of the identified risks within the local context. The interviewees were selected based on their job roles, experience, and involvement in the operation in the e-waste recycling industry, as presented in Table 1. The experts selected for the first phase of interviews were chosen based on their direct involvement in operational and safety functions within the e-waste recycling industry, rather than solely on the number of years of experience.

Table 2: Profile of Phase One Interviewees

Interviewee Code	Designation	Job Role	Years of Experience
P1I1	Director	Leads and oversees the entire plant operation	10 years
P1I2	Executive-Operations Engineer	Manage daily operations of the plant, ensure safety, and collaborate with machinery maintenance teams.	5 years
P1I3	Assistant Manager	Manage the plant operation, resource allocation, and ensure the safety and efficiency of the plant	6 Years
P1I4	Operations Engineer	Monitors the plant machinery system, ensures continuous operation and manages daily operations of the plant.	5 Years
P1I5	Operations Manager	Manage the overall operations of the plant, handle logistics, inventory management	7 Years

Secondly, the questionnaire survey was conducted to identify the probability and impact of the identified risks. The questionnaire survey involved a selected sample of 32 participants who are involved with the e-waste recycling process in Sri Lanka. The participants include the operational employees, supervisors, middle managers, and top managers, all of whom had a minimum five years of experience in the e-waste recycling industry. The survey consisted of 2 sections. Section one of the survey contained demographic questions about the respondent, such as age and experience. The second section contained impact and probability identification of each identified health and safety risk. The available choices for the risk impact questions were ranked 1 to 5. The probability options given to the respondents were very low, low, moderate, high, and very high. Then, the five expert interviews were conducted to identify the mitigation strategies to overcome these risks. The interviewees were selected based on the specialised nature of their roles, experience and their direct involvement in health and safety management within e-waste or related industries.

Table 3: Profile of Phase Two Interviewees

Interviewer Code	Designation	Role	Years of Experience
E1	Health and Safety officer	Responsible for implementing and monitoring the workplace safety protocols.	6 years
E2	Assistant Manager – Health, Safety, and Environment	Manage the health, safety, and environmental aspects of the workplace	7 years
E3	Health, Safety, Environment Manager	Manage overall health and safety and environmental strategies and ensure compliance.	9 years
E4	Manager - Health and Safety	Manage the health and safety of the workplace and ensure compliance	7 years
E5	Senior Executive- Health and Safety	Implement the health and safety policies and oversee the health and safety of the organisation.	5 years

The Risk Priority Number(RPN) method was adopted to prioritisation of identified mitigation strategies. This method has been previously applied in similar studies for risk-based prioritisation of mitigation strategies in other industrial contexts (Sugathadasa & Perera, 2021). The RPN was calculated using the following formula;

$$\text{RPN} = \text{Severity (S)} \times \text{Occurrence (O)}$$

The data for severity and the occurrence of the risks were gathered through the questionnaire survey. This method enabled the study to systematically prioritise the mitigation strategies and identify the most effective mitigation strategies to overcome the identified risks.

4. Research Findings

4.1 HEALTH AND SAFETY RISKS ASSOCIATED WITH E-WASTE RECYCLING WORKERS AND MITIGATION STRATEGIES TO OVERCOME RISKS

According to the phase one interviews, The interviews revealed three significant health and safety risks associated with the shredding and plastic recycling processes that were not previously identified in the literature review. One major risk highlighted during the shredding process is the fire hazard, which arises from operational factors such as overloading of shredding machines and insufficient maintenance practices. Similarly, within the plastic recycling process, the risk of fire incidents was also identified. This risk primarily stems from the use of high temperatures required for heating and melting plastic. Moreover, according to the experts interviewed, certain stages identified through the literature review including the pyro-metallurgical and hydrometallurgical, acid extraction are not utilized in the context of Sri Lanka's e-waste recycling industry. These processes are currently not practice in the local plants.

The Table 4 presents the e-waste recycling activity and the health and safety risks under each activity. The mitigation strategies are provided for each identified with the level of hierarchy of control

The risk code and mitigation strategy code are also indicated along with the risk and mitigation strategy in the following table.

Table 4: Health and Safety Risks with Mitigation Strategies

Activity	Health and Safety risks with risk code	Mitigation Strategies with code	Hierarchy of control	Interviewee				
				E1	E2	E3	E4	E5
Collection and Dismantling	Cuts and injuries from sharp objects (R1)	Employee training on handling sharp objects (M1)	Administrative control	✓	✓	✓	✓	✓
		Provide safe work procedures (M2)	Administrative control	✓		✓	✓	
		Use sign boards and warning signs (M3)	Administrative control				✓	
		Proper housekeeping (M4)	Administrative control		✓	✓		

		Provide cut resistant gloves, apron (M5)	PPE	✓	✓	✓	✓	✓
	Respiratory issues by inhaling dust containing various compound during dismantling activities (R2)	Install local exhaust system (M6)	Engineering control	✓	✓	✓	✓	
		Install proper filtration system (M7)	Engineering control	✓	✓	✓	✓	
		Compressed air cleaning (M8)	Engineering control			✓	✓	
		KN-95 mask or filter mask with double cartridge(M9)	PPE					✓
	Musculoskeletal disorders from lifting (R3)	Use lifting carts or equipment such as push carts and hand-trunk (M10)	Engineering control	✓	✓	✓	✓	✓
		Employee training on proper equipment lifting and manual handling (M11)	Administrative control	✓			✓	✓
		Provide work rotation (M12)	Administrative control	✓				✓
		Provide regular breaks (M13)	Administrative control		✓			
Shredding	Fire hazardous due to machine overloading (R4)	fixing overload limit sensors (M14)	Engineering control	✓	✓	✓	✓	✓
		Provide unobstructed exits from rooms (M15)	Engineering control	✓	✓	✓		
		Provide fire extinguishers (M16)	Engineering control	✓	✓	✓	✓	✓
		Regular maintenance of the machines (M17)	Engineering control				✓	
	Respiratory issues from fine particulate dust (R5)	Install local exhaust system (M6)	Engineering control	✓	✓	✓	✓	✓

		Installed proper filtration system (M7)	Engineering control		✓			✓
		Compressed air cleaning (M8)	Engineering control		✓	✓		
		Use KN-95 mask or filter mask with double cartridge (M9)	PPE					✓
	Injury from machine operations (R6)	Attach proper guards to dangerous moving parts of machines (M18)	Engineering control	✓	✓	✓	✓	✓
		Ensure safe wiring connections for supplying electricity to machines (M19)	Engineering control				✓	
		prevent unauthorized entry (M20)	Administrative control	✓	✓	✓	✓	✓
		provide interlock system for the machines (M21)	Engineering control		✓	✓		✓
		use log out tag out system (LOTO) (M22)	Engineering control	✓	✓	✓	✓	✓
		Proper maintenance of machines (M17)	Engineering control				✓	
		Eye protection such as goggles, gloves (M23)	PPE			✓		
Plastic Recycling	Risk of burns and injuries from hot plastic handling (R7)	use heat resistant gloves and clothing (M24)	PPE	✓	✓	✓	✓	✓
	Respiratory issues from dust and fumes and some metal additives such as hydrochloride acids, styrene (R8)	Install local exhaust system (M6)	Engineering control	✓	✓	✓	✓	✓
		Installed proper filtration system (M7)	Engineering control		✓			✓
		Compressed air cleaning (M8)	Engineering control		✓	✓		
		Use KN-95 mask or filter mask with double cartridge (M9)	PPE					✓

	Fire hazard due to high temperature (R9)	Install heat detectors (M25)	Engineering control	✓	✓	✓		
		Provide unobstructed exits from rooms (M15)	Engineering control	✓	✓	✓		
		Provide fire extinguishers (M16)	Engineering control	✓	✓	✓	✓	✓
		Regular maintenance of the machines (M17)	Engineering control				✓	
PC board heating	Injury from improper handling of heated materials (R10)	use heat resistant gloves and clothing (M24)	PPE	✓	✓	✓	✓	✓
		Install local exhaust system (M6)	Engineering control		✓			✓
	Chronic respiratory issues from toxic fumes of various compounds from solder and PC board components, such as lead, volatile organic compounds, Polybrominated Flame Retardants (R11)	Installed proper filtration system (M7)	Engineering control		✓	✓		
		Compressed air cleaning (M8)	Engineering control					✓
		Use KN-95 mask or filter mask with double cartridge (M9)	PPE	✓	✓	✓	✓	✓
Toner Sweeping	Respiratory issues from toner dust including carbon black (R12)	Install local exhaust system (M6)	Engineering control	✓	✓	✓	✓	✓
		Installed proper filtration system (M7)	Engineering control		✓			✓
		Compressed air cleaning (M8)	Engineering control		✓	✓		
		Install high Efficiency particulate Air (HEPA) filters (M7)	Engineering control	✓	✓			✓
		KN-95 mask or filter mask with double cartridge (9)	PPE					✓
	Musculoskeletal disorders from repetitive motions (R13)	providing adjustable worktables (M26)	Engineering control	✓	✓	✓		

		Frequent short breaks during work	Administrative control				✓	✓

4.2 PRIORITIZATION OF MITIGATION STRATEGIES

The level of each risk was identified by calculating the probability and the impact. According to the probability and the impact, RPN (Risk Priority Number) values were calculated. A visual representation of the RPN Calculation Process is provided in Figure 2.

Figure 1, RPN calculation process

The following formula has been used to calculate the RPN values for each risk factor.

$$\text{RPN} = \text{Severity (S)} \times \text{Occurrences (S)}$$

According to the above formula, the RPN value is the severity of the consequences and the frequency of the occurrence of each risk. Data for severity and occurrence were gathered through a structured questionnaire survey. Respondents rated the probability (occurrence) and impact (severity) of each identified risk using a five-point Likert scale. To identify the severity and the occurrence of each risk, the mod of the responses was selected (refer to Figure 1). For instance, if the mod of the R1 from probability responses is low, the probability of the R1 is considered as low (Low probability), and if the mod of the occurrence responses is 4, the impact is considered as high.

Risk Factor	Probability Responses					Impact Responses					Probability	Impact	Risk Level
	1	2	3	4	5	1	2	3	4	5			
	Very Low	Low	Moderate	High	Very high	Very Low	Low	Moderate	High	Very high			
R1		4	1	17	1		5	2	14	2	4	4	16
R2	2	13		8				6	17		2	4	8
R3		2	5	16			19	1	3		4	2	8
R4		12	2	6			1	1	8	10	2	5	10
R5		14	1	5			3	2	15		2	4	8
R6	2	14	2	2			1	1	13	5	2	4	8
R7			2	9			1		8	2	4	4	16
R8		10	1				3		8		2	4	8
R9		7	1	3			2	1	4	4	2	4	8
R10		3	2	9			2	1	10	1	4	4	16
R11		11	1	2			3	2	9		2	4	8
R12	1	8	2	1			1	1	8	2	2	4	8
R13	1	7	1	3			7	2	3		2	2	4

Figure 1: RPN Calculation

The ability of the mitigation strategies to reduce the risks found in the research was measured using the RMN (Risk Mitigation Number) calculation (refer to Figure 2), which was used to determine the optimal approaches. The RMN calculation prioritises the important risk mitigation strategies that target the greatest number of risks.

According to the following RMN calculation, providing safe work procedures (M2) is the best mitigation strategy for the e-waste recycling plants. It can mitigate most of the risks that occur in e-waste recycling plants by providing safe work procedures. Use of sign boards and warning signs (M3) was identified as the second effective mitigation strategy for the health and safety risks.

Mitigation Strategy ID	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	RMN
	16	8	8	10	8	8	16	8	8	16	8	8	4	
M1	1	0	0	0	0	0	0	0	0	0	0	0	0	16
M2	1	1	1	1	1	1	1	1	1	1	1	1	1	126
M3	1	1	1	1	1	1	1	1	1	0	1	1	1	118
M4	0	1	1	1	0	1	0	0	1	0	0	1	1	48
M5	1	0	0	0	0	0	0	0	0	0	0	0	0	16
M6	0	1	1	0	0	1	0	0	1	0	0	1	1	48
M7	0	1	1	0	1	0	0	1	0	0	1	1	0	48
M8	0	1	1	0	1	0	0	1	0	0	1	1	0	48
M9	0	1	1	0	1	0	0	1	0	0	1	1	0	48
M10	0	0	0	0	0	0	0	0	0	0	0	0	1	4
M11	0	0	0	0	0	0	1	0	0	1	0	0	1	36
M12	0	0	1	0	0	0	0	0	0	0	0	0	1	12
M13	0	0	0	0	0	0	0	0	0	0	0	0	1	4
M14	0	0	0	0	0	0	0	0	1	0	0	0	0	8
M15	0	0	0	1	0	0	0	0	1	0	0	0	0	18
M16	0	0	0	1	0	0	0	0	1	0	0	0	0	18
M17	0	0	0	1	0	1	0	0	1	0	0	0	0	26
M18	0	0	0	0	0	1	0	0	0	1	0	0	0	24
M19	0	0	0	1	0	0	0	0	1	0	0	0	0	18
M20	0	0	0	0	0	1	0	0	0	0	0	0	0	8
M21	0	0	0	0	0	1	0	0	0	0	0	0	0	8
M22	0	0	0	0	0	1	0	0	0	0	0	0	0	8
M23	1	0	0	0	0	1	0	0	0	0	0	0	0	24
M24	0	0	0	0	0	0	0	0	0	1	0	0	0	16
M25	0	0	0	0	0	0	0	0	0	0	1	0	0	8
M26	0	0	0	0	0	0	0	0	0	0	0	1	1	4

Figure 2: RMN Calculation

5. Conclusion

This study highlights the health and safety risks posed by e-waste recycling workers in Sri Lanka and proposed mitigation strategies to address them. A mixed research approach was used, combining a questionnaire survey and two expert interviews to identify the key risks and the mitigation strategies to overcome those risks. The Risk Priority Number (RPN) was enabled to identify the risk level of each risk which was calculated based on the severity and occurrence of each risk, and then the Risk Mitigation Number (RMN) was enabled to prioritisation of mitigation strategies. According to the RMN calculation, providing safe work procedures (M2) was identified as the most effective mitigation strategy. These findings underscore the importance of risk management practices in the e-waste recycling industry and ensure the health and safety of the workers. The implications of this study suggest that targeted interventions such as employee training, machine maintenance, and implementation of clear safety procedures can significantly reduce occupational hazards. Future research could expand on this work by assessing the long-term effectiveness of implemented mitigation strategies

6. References

- A. Lucier, C., & J. Gareau, B. (2020). Electronic Waste Recycling and Disposal: An Overview. *Assessment and Management of Radioactive and Electronic Wastes*, 1–12. <https://doi.org/10.5772/intechopen.85983>
- Acquah, A. A., D'Souza, C., Martin, B. J., Arko-Mensah, J., Botwe, P. K., Tettey, P., Dwomoh, D., Nti, A. A., Kwarteng, L., Takyi, S., Quakyi, I. A., Robins, T. G., & Fobil, J. N. (2021). A preliminary assessment of physical work exposures among electronic waste workers at Agbogbloshie, Accra Ghana. *International Journal of Industrial Ergonomics*, 82(October 2020), 103096. <https://doi.org/10.1016/j.ergon.2021.103096>
- Ahirwar, R., & Tripathi, A. K. (2021). E-waste management: A review of recycling process, environmental and occupational health hazards, and potential solutions. *Environmental Nanotechnology, Monitoring & Management*, 15, 100409. <https://doi.org/https://doi.org/10.1016/j.enmm.2020.100409>
- Alahakoon, Y., & Gunaratne*, N. (2022). E-waste Management in Sri Lanka. In *Paradigm Shift in E-waste Management*. <https://doi.org/10.1201/9781003095972-7>
- Arain, A. L., & Neitzel, R. L. (2019). A review of biomarkers used for assessing human exposure to metals from E-waste. *International Journal of Environmental Research and Public Health*, 16(10). <https://doi.org/10.3390/ijerph16101802>
- Attia, Y., Soori, P. K., & Ghaith, F. (2021). *Behavior , and Estimation of Potential Waste Mobile Phones*.
- Borthakur, A., & Sinha, K. (2013). Electronic Waste Management in India: A Stakeholder's Perspective Anwesha Borthakur and Kunal Sinha Jawaharlal Nehru University, New Delhi, India and Central University of Gujarat, Gandhinagar, Gujarat, India. *Electronic Green Journal*, 36, 1–21.

- Burns, K. N., Sun, K., Fobil, J. N., & Neitzel, R. L. (2016). Heart rate, stress, and occupational noise exposure among electronic waste recycling workers. *International Journal of Environmental Research and Public Health*, 13(1). <https://doi.org/10.3390/ijerph13010140>
- California Department of Public Health. (2012). *Electronic Waste Recycling Fee. August*.
- Cayumil, R., Khanna, R., Rajarao, R., Ikram-ul-Haq, M., Mukherjee, P. S., & Sahajwalla, V. (2016). Environmental Impact of Processing Electronic Waste – Key Issues and Challenges. *E-Waste in Transition - From Pollution to Resource*. <https://doi.org/10.5772/64139>
- Chatterjee, S., & Kumar, K. (2009). Effective electronic waste management and recycling process involving formal and non-formal sectors. *International Journal of Physical Sciences*, 4.
- Decharat, S., & Kiddee, P. (2020). Health Problems Among Workers Who Recycle Electronic Waste in Southern Thailand. *Osong Public Health and Research Perspectives*, 11(1), 34–43. <https://doi.org/10.24171/j.phrp.2020.11.1.06>
- Fischer, D., Seidu, F., Yang, J., Felten, M. K., Garus, C., Kraus, T., Fobil, J. N., & Kaifie, A. (2020). Health consequences for E-waste workers and bystanders—a comparative cross-sectional study. *International Journal of Environmental Research and Public Health*, 17(5). <https://doi.org/10.3390/ijerph17051534>
- Frazzoli, C., Orisakwe, O. E., Dragone, R., & Mantovani, A. (2010). Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. *Environmental Impact Assessment Review*, 30(6), 388–399. <https://doi.org/10.1016/j.eiar.2009.12.004>
- Garcia, M. G., Läubli, T., & Martin, B. J. (2015). Long-term muscle fatigue after standing work. *Human Factors*, 57(7), 1162–1173. <https://doi.org/10.1177/0018720815590293>
- Goel, S. (2017). Advances in solid and hazardous waste management. *Advances in Solid and Hazardous Waste Management*, 1–371. <https://doi.org/10.1007/978-3-319-57076-1>
- Gong, W., Zhao, L., Ceballos, D., & Zhu, B. (2020). Lead and noise exposures at eight Chinese registered electronics recycling facilities. *International Journal of Hygiene and Environmental Health*, 230(September), 113611. <https://doi.org/10.1016/j.ijheh.2020.113611>
- Gravel, S., Roberge, B., Calosso, M., Gagné, S., Lavoie, J., & Labrèche, F. (2023). Occupational health and safety, metal exposures and multi-exposures health risk in Canadian electronic waste recycling facilities. *Waste Management*, 165(October 2022), 140–149. <https://doi.org/10.1016/j.wasman.2023.04.026>
- Issah, I., Arko-Mensah, J., Agyekum, T. P., Dwomoh, D., & Fobil, J. N. (2022). Health Risks Associated with Informal Electronic Waste Recycling in Africa: A Systematic Review. *International Journal of Environmental Research and Public Health*, 19(21), 8–10. <https://doi.org/10.3390/ijerph192114278>
- Kaya, M. (2016). Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. *Waste Management*, 57, 64–90. <https://doi.org/https://doi.org/10.1016/j.wasman.2016.08.004>
- Khanna, R., Mukherjee, P. S., & Park, M. (2020). A critical assessment on resource recovery from electronic waste: Impact of mechanical pre-treatment. *Journal of Cleaner Production*, 268, 122319. <https://doi.org/https://doi.org/10.1016/j.jclepro.2020.122319>
- Kiddee, P., Naidu, R., & Wong, M. H. (2013). Electronic waste management approaches: An overview. *Waste Management*, 33(5), 1237–1250. <https://doi.org/10.1016/j.wasman.2013.01.006>
- Kumar, A., Holuszko, M., & Espinosa, D. C. R. (2017). E-waste: An overview on generation, collection, legislation and recycling practices. *Resources, Conservation and Recycling*, 122, 32–42. <https://doi.org/10.1016/j.resconrec.2017.01.018>
- Lau, W. K. Y., Liang, P., Man, Y. B., Chung, S. S., & Wong, M. H. (2014). Human health risk assessment based on trace metals in suspended air particulates, surface dust, and floor dust from e-waste recycling workshops in Hong Kong, China. *Environmental Science and Pollution Research*, 21(5), 3813–3825. <https://doi.org/10.1007/s11356-013-2372-8>
- Liu, K., Tan, Q., Yu, J., & Wang, M. (2023). A global perspective on e-waste recycling. *Circular Economy*, 2(1), 100028. <https://doi.org/10.1016/j.cec.2023.100028>
- López, M., Reche, C., Pérez-Albaladejo, E., Porte, C., Balasch, A., Monfort, E., Eljarrat, E., & Viana, M. (2022). E-waste dismantling as a source of personal exposure and environmental release of fine and ultrafine particles. *Science of the Total Environment*, 833(March), 1–12. <https://doi.org/10.1016/j.scitotenv.2022.154871>
- LY, NHT; GIAO, N. (2025). *Review and Analyze the Sources , Characteristics and Composition of Electronic Waste*.
- Ministry of Health, Nutrition & Indigenous Medicine Sri Lanka (Vol. 11, Issue 8). (2023). <https://doi.org/10.2196/38201>

- Ohajinwa, C. M., Van Bodegom, P. M., Vijver, M. G., & Peijnenburg, W. J. G. M. (2017). Health risks awareness of electronic waste workers in the informal sector in Nigeria. *International Journal of Environmental Research and Public Health*, 14(8). <https://doi.org/10.3390/ijerph14080911>
- Okeme, J. O., & Arrandale, V. H. (2019). Electronic Waste Recycling: Occupational Exposures and Work-Related Health Effects. *Current Environmental Health Reports*, 6(4), 256–268. <https://doi.org/10.1007/s40572-019-00255-3>
- Parthasarathy, M. (2021). Challenges and emerging trends in toner waste recycling: A review. *Recycling*, 6(3). <https://doi.org/10.3390/recycling6030057>
- Perkins, D. N., Brune Drisse, M. N., Nxele, T., & Sly, P. D. (2014). E-waste: A global hazard. *Annals of Global Health*, 80(4), 286–295. <https://doi.org/10.1016/j.aogh.2014.10.001>
- Priyashantha, A. K. H., Pratheesh, N., & Pretheeba, P. (2022). E-waste scenario in South-Asia: an emerging risk to environment and public health. *Environmental Analysis, Health and Toxicology*, 37(3), e2022022-0. <https://doi.org/10.5620/eaht.2022022>
- Roffey, D. M., Wai, E. K., Bishop, P., Kwon, B. K., & Dagenais, S. (2010). Causal assessment of awkward occupational postures and low back pain: results of a systematic review. *Spine Journal*, 10(1), 89–99. <https://doi.org/10.1016/j.spinee.2009.09.003>
- Singh, M., Thind, P. S., & John, S. (2018). Health risk assessment of the workers exposed to the heavy metals in e-waste recycling sites of Chandigarh and Ludhiana, Punjab, India. *Chemosphere*, 203, 426–433. <https://doi.org/10.1016/j.chemosphere.2018.03.138>
- Sugathadasa, P. T. R. S., & Perera, H. N. (2021). *Analysis of Risk Factors for Temperature- Controlled Warehouses*. 14(3), 320–337.
- Tsydenova, O., & Bengtsson, M. (2011). Chemical hazards associated with treatment of waste electrical and electronic equipment. *Waste Management*, 31(1), 45–58. <https://doi.org/10.1016/j.wasman.2010.08.014>
- Vats, M., & Singh, S. (2014). E-Waste characteristic and its disposal. *International Journal of Ecological Science and Environmental Engineering*, 1, 49–61.
- Wang, H., Zhang, S., Li, B., Pan, D., Wu, Y., & Zuo, T. (2017). Recovery of waste printed circuit boards through pyrometallurgical processing: A review. *Resources, Conservation and Recycling*, 126, 209–218. <https://doi.org/https://doi.org/10.1016/j.resconrec.2017.08.001>
- Yohannessen, K., Pinto-Galleguillos, D., Parra-Giordano, D., Agost, A., Valdés, M., Smith, L. M., Galen, K., Arain, A., Rojas, F., Neitzel, R. L., & Ruiz-Rudolph, P. (2019). Health assessment of electronic waste workers in chile: Participant characterization. *International Journal of Environmental Research and Public Health*, 16(3), 1–14. <https://doi.org/10.3390/ijerph16030386>

CONSTRAINTS FOR REDUCING CARBON EMISSIONS AND ENERGY CONSUMPTION IN BUILDINGS - A SYSTEMATIC REVIEW

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Abstract. Even though a significant emphasis is placed on carbon emission reduction in buildings, several constraints continue to hinder its practical implementation in buildings. Over the past 25 years, much research has been conducted to explore the constraints of delivering low-energy/ carbon buildings in different sectors. However, those constraints have not been organized properly, requiring a detailed and comprehensive approach to identifying and listing the constraints to deliver low-energy/carbon buildings. Furthermore, a systematic review has still not been conducted to explore these studies, which have identified and discussed constraints. Therefore, this paper aims to systematically explore the previous literature to identify and list the constraints to delivering low-energy/carbon buildings. The presented outcomes are based on a review of published journal papers from 2001 to 2024. According to the findings of the literature review, 92 constraints were identified under 9 categories. It was revealed that the adaptation of low-energy/ carbon buildings in developed countries has gradually increased over time, while there is no significant movement in developing countries.

Keywords. Energy, Carbon Reduction, Low Energy/Carbon Buildings, Constraints For Low Energy/Carbon Buildings, Sustainability

1. Introduction

Climate change and resource scarcity have increased the awareness of sustainable practices worldwide during the past two decades (Pérez-Navarro et al., 2023). With the rapid development of industrialization and urbanization, the world has been shifting towards low-energy/carbon buildings over the last few years (Hafez et al., 2023). Since one-third of global greenhouse gas (GHG) emissions and one-third of energy consumption are accounted for by buildings, the building sector is one of the main targeted industries to reduce greenhouse gas emissions and energy consumption (Dino & Meral Akgül, 2019). The buildings cause negative impacts on the environment during different stages in their life cycle, such as the processing of raw materials, transportation of raw materials, construction, operation and maintenance, and demolition (Zou & Couani, 2012). In addition to that, global GHG emissions and energy consumption are increasing continuously due to higher population growth rates, changes in lifestyles and increasing building stocks (Urge-Vorsatz et al., 2013). This continued increase in energy consumption has affected the global temperature increase, leading to severe climate changes in future (McCarthy et al., 2010). In addition to that, international organizations related to energy/carbon such as the International Energy Agency [IEA], Regulatory Indicators for Sustainable Energy [RISE], and the findings of much research have emphasized the impact of the rapid increase of energy demand and carbon emissions from building construction industry and existing building stocks.

Many scholars have emphasized that low-energy/carbon buildings are the more significant and highly supportive strategy for achieving environmental sustainability goals in the building industry (Isiadinso et al., 2011; Li et al., 2023; Sartori & Hestnes, 2007). Low-energy carbon buildings can be interpreted as buildings which have low GHG emissions and less energy consumption using energy efficiency improvement measures throughout their lifecycle (Li et al., 2023). Low-energy/ carbon buildings aim to reduce carbon emission and energy consumption in different stages of the building life cycle, such as planning, designing, construction, operation, demolition and recycling (Sartori & Hestnes, 2007). Currently, building floor area is rapidly increasing globally due to the higher growth rate of the population. However, most countries are trying to reduce the carbon emissions and energy consumption of new constructions and existing

building stock through various macro-level and micro-level carbon reduction and energy-saving initiatives (Pan & Ning, 2015). Further, accepting the adverse impact of rapid urbanization, the entire world is taking action to shift urban areas towards low-carbon cities (Ng et al., 2013).

Nevertheless, a significant reduction in carbon emissions and energy consumption cannot be seen despite several efforts taken. It is also important to note that delivery and development of low energy/ carbon buildings require advanced technologies in construction and building operation, sustainable building materials, reliable simulation analysis, complex architectural designs, strong policy support, consumer acceptance, higher capital, proper supply chain, skilled labour, proper awareness, education and training, etc...Therefore, delivering low energy/ carbon buildings have become challenging than that of conventional buildings (Olanipekun et al., 2017). This emphasises that there may be multiple constraints which hinder the development and delivery of low-energy/ carbon buildings. There may be several factors, obstacles and conditions that reduce the effectiveness of the delivery of low-energy/ carbon building projects and adaptation strategies (Huang et al., 2018). Several studies reveal that the approach of moving towards low-carbon buildings has been retarded due to several socio-technical factors, rather than solely social Barriers or solely technical barriers. According to Osmani & O'Reilly (2009), challenges to the delivery of low-carbon buildings can mainly be identified under legislative, cultural, financial and technological factors.

However, Zou et al. (2018) identified the availability of previous pilot projects, demand in the construction market for low-carbon buildings, construction technologies, support from the government, awareness, knowledge and training regarding sustainable practices as the factors which hinder the development and the delivery of low-carbon buildings. From a financial perspective, Baek & Park (2012) discussed that higher capital costs for low energy/ carbon buildings and prolonged payback periods for the initial investment adversely affect investment decisions in the low energy/carbon buildings. When considering the financial risk associated with low-carbon/energy buildings, the cost of projects is highly uncertain and therefore, it is unpredictable in the long-term and medium-term. Chan & Grace (2006) identified that the lack of financial incentives for low-energy/ carbon projects is another main constraint. Lack of public awareness and knowledge regarding carbon emission and energy consumption, and high-energy-consuming lifestyles have been identified as social barriers by Afshari et al. (2016). Liu et al. (2010) identified four major problems in low-carbon building projects, such as a lack of social participation, a lack of regulatory support and mechanisms, and a lack of low-carbon techniques and funding sources. In addition to that, the behaviours of the occupants, cultural backgrounds, and consumer choices directly affect the effectiveness of low-carbon building projects. Zhang & Wang (2013) emphasise that different types of legal, administrative, financial, non-governmental and social factors restrict the implementation and promotion of low-carbon buildings in the construction industry. Moreover, lack of information, lack of required skills and geographical barriers are some of the issues identified to reduce the effectiveness of low carbon building projects (Du et al., 2014; Rock et al., 2019).

Even though several studies have been conducted to outline barriers to the implementation of low energy/ carbon buildings, there is no proper systematic review to explore all the barriers in different dimensions. Since there is a growing trend towards low-energy/ carbon buildings, it is important to ensure that these projects are delivered more efficiently and effectively. Therefore, identification of constraints is essential for academics and professional practitioners to set strategies to overcome these constraints in planning and implementing low-energy/carbon building projects. To contribute to fulfilling this requirement, this study aimed to identify and categorize the constraints to delivering low energy/ carbon buildings through a systematic literature review of published journal papers from 2001 to 2024. This paper presents the list of the constraints and categorization of the constraints to delivering low-carbon buildings.

2. Review methods

Peer-reviewed journal papers were reviewed to conduct the systematic review to explore the previous publications to identify the constraints affecting the delivery of low energy/ carbon buildings. According to Pickering & Byrne (2014), a systematic review differs from a traditional literature review which involves a small and often incomplete number of publications because a systematic review involves a stand-alone piece of research that explores the existing knowledge in the field and provides insights into quite specific areas.

The steps which were outlined by Hu et al., (2013) and Moher et al., (2009) Were used to present this study and to conduct the intended review. Related papers were identified through one of the most popular and comprehensive databases which is called the 'Web of Science' electronic publications repository. "(Barriers OR Constraints OR Challenges) AND (Energy OR Carbon) AND (Buildings OR Building)" are the keywords used for the database search. The articles were searched by its title and the journal articles which were published from 2001 to 2024 were considered for the study. Only the published articles in journals were considered to ensure the quality. Book reviews, editorials, and papers for conference proceedings were excluded from the review. After applying the above search strategy, 220 publications were found in the database. After the manual screening, 115 publications were utilized to explore the constraints of delivering low energy. The data retrieval process from the selected journal articles was conducted using a manual data extraction approach by carefully reviewing each article and manually recording relevant data in an Excel spreadsheet. Finally, collected data were manually analyzed to identify identical constraints and to categorize them accordingly.

3. Results and Analysis

This section presents the overview of the review of the 220 reviewed articles through the keyword search as mentioned in the methodology. Even though 220 articles were received by the keyword search, 34 publications were removed from that list after the abstract screening. Further, 8 articles were removed from the list after assessing the full text for eligibility. In addition to that, 11 articles were removed due to issues in retrieving full-text articles. Finally, 167 publications were reviewed for this study. Among them only 115 papers were used to identify the constraints that hinder the delivery of low energy/ carbon buildings. The primary target of this section is to present the trend of the publications and highlight the identified constraints that hinder the delivery of low energy/ carbon buildings and time series analysis of the identified constraints. Figure 1 shows the article retrieving process.

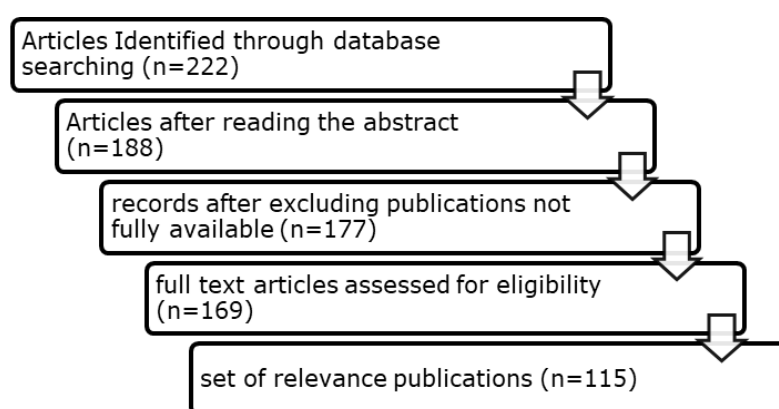


Figure 1: Article retrieving process

3.1 TRENDS OF PUBLICATIONS

Throughout the past 25 years, a notable increase can be seen in published studies on low-energy/ carbon buildings. The evolution was started in 2012 and gradually increased thereafter. A little attention has been given by scholars to studies related to low energy/ carbon buildings during the years 2001-2011. Accepting the rapid urbanization, increasing building stocks and associated climate changes, more countries have started to focus on decarbonization in the built environment over the past two decades. The amount of research on exploring the constraints has increased in line with the escalation of global commitments to delivering low-energy/carbon buildings. Figure 2 shows the number of publications related to low-energy/carbon buildings over the last 25 years.

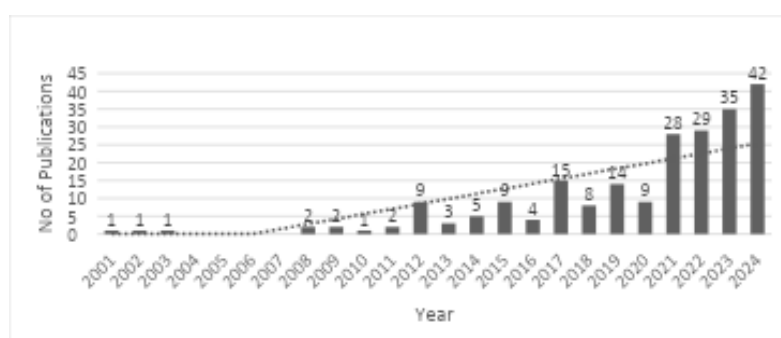


Figure 2: Number of publications from 2021 to 2024

When considering the geographical distribution of the papers, publications have been spread all over the world. Figure 03 shows the geographical distribution of articles.

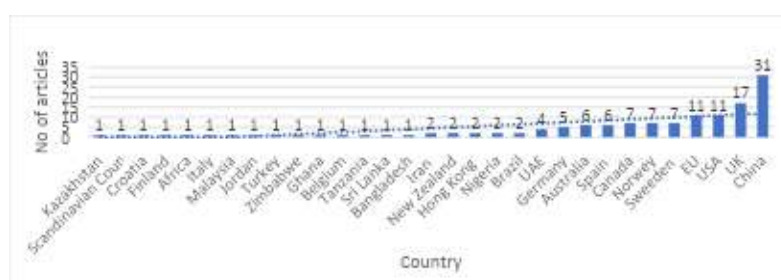


Figure 3: No of papers published in different countries

Accordingly, China and the UK had 31 and 17 articles respectively. The USA and European region had 8 publications each, Canada, Sweden and Norway had 7 publications each, Australia and Spain had 6 publications each, Germany had 5 publications, UAE had 4 publications, Iran, New Zealand, Hong Kong, Nigeria, and Brazil had 2 publications, and remaining countries had 1 publication focusing on specifically exploring the constraints to delivering low carbon and low energy buildings. This highlights that the attention towards delivering low-carbon buildings has gradually increased over time in economically developed countries. Most of the developed countries have proactively planned to include carbon emission reduction and energy-saving initiatives in their future action plans to reduce the adverse impact on the environment. Hence there could be more concern about researching potential constraints to implement the planned

initiatives aiming to achieve the intended sustainability development goals in those countries by overcoming the prevailing issues. However, there were few publications from developing countries highlighting their backward approach to delivering low-energy/ carbon buildings. Most of the developing countries focus on economic prosperity and enhancing sociological aspects, thereby most of the time environmental aspects are deprioritized neglecting the opportunities to pursue sustainability and overcome the climate change issue (Khosla et al., 2017). However, numerous socio-technical constraints can be identified in developing countries which restrict the effective uptake of delivering low-energy/ carbon buildings due to regulatory barriers, unstable economic conditions, and low levels of technical adaptation (F. Liu et al., 2010). Therefore, constraints in delivering low/carbon energy buildings in developing countries would be beneficial for rapid uptake of implementing suitability initiatives while achieving economic prosperity to overcome climate change issues.

In addition to the aforementioned trends, a brief emphasis on the productive journals in this specific area will be beneficial for future researchers to focus and explore more on the related publications. A total of 115 journals have contributed to this particular research area of identifying the constraints to delivering low-energy/carbon buildings. Among these journals, 'Energy and Buildings', 'Buildings', 'Energies', and 'Sustainability' had 13, 12, 11 and 8 publications respectively. 'Building and environment', and 'Energy policy' had 7 publications each while 'Journal of Cleaner Production' and 'Energy' had 6 publications each. 'Sustainable cities and society' accounted for 5 publications each while 'Building research and information' had 3 publications under this specific topic. These journals can be identified as the most productive journals in this area. All the other journals had 2 or 1 publications under their names.

4. Discussion

According to the geographical distribution of the identified 115 papers, China has published the highest number of papers accounting for 31 publications followed by the UK had 17 publications. European countries had 25 publications while Scandinavian countries had 23 publications including, Norway, Sweden and Canada. In addition to that, the USA had 11 publications. It is noteworthy that 85.40% of the publications originated from developed countries with stable economies. It highlights that higher consideration for sustainability practices by delivering low-energy/carbon buildings can be seen in developed countries. A few numbers of publications have been published in developing countries highlighting their backward uptake of delivering low-energy/ carbon buildings. Only 20 papers among the identified papers originated from developing countries (India, Malaysia, West Indies, Sri Lanka, Bangladesh, Tanzania, Iran, Nigeria, Zimbabwe, Kazakhstan and Thailand). This implies the slow uptake in delivering low-energy/ carbon buildings in developing countries.

The total floor area of buildings in developing countries is rapidly growing in developing countries. More than 3 billion m², the majority being from the developing countries were built in 2018 with neither governing /oversight policies, nor mandatory energy and carbon performance requirements (IEA, 2019). This critical situation is a sign of very slow energy and carbon policy progress, demonstrating that the evolution of building energy usage and carbon emission reduction initiatives in particular is not keeping up with the rapid growth in developing countries (Madhusanka et al., 2020). Nevertheless, sufficient attention from scholars was not evident in doing research focusing on the contexts of developing countries. Therefore, there is a timely research requirement to explore the constraints which hinder the development and delivery of low-energy/carbon buildings in the contexts of developing countries and to determine feasible strategies to overcome these constraints.

Considering the publication years, most of the publications (136 papers) were published during the years 2020-2024. Articles published in early years from 2001-2012 focus on constraints

related to more generic aspects such as green buildings, sustainable buildings, policy-related issues, organizational issues etc. However, in recent years research on more specific and low energy/ carbon focus has been published. Along with that, more scholars have focused on identifying the barriers, challenges, constraints, issues and obstacles in life cycle carbon emission, adaptation of technology, energy/ carbon calculations and information management in energy/ carbon reduction programs. In addition to that, in recent publications, many researchers have studied more net zero energy/ carbon buildings focusing on different perspectives. Therefore, according to the review findings, research had been started with a broad area and gradually it has broken into more specific areas.

4.1 LIST OF CONSTRAINTS IDENTIFIED THROUGH LITERATURE REVIEW

Constraints to deliver low energy/carbon buildings were extracted after examining the content of the 115 screened papers (out of 220) from the literature search. The final and summarized list of 92 constraints under 9 categories is indicated in Figure 5 below. Constraint categories were also determined through the literature review. Different literatures had covered different categories and after retrieving data from each article, 9 different constraint categories were identified. When there was no indication of the category of a particular constraint, the most suitable one was selected from the identified list of categories and grouped accordingly.

Among the above-identified constraints, policy-related constraints, economic-related constraints, knowledge-related constraints, and technology-related constraints are the most highlighted categories of constraints. Accordingly, most scholars have proven that the overall progress and delivery of low-energy/ carbon buildings are significantly affected by these constraints. According to Yeatts et al., (2017) and Kangas et al., (2018) most of the micro-level constraints come under those categories. Concerning the present study, the radar chart (Figure 5) shows the number of studies which reported the constraints under each category, as well as the number of specific constraints reported under each category. Most scholars have paid attention to financial constraints, policy-related constraints, technical constraints, knowledge, skills and awareness-related constraints. Accordingly, 74 studies have reported from the financial area of constraints, 65 studies on policy-related constraints, 61 studies from knowledge, skills and awareness-related constraints, and 55 studies focused on technology-related constraints. Figure 04 shows the number of studies that have been conducted under each category of constraints.



Figure 4: Constraint categories

Figure 5 shows the illustration of all the identified constraints under each category.

Financial Barriers	Market Structure and Supply Constraints	Regulatory/ Policy Level Constraints	Information Related Constraints	Knowledge, Skills and Awareness related Constraints	Organizational Constraints	Technological Constraints	Behavioural Constraints	Geographical and Environmental Constraints
- High capital cost - Long payback period - Lack of funding sources - Risk and uncertainty - Higher time consumption - Lack of financial incentives - Limitations posed by leasing agreements - Non-liquid nature - Difficulties in getting financial approvals - No direct financial benefit - Higher operational and maintenance cost	- Lack of market awareness - Lack of low energy/carbon material availability - Lack of suppliers - Lack of promotion and publicity - Lack of demand for low energy/carbon initiatives - Priorities given for aesthetic appearance - Less availability of long-term incentives and warranties - Poor after sale services of energy efficient equipment - Contractual conflicts	- Lack of national level standard/regulation - Lack of support from the government - No proper implementation of carbon tax scheme - No proper building carbon emission trading mechanisms - Contradictions with other compliance - Lack of energy and carbon labelling schemes - Frequently changing regulations - Lack of penalties for non-compliance - Non-availability of a proper energy quota mechanism - Lack of collaboration and coordination in the government - Loopholes of existing Policy initiatives - Political instability	- Poor information on alternative solutions - Lack of time and resources to gather information - Lack of feasibility studies - Lack energy and carbon related data - Lack of proper information exchange platforms - Lack of performance evaluation methods - Lack of customized research and development - Non-availability of proper energy feedback mechanisms - Data security	- Lack of skilled workforce - Aged workforce - Lack of training - Lack of expertise in energy auditing - Lack of understanding of performance measures - Less awareness, experience and knowledge of stakeholders - The integration between IEQ - Lack of research and development - Lack of knowledge in business case development - Lack of motivation of clients - No proper auditing mechanisms	- Management tradition and habit - Incompatible goals of decision makers - Rigid contract structures - Competing investment priorities - Complex procurement models - Higher priority for user satisfaction - Lack of capacity to meet the strict requirements - Deviations with strategic direction - Less coordination between stakeholders - Lack of control over the energy use of users - Lengthy approval processes - Communication gaps	- Lack of integration of different technologies - Lack of pilot projects - Lack of behaviour analyses - Lack of new technological advancements and innovation - Safety issues - Inefficient building energy carbon modeling tools - Lack of automation of building systems - Contradictions with quality and low energy carbon requirements - Lack of practical implementation of academic theories - Lack of cost-effective technologies - Complexity of the new technologies - Poor performance of building materials - Issues in scalability and system integration	- Poor decision making of the stake holders - Heterogeneity of consumers - Satisfaction level of users - High energy consuming lifestyle and culture - Resistance to change - Uncertain and diversified energy behaviour patterns - Changes of metabolic uses of users	- Lack of space install suitable renewable energy technologies - Issues in old existing buildings stock - High building density - Wind load and air movement - Building materials which increase the urban heat island effect - Logistical challenges - Difficulties to model /investigate the microclimate

Figure 5: List of constraints identified through the systematic review

List of citations for the respective numbers of publications:

1- (Cattano et al., 2013), 2- (Afshari et al., 2016), 3- (Zhang and Wang, 2013), 4-(Du et al., 2014), 5- (Sudhakara Reddy, 2013), 6-(Baek and Park, 2012), 7-(Wang et al., 2016), 8-(Tuominen et al., 2012), 9-(Gerrish et al., 2017), 10-(Persson and Grönkvist, 2015), 11-(Olazabal and Pascual, 2015), 12-(Bertone et al., 2019), 13-(Andrić et al., 2019), 14-(Zhang et al., 2012), 15- (Abdellah and Masrom, 2018), 16-(Cherrafi et al., 2017), 17-(Iwaro and Mwasha, 2010), 18-(Rock et al., 2019), 19- (Biekša et al., 2011), 20-(Ucci and Yu, 2014), 21-(Jiang and Tovey, 2010), 22-(Attia et al., 2017), 23- (Thollander et al., 2016), 24- (Williams and Dair, 2007), 25-(Pitts, 2017), 26-(Shen et al., 2018), 27-(Häkkinen and Belloni, 2011), 28- (Li et al., 2019), 29- (Zhang et al., 2017), 30- (Nižetić, 2016), 31-(Oregi et al., 2015), 32-(Ng et al., 2013), 33-(Paiho and Ahvenniemi, 2017), 34- (Dadzie et al., 2018), 35-(Geissler et al., 2019), 36-(Kangas

et al., 2018), 37-(Pan et al., 2019), 38-(Yeatts et al., 2017), 39-(Alam et al., 2019), 40-(Szumilo and Fuerst, 2017), 41-(Gupta et al., 2017), 42-(Yu et al., 2016), 43-(Masrom et al., 2017), 44-(Yu et al., 2015), 45-(Cagno et al., 2014), 46-(Vogel et al., 2015), 47- (Xing et al., 2018), 48-(Zhao et al., 2015), 49-(Palm & Bryngelson, 2023), 50-(Prieto et al., 2024), 51-(Pérez-Navarro et al., 2023), 52-(Kazemi & Kazemi, 2022), 53-(Carvajal Quintero, 2022), 54- (Carvajal Quintero, 2022), 55-(Khafiso et al., 2024), 56-(Cabeza et al., 2021), 57-(Y. Chen et al., 2022), 58-(Formolli et al., 2021), 59-(Madhusanka et al., 2022), 60-(Huang et al., 2023), 61-(Ohene et al., 2022), 62-(Cerić & Ivić, 2023), 63-(X. Chen et al., 2024), 64-(Xi & Cao, 2022), 65-(Brown et al., 2024), 66-(Liu et al., 2023), 67-(Bui et al., 2023), 68-(Pan & Pan, 2021), 69- (Antoniou & Mageiropoulos, 2024), 70-(Ala-juusela et al., 2021), 71-(Gluckman & Bardsley, 2022), 72-(Mustaffa & Kudus, 2022), 73-(Unuigbo et al., 2023), 74-(Rauniyar et al., 2024), 75-(Himeur et al., 2021), 76-(Moudgil et al., 2023), 77-(Attia et al., 2022), 78-(Ghasemi et al., 2024), 79-(Jaradat et al., 2024), 80-(Lane et al., 2024), 81-(Le Dréau et al., 2023), 82-(Blomqvist et al., 2022), 83-(Kazemi & Udall, 2023), 84-(Cristino et al., 2021), 85-(Mapfumo et al., 2024), 86-(Banfi et al., 2024), 87-(Nair et al., 2022), 88-(Vimal et al., 2022), 89-(Carlander & Thollander, 2023), 90-(Osuizugbo et al., 2024), 91-(Kumaraswamy et al., 2023), 92-(Kamel, 2022), 93-(Simó-Solsona et al., 2021), 94-(Alabid et al., 2022), 95-(Poyyamozi et al., 2024), 96-(Mir et al., 2021), 97-(Zahir et al., 2023), 98-(Akbarinejad et al., 2023), 99-(Gabrielli et al., 2023), 100-(Ohene et al., 2023), 101-(Keser & Kerestecioğlu, 2024), 102-(Rostami & Heravi, 2022), 103-(Cielo & Subiantoro, 2021), 104-(Cielo & Subiantoro, 2021), 105-(Albrecht & Hamels, 2021), 106-(Noh et al., 2024), 107-(Taylor et al., 2021), 108-(Gajaba & Dissanayake, 2024), 109-(Xiaoxiang et al., 2024), 110-(Chen et al., 2024), 111-(Hafez et al., 2023), 112-(Gholami et al., 2021), 113-(Siddique et al., 2021), 114-(Lassandro et al., 2024), 115-(Imran Khan et al., 2024)

The absence of mandatory standards at the national level and lack of regulations for carbon emission reduction and energy management in buildings have been identified as key policy and regulatory constraints caused by mitigation of the adaptation of low energy/ carbon initiatives (Afshari et al., 2016). The lack of incentives from the government and financial institutions for the owners and the investors of low-energy/ carbon projects has reduced the motivation of those parties to adopt the low-energy/ carbon initiatives (Andrić et al., 2019).

The high initial cost is another significant factor that hinders the delivery of low-energy/ carbon buildings, and it has been highlighted by several authors. Therefore, investors do not tend to invest in low carbon/ energy projects due to uncertainty of the return on investment for their investment (Andrić et al., 2019; Du et al., 2014). In addition to the high capital cost, varied expenses, different responsibilities and time taken to low energy/ carbon compliance, documentation and reporting cost, high operational and maintenance cost of low carbon emitting and energy saving equipment, labour cost and expenses for experts to consult on the implementation and management of low energy/ carbon buildings are some of most highlighted expenses that hinder the delivery of low energy/ carbon buildings (Shen et al., 2018; Wang et al., 2016).

In addition to that, the absence of technical advancements and innovations for convenient operation and implementation of low-energy/ carbon buildings is another significant barrier that has been identified by many researchers (Gupta et al., 2017; Vogel et al., 2015). The lack of production technologies to produce products cost-effectively has caused the unavailability of low-energy/ carbon products in the market. In addition to that, the complexity of technologies to install energy-efficient equipment and the incompatibility with other technologies restrict the opportunities to implement low-energy/ carbon buildings (Masrom et al., 2017; Rock et al., 2019).

Lack of customized research and inability to effectively transfer the research outputs into practical scenarios are some of the reasons for slowing down the adaptation of low energy/

carbon initiatives and reducing the effectiveness of implemented projects (Vogel et al., 2015). Lack of knowledge, awareness and expertise of the project management and facilities management professionals in this area is another significant issue which hinders the delivery of low energy/ carbon buildings. Due to a lack of technical understanding of low energy/ carbon initiatives, many projects lose the opportunity to adapt these sustainable practices (Du et al., 2014; Wang et al., 2016; Yeatts et al., 2017). Lack of training and knowledge-sharing programs restricted industry professionals from improving the skills required to work with low-energy/ carbon buildings (Afshari et al., 2016). Due to the lack of collaborative design practices, industry professionals have reduced the chance to share the knowledge and experience of these technologies (Häkkinen & Belloni, 2011).

According to the findings of the study, constraints to deliver low-energy/ carbon buildings vary with the economic condition of the country. Many scholars highlighted that lack of finance to invest in low energy/ carbon projects, outdated laws and regulations and unavailability of raw materials to implement energy efficient programs as challenges to achieving energy efficiency in buildings in developing countries (Gajaba & Dissanayake, 2024; Mapfumo et al., 2024). In addition to that, a lack of access and awareness related to technological integration and innovation has restricted the delivery of energy-efficient initiatives in developing countries (Osuizugbo et al., 2024). However, low electricity costs, split incentives, lack of standard procedures, conservatism in the industry and lack of information have been identified by scholars as challenges to implementing low energy/ carbon initiatives in developed countries (Palm & Bryngelson, 2023).

During the early years from 2001 to 2012, there were no significant studies that have been conducted on low-energy/ carbon buildings. In that period, the lack of awareness of the stakeholders on environmental sustainability, knowledge barriers and lack of research are the most highlighted challenges between 2001 and 2012 (Williams & Dair, 2007). Lack of finance, regulatory constraints and challenges related to market structure and the supply chain are the most identified challenges during 2013-2015 (2013; Du et al., 2014; Zhang & Wang, 2013). Organizational constraints such as lack of coordination and alignment of strategic goals with sustainable goals, behavioural challenges, and higher expectations of the building occupants have highly identified constraints during 2015-2020 (Gupta et al., 2017; Masrom et al., 2017). However, informational barriers such as data security, unavailability of reliable information, technological barriers such as lack of cost-effective technologies and lack of compatibility of different building systems with new energy-efficient systems can be identified during 2021-2024 (Lassandro et al., 2024; Siddique et al., 2021).

5. Conclusion

In recent years, low-energy/ carbon buildings have gained considerable attention worldwide as a more effective solution to reduce energy consumption and carbon emissions. However, a systematic review on identifying constraints in delivering low-energy/carbon buildings is still lacking. Therefore, this paper aimed to review relevant journal publications from 2001 to 2024 and identify the constraints in delivering low-energy/ carbon buildings.

Primarily 220 papers published in journals were identified and after the screening process, 115 papers were selected for the review. Among them, 95 papers were from economically developed countries while only 20 papers were from developing countries highlighting the greater focus of developed countries to deliver low energy/carbon buildings to achieve sustainable development goals. After reviewing papers, 92 constraints were identified under 9 categories such as financial, market and supply constraints, policy and regulatory, knowledge, skills and awareness related, technical, information related, organizational, behavioural, geographical and environmental related constraints. In recent years more research has been conducted on advancement in

technology and innovation, system integration in low energy/ carbon buildings, net zero energy buildings and information management in energy management systems.

Policy and regulatory impact assessment and development of a context-specific strategical framework to overcome the identified issues are suggested as future research directions. Moreover, the provided list of constraints will be useful for relevant stakeholders such as policymakers, managers, government institutions and so on to implement strategies to overcome the constraints to promote low energy/ carbon buildings.

6. References

- Afshari, H., Issa, M. H., & Radwan, A. (2016). Using failure mode and effects analysis to evaluate barriers to the greening of existing buildings using the Leadership in Energy and Environmental Design rating system. *Journal of Cleaner Production*, 127, 195–203. <https://doi.org/10.1016/J.JCLEPRO.2016.03.140>
- Andrić, I., Koc, M., & Al-Ghamdi, S. G. (2019). A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries. *Journal of Cleaner Production*, 211, 83–102. <https://doi.org/10.1016/J.JCLEPRO.2018.11.128>
- Baek, C., & Park, S. (2012). Policy measures to overcome barriers to energy renovation of existing buildings. *Renewable and Sustainable Energy Reviews*, 16(6), 3939–3947. <https://doi.org/10.1016/J.RSER.2012.03.046>
- <https://doi.org/10.1080/15623599.2022.2110642>
- Chan, H. W. E., & Grace, L. K. L. (2006). *Design-led sustainable urban renewal approach for Hong Kong*. <https://hkapi.lib.cuhk.edu.hk/handle/ms08s77aBT/17933>
- Dino, I. G., & Meral Akgül, C. (2019). Impact of climate change on the existing residential building stock in Turkey: An analysis on energy use, greenhouse gas emissions and occupant comfort. *Renewable Energy*, 141, 828–846. <https://doi.org/10.1016/j.renene.2019.03.150>
- Du, P., Zheng, L. Q., Xie, B. C., & Mahalingam, A. (2014). Barriers to the adoption of energy-saving technologies in the building sector: A survey study of Jing-jin-tang, China. *Energy Policy*, 75, 206–216. <https://doi.org/10.1016/J.ENPOL.2014.09.025>
- Gajaba, P. A. P. Y., & Dissanayake, D. M. P. P. (2024). Barriers to implement energy efficiency strategies to heating, ventilation, air conditioning of airside system in commercial buildings in Sri Lanka. *International Journal of Construction Management*. <https://doi.org/10.1080/15623599.2024.2417627>
- Gupta, P., Anand, S., & Gupta, H. (2017). Developing a roadmap to overcome barriers to energy efficiency in buildings using best worst method. *Sustainable Cities and Society*, 31, 244–259. <https://doi.org/10.1016/J.SCS.2017.02.005>
- Hafez, F. S., Sa'di, B., Safa-Gamal, M., Taufiq-Yap, Y. H., Alrifay, M., Seyedmahmoudian, M., Stojcevski, A., Horan, B., & Mekhilef, S. (2023). Energy Efficiency in Sustainable Buildings: A Systematic Review with Taxonomy, Challenges, Motivations, Methodological Aspects, Recommendations, and Pathways for Future Research. *Energy Strategy Reviews*, 45. <https://doi.org/10.1016/J.ESR.2022.101013>
- Häkkinen, T., & Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research & Information*, 39(3), 239–255. <https://doi.org/10.1080/09613218.2011.561948>
- Hu, Y., Chan, A. P. C., Le, Y., & Jin, R. (2013). From Construction Megaproject Management to Complex Project Management: Bibliographic Analysis. *Journal of Management in Engineering*, 31(4), 04014052. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000254](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000254)
- Huang, N., Bai, L., Wang, H., Du, Q., Shao, L., & Li, J. (2018). Social Network Analysis of Factors Influencing Green Building Development in China. *International Journal of Environmental Research and Public Health* 2018, Vol. 15, Page 2684, 15(12), 2684. <https://doi.org/10.3390/IJERPH15122684>
- Isiadinso, C., Goodhew, S., Marsh, J., & Hoxley, M. (2011). Identifying an appropriate approach to judge low carbon buildings. *Structural Survey*, 29(5), 436–446. <https://doi.org/10.1108/02630801111182457>
- Kangas, H. L., Lazarevic, D., & Kivimaa, P. (2018). Technical skills, disinterest and non-functional regulation: Barriers to building energy efficiency in Finland viewed by energy service companies. *Energy Policy*, 114, 63–76. <https://doi.org/10.1016/J.ENPOL.2017.11.060>

- Khosla, R., Sagar, A., & Mathur, A. (2017). Deploying Low-carbon Technologies in Developing Countries: A view from India's buildings sector. *Environmental Policy and Governance*, 27(2), 149–162. <https://doi.org/10.1002/EET.1750>
- Lassandro, P., Devitofrancesco, A., Bellazzi, A., Cascardi, A., De Aloysio, G., Laghi, L., & Malvezzi, R. (2024). Facing the Constraints to the Deep Energy Renovation Process of Residential Built Stock in European Markets. *Sustainability (Switzerland)*, 16(1). <https://doi.org/10.3390/SU16010294>
- Li, Y., Li, S., Xia, S., Li, B., Zhang, X., Wang, B., Ye, T., & Zheng, W. (2023). A Review on the Policy, Technology and Evaluation Method of Low-Carbon Buildings and Communities. In *Energies* (Vol. 16, Issue 4). MDPI. <https://doi.org/10.3390/en16041773>
- Liu, F., Meyer, A. S., & Hogan, J. F. (2010). *Mainstreaming Building Energy Efficiency Codes in Developing Countries: Global Experiences and Lessons from Early Adopters*. <https://doi.org/10.1596/978-0-8213-8534-0>
- Madhusanka, N., Pan, W., & Kumaraswamy, M. (2020). Social Network Analysis of Building Energy and Carbon Policy Networks in Developing Countries. *IOP Conference Series: Earth and Environmental Science*, 588(2), 022004. <https://doi.org/10.1088/1755-1315/588/2/022004>
- Mapfumo, E. T., Emuze, F., Smallwood, J., & Ebekozi, A. (2024). Appraising challenges facing Zimbabwe's building retrofitting for energy efficiency using structural equation model approach. *International Journal of Building Pathology and Adaptation*, 42(7), 76–92. <https://doi.org/10.1108/IJBPA-05-2024-0105>
- Masrom, M. A. N., Rahim, M. H. I. A., Ann, S. C., Mohamed, S., & Goh, K. C. (2017). A Preliminary Exploration of the Barriers of Sustainable Refurbishment for Commercial Building Projects in Malaysia. *Procedia Engineering*, 180, 1363–1371. <https://doi.org/10.1016/J.PROENG.2017.04.299>
- McCarthy, M. P., Best, M. J., & Betts, R. A. (2010). Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, 37(9). <https://doi.org/10.1029/2010GL042845>
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., Gøtzsche, P. C., ... Tugwell, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine*, 151(4), 264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135/SUPPL_FILE/PRISMA_FIGURE-S1.DOC
- Ng, S. T., Skitmore, M., & Cheung, J. N. H. (2013). Organisational obstacles to reducing carbon emissions in Hong Kong. *Habitat International*, 40, 119–126. <https://doi.org/10.1016/J.HABITATINT.2013.03.004>
- Olanipekun, A. O., Xia, B. (Paul), Hon, C., & Hu, Y. (2017). Project Owners' Motivation for Delivering Green Building Projects. *Journal of Construction Engineering and Management*, 143(9). [https://doi.org/10.1061/\(asce\)co.1943-7862.0001363](https://doi.org/10.1061/(asce)co.1943-7862.0001363)
- Osmani, M., & O'Reilly, A. (2009). Feasibility of zero carbon homes in England by 2016: A house builder's perspective. *Building and Environment*, 44(9), 1917–1924. <https://doi.org/10.1016/J.BUILDENV.2009.01.005>
- Osuizugbo, I. C., Orekan, A. A., Omer, M. M., & Simon, R. F. (2024). An exploratory factor analysis on technological-related barriers to the construction of zero-energy buildings in Nigeria. *International Journal of Building Pathology and Adaptation*. <https://doi.org/10.1108/IJBPA-05-2024-0091>
- Palm, J., & Bryngelson, E. (2023). Energy efficiency at building sites: barriers and drivers. *Energy Efficiency*, 16(2). <https://doi.org/10.1007/S12053-023-10088-7>
- Pérez-Navarro, J., Bueso, M. C., & Vázquez, G. (2023). Drivers of and Barriers to Energy Renovation in Residential Buildings in Spain—The Challenge of Next Generation EU Funds for Existing Buildings. *Buildings*, 13(7). <https://doi.org/10.3390/BUILDINGS13071817>
- Pickering, C., & Byrne, J. (2014). The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. *Higher Education Research & Development*, 33(3), 534–548. <https://doi.org/10.1080/07294360.2013.841651>
- Rock, S., Hosseini, M. R., Nikmehr, B., Martek, I., Abrishami, S., & Durdyev, S. (2019). Barriers to “green operation” of commercial office buildings: Perspectives of Australian facilities managers. *Facilities*, 37(13–14), 1048–1065. <https://doi.org/10.1108/F-08-2018-0101/FULL/XML>
- Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, 39(3), 249–257. <https://doi.org/10.1016/J.ENBUILD.2006.07.001>

- Shen, W., Tang, W., Siripanan, A., Lei, Z., Duffield, C. F., & Peng Hui, F. K. (2018). Understanding the Green Technical Capabilities and Barriers to Green Buildings in Developing Countries: A Case Study of Thailand. *Sustainability* 2018, Vol. 10, Page 3585, 10(10), 3585. <https://doi.org/10.3390/SU10103585>
- Siddique, A. H., Tasnim, S., Shahriyar, F., Hasan, M., & Rashid, K. (2021). *Renewable Energy Sector in Bangladesh: The Current Scenario, Challenges and the Role of IoT in Building a Smart Distribution Grid*. <https://doi.org/10.3390/en14165083>
- Urge-Vorsatz, D., Petrichenko, K., Staniec, M., & Eom, J. (2013). Energy use in buildings in a long-term perspective. In *Current Opinion in Environmental Sustainability* (Vol. 5, Issue 2, pp. 141–151). <https://doi.org/10.1016/j.cosust.2013.05.004>
- Vogel, J. A., Lundqvist, P., & Arias, J. (2015). Categorizing Barriers to Energy Efficiency in Buildings. *Energy Procedia*, 75, 2839–2845. <https://doi.org/10.1016/J.EGYPRO.2015.07.568>
- Wang, T., Li, X., Liao, P. C., & Fang, D. (2016). Building energy efficiency for public hospitals and healthcare facilities in China: Barriers and drivers. *Energy*, 103, 588–597. <https://doi.org/10.1016/J.ENERGY.2016.03.039>
- Williams, K., & Dair, C. (2007). What is stopping sustainable building in England? Barriers experienced by stakeholders in delivering sustainable developments. *Sustainable Development*, 15(3), 135–147. <https://doi.org/10.1002/SD.308>
- Yeatts, D. E., Auden, D., Cooksey, C., & Chen, C. F. (2017). A systematic review of strategies for overcoming the barriers to energy-efficient technologies in buildings. *Energy Research & Social Science*, 32, 76–85. <https://doi.org/10.1016/J.ERSS.2017.03.010>
- Zhang, Y., & Wang, Y. (2013). Barriers' and policies' analysis of China's building energy efficiency. *Energy Policy*, 62, 768–773. <https://doi.org/10.1016/J.ENPOL.2013.06.128>
- Zou, P. X. W., & Couani, P. (2012). Managing risks in green building supply chain. *Architectural Engineering and Design Management*, 8(2), 143–158. <https://doi.org/10.1080/17452007.2012.659507>
- Zou, P. X. W., Xu, X., Sanjayan, J., & Wang, J. (2018). Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives. *Energy and Buildings*, 178, 165–181. <https://doi.org/10.1016/J.ENBUILD.2018.08.040>

USE OF THE INTERNET OF THINGS FOR WATER CONSUMPTION MONITORING IN APPAREL INDUSTRY

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Abstract Internet of Things (IoT) presents a promising solution for real-time monitoring and management. This study explores the key barriers to adopting IoT-based water consumption monitoring in Sri Lanka's apparel sector and proposes strategies to overcome them. A qualitative research approach was employed, involving semi-structured interviews with 11 industry professionals, including engineers, sustainability managers, and technical consultants. Findings reveal that high initial costs, lack of technical expertise, data security concerns, limited awareness, and integration complexities are major obstacles. Additional challenges include reliability issues, technological compatibility, and limited availability of high-quality IoT equipment, particularly in Sri Lanka. Despite these barriers, IoT has the potential to improve efficiency, reduce waste, and enhance sustainability in the apparel industry. Addressing these challenges requires strategic investments in training, financial incentives, government support, and enhanced cross-sector collaboration. These strategies can facilitate wider IoT adoption and drive sustainable transformation in Sri Lanka's apparel industry.

Keywords. Internet Of Things, Apparel Industry, Water Monitoring, Barriers, Strategies

1. Introduction

Water scarcity is a pressing global issue, with nearly 10 billion people expected to compete for limited freshwater resources by 2050 (Thiry, 2011). Although Earth contains approximately 1.4 billion km³ of water, only 0.01% is available for human and ecosystem use (UNEP, 2020). This scarcity significantly impacts industries that heavily rely on water, particularly the apparel sector, which ranks among the highest consumers of water due to its wet processing activities such as dyeing, washing, and finishing (Gupta et al., 2021). The situation is particularly concerning in Sri Lanka, where the apparel industry plays a vital role in the national economy but is also one of the largest contributors to freshwater depletion and wastewater production (De Fonseka T.S., 2023). Water shortages in the apparel industry are expected to increase due to rising domestic and agricultural water demands, leading to a projected 270.3% increase in apparel water demand compared to 2014, creating a water gap of 2.495 to 5.282 BCM (Billion Cubic Meters) per year (Haque et al., 2021). Despite its economic significance, Sri Lanka's apparel industry struggles with outdated water management practices, and while some factories have implemented process-based monitoring and wastewater treatment, real-time water consumption monitoring remains largely unexplored (De Fonseka, 2023). Current monitoring techniques, including process-based monitoring, life cycle assessment, and water accounting, provide insights into water consumption trends but lack real-time data analytics for proactive decision-making (Silva et al., 2015). Additionally, existing digital water monitoring systems are expensive, lack automation, and fail to provide immediate feedback (Swarnapali & Kumarage, 2020). Given these limitations, the core research problem addressed in this study is the absence of accessible, real-time, and data-driven water consumption monitoring systems in Sri Lanka's apparel industry. This gap hinders the industry's ability to detect inefficiencies promptly, respond to abnormal water usage, and implement timely conservation measures. Without the integration of intelligent technologies like the Internet of Things (IoT), water inefficiencies will persist undermining sustainability goals and placing further stress on national water resources. The integration of IoT-based water monitoring systems offers a potential solution by enabling real-time tracking, remote data storage, and automated alerts for parameter deviations (Liu et al., 2023; Wang et al., 2020). Without immediate intervention and technological advancements, the Sri Lankan apparel industry risks exacerbating water shortages and undermining long-term sustainability goals. Therefore, implementing cost-effective IoT-enabled monitoring systems can

enhance water efficiency, reduce environmental impact, and ensure the resilience of Sri Lanka's apparel industry amid growing water-related challenges. In this regard this paper aims to investigate the potential of Internet of Things (IoT) technologies for enhancing water consumption monitoring practices in Sri Lanka's apparel industry. The specific objectives are to identify the limitations of current water monitoring practices in the industry, and then to examine the key barriers to implementing IoT-based water monitoring systems and explore effective strategies to overcome these barriers and improve water efficiency and sustainability.

2. Literature Review

2.1. WATER CONSUMPTION IN APPAREL INDUSTRY

The apparel industry is notorious for its substantial water consumption throughout the textile manufacturing process, from fabric dyeing to finishing. Water is a critical resource in achieving the desired aesthetics, durability, and quality of textiles. Among the various stages, fabric dyeing is the most water-intensive, involving multiple dye baths and chemical treatments to ensure uniform colour absorption and fastness (Samanta et al., 2019). Beyond dyeing, other processes such as washing, finishing, and printing also require significant amounts of water to achieve specific fabric characteristics (Luo et al., 2021). The high water demand in textile processing contributes to environmental concerns, including water pollution, scarcity, and depletion (Yang et al., 2020). Wastewater discharge from textile factories often contains harmful chemicals and dyes, disrupting aquatic ecosystems and affecting water quality. The industry's excessive water consumption, coupled with inefficient management practices, threatens long-term sustainability (Asif, 2017).

To mitigate these challenges, water consumption monitoring has become essential for environmental, economic, and regulatory reasons (Chowdhury et al., 2022). Tracking water usage enables companies to optimize efficiency, reduce waste, and comply with environmental regulations (Ozek, 2017). Effective monitoring enhances brand reputation, regulatory compliance, and cost savings, particularly in an industry with narrow profit margins (Hossain & Khan, 2020). Apparel brands are also expected to ensure responsible water use throughout their supply chains, holding suppliers accountable for sustainable practices (Clifford et al., 2018).

2.2. CURRENT STATUS OF WATER CONSUMPTION MONITORING TECHNIQUES IN APPAREL INDUSTRY IN SRI LANKA

Sri Lanka's apparel industry is actively improving water consumption monitoring and management, aligning with global sustainability standards and buyer expectations (Muthukumarana et al., 2018). Advanced water management systems, including water meters, sensors, data analytics, and software platforms, are being implemented to track usage and detect inefficiencies (Thiry, 2014). Leading manufacturers such as MAS, Brandix, and Hirdaramani have committed to significant reductions in water consumption, with goals like zero water wastage and a 65% reduction in water intensity by 2025 (Mohanaraj et al., 2023).

Despite progress, integrating IoT solutions and digital monitoring technologies remains a challenge but offers opportunities for enhanced water management in the industry. Current water consumption monitoring practices in Sri Lanka's apparel industry are described in table 2.2.

Table 1: Water consumption monitoring practices and techniques in Sri Lankan Apparel Industry

Water monitoring Practices and techniques.	Description
Water audits	The absence of existing standards for water audits is notable. These assessments determine the amount of water generated by a system and the way it is utilized. (Silva et al., 2015)
Metering	Apparel's water consumption was addressed by utilizing water metering data to identify and correct water leaks. (Silva et al., 2015)
Retrofitting and replacing inefficient fixtures	Optimizing water flow rate by installing water-efficient fixtures, such as dual-flush toilets. (De Fonseka, 2023)
Water saving taps and faucet aerators	To enhance water conservation in the washroom and canteen areas, consider installing flow rate reduction aerators on the taps. (De Fonseka, 2023)
Installing sensor and peddle taps	This prevents wastage and flooding, where the taps may be left running. It relies on infrared sensors to trigger the water flow. (De Fonseka, 2023)

2.3. CHALLENGES ASSOCIATE WITH EXISTING PRACTICES

The apparel industry in Sri Lanka has made worthy progress in adopting water consumption monitoring practices and technologies. However, several issues and challenges continue, delaying the industry's path toward more efficient and sustainable water management. (Hildebrandt et al. 2021) found that it faces challenges due to water scarcity and environmental impact, including over-extraction, ecosystem degradation, and competition with local communities. This has increased the industry's responsibility to monitor and reduce its water footprint, as water resources are limited in certain regions.

Weerasiri, (2012) have examined Sri Lankan apparel manufacturers have implemented water monitoring systems, but their coverage and comprehensiveness vary. Some focus on specific processes, while others monitor water flow from intake to discharge, limiting the industry's ability to identify inefficiencies and areas for improvement. According to the study of Rupasinghe and Liyanaarachchi, (2017) discussed that encounters difficulties in managing and analyzing the vast amount of data generated by water consumption monitoring systems, including issues with storage, processing, and interpretation, which can delay informed decisions for optimizing water usage.

Munasinghe et al. (2016) have tested that implementing water monitoring systems can be costly, especially for smaller and medium-sized apparel manufacturers. Despite the long-term benefits, some companies struggle to allocate funds, making finding cost-effective solutions for accurate monitoring a challenge. According to the words of Perry et al. (2015) found that the Sri Lankan apparel industry must adhere to evolving national and international regulations regarding water

use and discharge, which are not only legal obligations but also environmental responsibility, making compliance complex and demanding for companies.

Hemchandra, (2014) revealed that organizations often face resistance to adopting new water consumption monitoring practices due to hesitancy from traditional employees. Overcoming this resistance requires employee training and change management efforts to foster a data-driven water management culture (Mohanaraj et al., 2023). Proper upkeep and calibration of sensors and equipment are crucial for the reliability and accuracy of monitoring systems, and apparel manufacturers must allocate resources for regular maintenance to ensure data quality (Khattak et al., 2015). The apparel industry faces challenges in monitoring water consumption due to the lack of standardized methods, making it difficult to benchmark and compare practices across facilities or companies (Mueller et al., 2015). This is due to the industry's complexity and the need for consistent practices across partners with varying technological capabilities.

Bailey et al. (2022) stated that the raising awareness about water consumption monitoring and its sustainability is a challenge, requiring a multi-faceted approach including technology investment, regulatory compliance, employee training, and industry-wide commitment. As per the statement of Munasinghe et al., (2021) described that the apparel industry in Sri Lanka evolves, these challenges present opportunities for growth, innovation, and enhanced environmental responsibility, highlighting the need for sustainable water management.

2.4. IOT IN MANAGING WATER CONSUMPTION MONITORING EFFECTIVELY

The Internet of Things (IoT) is a transformative concept that involves connecting physical objects implanted with sensors and software to exchange data with other devices and systems over the internet (Bhat et al., 2007). It has the potential to reform various aspects of our lives, including urban governance, healthcare, and manufacturing (Zhanlin et al., 2014). IoT is still in its early stages, but it has already found applications in healthcare, transportation, and automotive industries, with the potential for even more innovative applications as technology continues to mature (Institute of Electrical and Electronics Engineers, n.d). As technology matures, the scope for innovative IoT applications continues to grow especially in resource-intensive industries like textiles.

In the context of the apparel industry, water is a critical input used extensively in dyeing, washing, and finishing processes. However, traditional water management practices often lack transparency, accuracy, and real-time control, which results in excessive consumption, undetected leakages, and increased wastewater generation. Implementing IoT technologies in water monitoring can address these challenges by providing real-time data, enabling predictive maintenance, and optimizing water use throughout production stages. The following table 2 summarizes the key drivers for adopting IoT in water consumption monitoring within the apparel industry:

Table 2: Drivers of using IoT for water management monitoring in apparel industry

Drivers	References
Real-time data insights for monitoring water usage, detecting inefficiencies, and reducing waste	Abbate et al. (2023)
Accurate water consumption measurements at different textile production stages for better accountability	Hader et al. (2022)
Proactive leak detection to prevent waste and operational disruptions	Neri et al. (2023)
Water quality monitoring to ensure product quality and regulatory compliance	Liu et al. (2023)

Optimization of water usage, reduction of pollution risks, and conservation of local resources for sustainability	Chowdhury et al. (2022)
Cost savings by reducing operational expenses and optimizing resource use	Morales et al. (2023)
Alignment with sustainability goals, enhancing brand reputation and attracting eco-conscious consumers	Wang et al. (2020)
Demonstrating responsible water management as a moral and corporate responsibility	Tsai (2018)

2.5. BARRIERS OF USING IOT FOR WATER CONSUMPTION MONITORING IN APPAREL INDUSTRY

Barriers to implantation are presented in Table 03 These details elaborate according to the countries that already use IoT for water consumption monitoring, since it will help evaluate barriers regarding the Sri Lankan apparel industry context

Table 3: Barriers of using IoT for water management monitoring in the apparel industry

Barriers	References
High initial investment costs for sensors, infrastructure, and data analytics tools	Hynes et al. (2020)
Sensor reliability and maintenance challenges due to harsh textile production conditions	Wang et al. (2020)
Data privacy and security concerns requiring encryption and protection against cyber threats	Neri et al. (2023)
Need for skilled analysts to interpret IoT data effectively for actionable insights	Liu et al. (2023)
Integration challenges with existing operational and IT systems to avoid disruptions and data silos	Chowdhury et al. (2022)
Scalability and adaptability issues to meet different facility requirements while managing costs	Turner et al. (2022)
Dependence on reliable power supply and network connectivity for continuous data transmission	Achar (2020)
Resistance from traditional employees, requiring training and change management initiatives	Kant (2012)
Compliance with regulatory requirements and environmental reporting standards	Alves et al. (2022); Akram et al. (2022)
Need for a strategic approach to maximize cost savings and sustainability benefits	Rathore (2022)

3. Methodology

This study adopts a qualitative approach, Qualitative research involves gathering and assessing non-numerical data to gain an in-depth understanding of concepts, opinions, and experiences (Teherani et al., 2015). As Drury et al. (2011) described qualitative approach can greatly improve the comprehension of the research context, enabling the development of appropriate sampling frames and relevant research questions and leading to more precise data analysis and

interpretation. A semi-structured interview was adopted as the data collection method for implementing this research. Semi-structured interviews were carried out to validate the information gathered in the literature chapter and to check the progress of the research in the track. In addition, it was pointed out some solutions for the problems related to the implementation of smart features which are not identified in the literature. Purposive sampling was used to recruit participants who had substantial professional experience and subject matter expertise in areas relevant to the study. Experts were selected based on their roles in IoT systems, automation, information technology, engineering, or environmental sustainability within the apparel manufacturing sector in Sri Lanka. All the experts were chosen based on their expertise and experience. Semi-structured interviews with 11 participants were conducted which is considered sufficient in qualitative research to achieve data saturation where no new themes emerge from additional interviews to fulfil the objective of the expert interviews (Guest et al., 2006). Participants had between 5 and over 10 years of industry experience, ensuring reliable data. An interview guideline was created based on the findings of the literature review. The data from the expert interviews was manually analysed using code-based content analysis method. Six areas were covered in the expert interviews: the interviewee's background information; an overview of the Internet of Things in the apparel industry; the attributes and driving forces behind the IoT; potential benefits (positive enablers); barriers and limitations; strategies for overcoming those barriers and limitations. Table 04 provides a summary of the participants' professional backgrounds, outlining their designations and relevant areas of expertise to highlight the diversity and relevance of the selected interviewees.

Table 4: Summary of interview respondents

Expert ID	Designation	Area of Expertise	Years of Expertise
E1	Machine Learning Engineer	IoT, Machine Learning, Smart Systems	10+
E2	Chief Technology Officer	Technology Strategy, Apparel Manufacturing	8+
E3	Head of Automation	Industrial Automation, Process Optimization	10+
E4	Head of Engineering	Engineering Management, Apparel Sector	10+
E5	IT Support Engineer	IT Infrastructure, Systems Support	5+
E6	Technical Consultant	Automation, Industrial IT	8+
E7	Deputy General Manager – Compliance & Sustainability	Environmental Sustainability, Compliance	5+
E8	IT Executive	Information Systems, IT Support	5+
E9	IT Executive	IT Operations, Network Systems	8+
E10	Group Manager – ICT	Enterprise ICT, Digital Transformation	10+
E11	Textile Engineer	Textile Engineering, R&D, Smart Fabrics	10+

4. Findings

4.1. THE BARRIERS FACED BY APPERAL COMPANIES IN ADOPTING IOT FOR WATER CONSUMPTION MONITORING IN SRI LANKA

Table 5 was engaged in investigate the barriers to adopt Internet of Things in the apparel industry in Sri Lanka. It was investigated through a semi structured interview with someone who has expertise in both the Internet of Things and apparel industry.

Table 5: Barriers faced by apparel companies in adopting IoT.

Barriers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
High initial investment costs for sensors, infrastructure, and data analytics tools	✓	•✓	✓	•✓	✓	✓•	✓	✓	✓	✓•	✓
Sensor reliability and maintenance challenges due to harsh textile production conditions	✓	•✓	✓	•	•		•	•		•	•
Data privacy and security concerns requiring encryption and protection against cyber threats			✓		✓		✓	✓		✓	✓
Need for skilled analysts to interpret IoT data effectively for actionable insights	✓	✓	✓	•✓		✓	✓•		•✓	✓	•
Integration challenges with existing operational and IT systems to avoid disruptions and data silos	✓	•		•✓		✓	✓	✓			•
Scalability and adaptability issues to meet different facility requirements while managing costs	✓			✓	•			✓			•
Dependence on reliable power supply and network connectivity for continuous data transmission	✓	•			✓		•	•			
Resistance from traditional employees, requiring training and change management initiatives			•	•	•	✓•	✓	•	•	✓•	✓•
Compliance with regulatory requirements and environmental reporting standards	✓					•✓	✓		✓		
Need for a strategic approach to maximize cost savings and sustainability benefits			•		✓	•✓	•	✓		•	•
Low quality and unavailability of IoT devices and technologies in the local market	✓		✓								
Evolving technology and rapidly changing standards	✓	✓									

Both the literature and expert interviews identified high initial investment costs as a major barrier. Hynes et al. (2020) highlight the substantial upfront costs of implementing IoT systems, particularly for small and medium-sized enterprises. This is supported by the all the experts that

the capital required for infrastructure, sensors, and data analytics tools remains a significant challenge, especially for resource-constrained companies. The reliability of sensors in harsh textile environments is another barrier discussed in the literature by Wang et al. (2020), with sensors prone to failure due to exposure to chemicals and high-stress conditions. Experts (E1, E2, E3) confirmed this challenge, pointing out that maintaining sensor performance under these harsh conditions is a persistent issue for the apparel industry, highlighting the need for more durable and specialized IoT devices. Data privacy and security are critical barriers identified by Neri et al. (2023), emphasizing the need for strong encryption and protection against cyber threats. Experts E3, E5, E7, E8, E10 and E11 echoed this concern, underscoring the need for secure data management practices, particularly when handling large volumes of sensitive data. This barrier aligns with the literature, which stresses that security is a primary concern for IoT adoption across industries.

Liu et al. (2023) point out the lack of skilled personnel to interpret IoT data effectively. This was further highlighted by the most experts (E1, E2, E3, E4, E6, E7, E9, E10) that the shortage of trained professionals capable of managing and analysing IoT data is a significant impediment to IoT adoption. This gap in expertise aligns with the literature's call for specialized knowledge to support IoT systems. Chowdhury et al. (2022) discuss integration challenges with existing IT systems as a major barrier. Experts E1, E4, E6, E7 and E8 agreed, noting that integrating IoT systems with legacy systems can cause disruptions and requires careful planning. This finding reinforces the literature's concern that seamless integration with existing infrastructure is crucial to prevent operational disruptions and data silos. Technological compatibility emerged as a significant concern, as highlighted by experts E1, E4 and E8 that ensuring IoT systems work well with existing technologies like Wi-Fi, GSM, and GPS is vital for effective implementation. While scalability and adaptability were not directly mentioned in the expert interviews, these concerns are closely related to compatibility issues, as IoT systems must be flexible enough to meet the varying needs of different facilities, a point addressed by Turner et al. (2022). Resistance to adopting new technologies, as noted by Kant (2012), was identified by experts E6, E7, E10 and E11 as a significant barrier in the apparel industry. Experts pointed out that employees' reluctance to embrace change requires comprehensive training and change management initiatives to overcome. This aligns with the literature's suggestion that cultural and organizational factors play a critical role in the successful implementation of IoT systems. Experts E1, E6, E7 and E9 also noted limited awareness of the benefits of IoT, particularly regarding its role in water management and sustainability. This aligns with Alves et al. (2022), who stressed the importance of increasing awareness about IoT's regulatory advantages. Additionally, experts identified regulatory compliance as a challenge, particularly regarding environmental standards, which remains a key barrier in the Sri Lankan context. Apart from the barriers identified in the literatures some experts mentioned the barriers that relevant to Sri Lankan apparel industry such as the low quality and unavailability of IoT devices in the local market, identified by experts E1 and E3. They pointed out that local products are often of low quality or unavailable, forcing companies to rely on costly imports. This limitation highlights a gap in the literature and emphasizes the need for local IoT suppliers to meet the demand for reliable devices. Finally, evolving technology was mentioned by experts E1 and E2, noting the challenge of keeping up with rapidly changing IoT standards and innovations. This concern reflects the literature's acknowledgement that the fast pace of technological advancements can create uncertainty for businesses, making it difficult to ensure the long-term viability of IoT investments.

4.2. STRATEGIES TO OVERCOME IDENTIFIED BARRIERS IN IOT ENABLED WATER CONSUMPTION MONITORING SYSTEM IN APPAREL INDUSTRY IN SRI LANKA

Table 6 presents the strategies suggested by experts to overcome the identified barriers through literature review and the expert interviews

Table 6: Expert Responses on Strategies to Overcome the barriers.

Strategies to Overcome Barriers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Bulk purchase & maintenance	✓	▪	▪	▪	▪	▪				▪	▪
Scalability & futureproofing	✓	▪	▪	▪	▪		▪	▪	✓	▪	▪
Raising adaptation.	✓	▪	▪	▪	▪	▪	▪	▪	✓	▪	▪
Develop a data governance strategy	✓	✓	▪	▪	✓		✓	✓	▪	✓	✓
Proper documentation and installation	✓			▪	▪	▪		✓			▪
Training and improvement	✓	✓	▪	✓	✓		✓	✓	✓	✓	✓
Financial support	▪	✓	▪	▪	▪	▪	✓	▪	▪	✓	✓
Government must offer incentives & subsidies.		✓	✓	✓	✓	▪	✓	✓	✓	▪	✓
Market availability			✓	▪	✓	▪	▪	▪	▪	▪	▪
Continuous knowledge enhancement		✓		✓	✓			✓			
Consulting services to organizations.		✓		▪	✓	▪	✓	▪	✓	▪	✓
Standardization, Collaboration & User adoption		✓		✓	▪	✓	✓	✓		✓	✓
Government-led IoT water management.						✓				✓	✓
Conduct a pilot project										✓	

Experts proposed various strategies to overcome barriers and successfully adopt IoT-enabled water consumption monitoring systems in the apparel industry. To address high initial costs, they suggested progressive investment options, including government incentives and subsidies. E2 emphasized that government initiatives providing tax breaks, grants, and subsidies can reduce financial burdens, making IoT adoption more feasible. E3 recommended reducing or removing import taxes on IoT technology to promote local production, while E4 stressed the importance of creating a supportive regulatory environment. Financial support through leasing programs, as suggested by E2, and exploring financing options or initiating small-scale projects to demonstrate ROI, as noted by E11, were also highlighted. Bulk purchasing was identified as another way to reduce costs, as buying in larger quantities significantly lowers per-unit expenses, making IoT investment more manageable for companies. Lack of technical expertise and training gaps were identified as major barriers, with experts advocating for training and workforce improvement programs. E1 pointed out that many employees lack knowledge about IoT, making training essential. E4 suggested developing user-friendly dashboards and reports to simplify data interpretation, while E10 emphasized that in-house training programs can help build expertise necessary for implementing and maintaining IoT systems. Additionally, E7

highlighted that organizing training sessions and engaging employees in the adoption process can help reduce resistance to change.

Addressing data security and privacy concerns, experts recommended developing a strong data governance strategy. E10 suggested implementing policies and procedures for data collection, storage, and sharing to ensure secure and responsible management. E2 stressed the importance of understanding how data is stored and secured, advocating for reputable tech providers with proven cybersecurity measures. Industry-standard security protocols, data encryption, and staff education on data protection were seen as crucial components of a secure IoT system. E8 reinforced this view by advocating for strict cybersecurity safeguards and encryption standards, while E11 highlighted the need for strong security measures, including secure access controls and compliance with data privacy laws. A robust cybersecurity system also improves reliability, as noted by E1, who stated that better security ensures more reliable IoT performance. The complexity of implementation and technological compatibility issues were addressed through strategies like proper documentation, standardization, and collaboration. E1 emphasized that having detailed implementation documentation and proper installation practices, such as securing wiring and correctly positioning sensors, can facilitate a smoother setup process. E8 supported this by stressing the need for technical assistance and collaboration with tech companies to improve interoperability. Many experts, including E7 and E8, proposed industry-wide standardization initiatives and collaborations to tackle interoperability challenges. E4 suggested developing standardized plug-and-play systems to simplify IoT integration, while E6, E10, and E11 believed that apparel companies should participate in industry groups promoting IoT adoption and develop user-friendly monitoring solutions. Consulting services were also recommended, with E2 suggesting that technology providers offer on-site or remote consulting to assist organizations in implementation. E5, E7, and E9 noted that industry associations could promote IoT adoption through workshops, best practices, and research-driven initiatives to reduce complexity.

The low quality and unavailability of IoT solutions were addressed by ensuring market availability and competitive pricing. E3 emphasized the importance of bringing high-quality IoT products to the market at reasonable prices, while E5 highlighted the need for tailored IoT packages, training programs, and continuous support from technology providers. Similarly, the challenge of limited awareness was countered with continuous knowledge enhancement. E2 proposed that industry associations and technology providers develop educational materials, webinars, and workshops to raise awareness about IoT-based water efficiency. E4 stressed the importance of showcasing real-world case studies to demonstrate cost savings and environmental benefits, while E5 and E8 supported the idea of organizing industry events, training programs, and awareness campaigns to promote innovation and adoption. To mitigate the challenges posed by evolving technology, experts recommended scalability and future-proofing strategies. E1 and E9 emphasized the need for a well-planned approach that minimizes device waste, ensures proper maintenance, and facilitates phased implementation. Starting with small-scale projects and gradually scaling up was seen as a practical way to ensure long-term success. Resistance to change was another critical issue, with experts emphasizing the importance of communication and adaptation. E9 noted that effective communication is key to convincing stakeholders about the benefits of IoT, demonstrating how it simplifies operations and improves efficiency.

Government led IoT water management was another proposed strategy. E6 suggested that government institutions take the lead in IoT adoption for water monitoring, creating centralized initiatives that pool resources and knowledge to support widespread implementation. E10 and E11 emphasized that companies require clear government guidelines and regulatory support to confidently invest in IoT solutions. Clear regulations would also ensure data security and promote water conservation efforts. Additionally, conducting pilot projects was recommended as a risk

mitigation strategy. E10 suggested that before implementing large-scale IoT solutions, companies should test pilot projects to identify potential issues, measure benefits, and refine implementation strategies. Overall, experts provided a comprehensive set of strategies addressing financial, technical, security, and awareness related barriers to IoT adoption in water consumption monitoring. By leveraging government support, improving workforce training, ensuring cybersecurity, simplifying implementation, enhancing market availability, promoting awareness, and planning for future scalability, apparel companies can successfully integrate IoT solutions for more efficient water management.

5. Conclusion

The adoption of the Internet of Things (IoT) for water consumption monitoring in Sri Lanka's apparel industry presents both promising opportunities and substantial challenges. This study has revealed that despite the transformative potential of IoT to enhance operational efficiency, minimize water waste, and promote environmental sustainability, several critical barriers impede its widespread adoption. These include high initial capital costs, limited technical expertise, data security concerns, lack of awareness, and complexities in system integration. Technological issues such as equipment reliability and compatibility, as well as the availability of quality IoT devices, further constrain implementation. The high upfront investment in IoT infrastructure remains the most significant hurdle, compounded by a shortage of trained personnel and insufficient capacity to interpret and utilize IoT-generated data effectively.

Importantly, the implications of this research are multi-dimensional. At the industry level, it underscores the urgent need for digital transformation in water management to meet both economic and environmental sustainability goals. At the policy level, the findings suggest a call for targeted interventions, including financial incentives, regulatory frameworks for data protection, and structured capacity-building programs. For technology providers, the study highlights opportunities to develop cost-effective, scalable, and user-friendly IoT solutions tailored to the needs of emerging economies like Sri Lanka. However, this study has several limitations. It primarily focuses on the current state and stakeholder perceptions within a limited sample of apparel manufacturing firms. The research did not include longitudinal data or pilot implementations of IoT systems, which could provide more detailed insights into real-time operational impacts. Additionally, economic analysis of return on investment (ROI) for IoT systems was beyond the scope of this study, though it remains a critical factor for adoption decisions.

In conclusion, while challenges persist, this research provides a foundational understanding of the enablers and barriers to IoT adoption in the Sri Lankan apparel industry. By addressing these issues through strategic collaboration among policymakers, industry leaders, and technology developers, the sector can unlock the full potential of IoT for improved water management, operational efficiency, and sustainability. Future research should explore empirical case studies, long-term cost-benefit analyses, and integrated implementation frameworks to further guide effective adoption and scale-up across the industry.

6. References

- Abbate, S., Centobelli, P., & Cerchione, R. (2023). From Fast to Slow: An Exploratory Analysis of Circular Business Models in the Italian Apparel Industry. *International Journal of Production Economics*, 260, 108824. <https://doi.org/10.1016/j.ijpe.2023.108824>
- Achar, S. (2020). Influence of IoT Technology on Environmental Monitoring. *Asia Pacific Journal of Energy and Environment*, 7(2), 87–92. <https://doi.org/10.18034/apjee.v7i2.649>
- Akram, S. V., Malik, P. K., Singh, R., Gehlot, A., Juyal, A., Ghafoor, K. Z., & Shrestha, S. (2022). Implementation of Digitalized Technologies for Fashion Industry 4.0: Opportunities and Challenges. *Scientific Programming*, 2022, 1–17. <https://doi.org/10.1155/2022/7523246>

- Alves, L., Ferreira Cruz, E., Lopes, S. I., Faria, P. M., & Rosado da Cruz, A. M. (2022). Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 40(1), 3–23. <https://doi.org/10.1177/0734242X211052858>
- Bailey, K., Basu, A., & Sharma, S. (2022). The Environmental Impacts of Fast Fashion on Water Quality: A Systematic Review. *Water*, 14(7), 1073. <https://doi.org/10.3390/w14071073>
- Bhat, O., Gokhale, P., & Bhat, S. (2007). Introduction to IOT. *International Advanced Research Journal in Science, Engineering and Technology ISO*, 3297(1). <https://doi.org/10.17148/IARJSET.2018.517>
- Caballero-Morales, S.-O., Cuautle-Gutiérrez, L., Cordero-Guridi, J.-J., & Alvarez-Tamayo, R.-I. (2023). Six-Sigma Reference Model for Industry 4.0 Implementations in Textile SMEs. *Sustainability*, 15(16), 12589. <https://doi.org/10.3390/su151612589>
- Clifford, E., Mulligan, S., Comer, J., & Hannon, L. (2018b). Flow-Signature Analysis of Water Consumption in Nonresidential Building Water Networks Using High-Resolution and Medium-Resolution Smart Meter Data: Two Case Studies. *Water Resources Research*, 54(1), 88–106. <https://doi.org/10.1002/2017WR020639>
- Chowdhury, N. R., Chowdhury, P., & Paul, S. K. (2022). Sustainable practices and their antecedents in the apparel industry: A review. *Current Opinion in Green and Sustainable Chemistry*, 37, 100674. <https://doi.org/10.1016/j.cogsc.2022.100674>
- Das Gupta, A., Sadek, Z., Bhuiyan, M. H. R., Kibria, M. G., Toha, T. R., & Alam, S. M. M. (2021). A Low-Cost IoT Based Automatic Water Quality Monitoring System for Textile Industry. *ACM International Conference Proceeding Series*, 67–76. <https://doi.org/10.1145/3491371.3491375>
- D. Rupasinghe, T., & Liyanaarachchi, N. (2017). AN ANALYTICAL MODELLING APPROACH TO ASSESS THE APPLICABILITY OF GREEN CHAIN OPERATIONS: A CASE STUDY FROM THE SRI LANKAN APPAREL INDUSTRY. 1–16. <https://doi.org/10.17501/wcosm.2017.2101>
- De Fonseka, T. S. (2023). Determination of environmental sustainability practices in the apparel sector of Sri Lanka. *European Journal of Sustainable Development Research*, 7(4), em0237. <https://doi.org/10.29333/ejosdr/13816>
- Drury, R., Homewood, K., & Randall, S. (2011). Less is more: the potential of qualitative approaches in conservation research. *Animal Conservation*, 14(1), 18–24. <https://doi.org/10.1111/j.1469-1795.2010.00375.x>
- 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://doi.org/10.1177/1525822X05279903>
- Hader, M., Tchoffa, D., Mhamedi, A. El, Ghodous, P., Dolgui, A., & Abouabdellah, A. (2022). Applying integrated Blockchain and Big Data technologies to improve supply chain traceability and information sharing in the textile sector. *Journal of Industrial Information Integration*, 28, 100345. <https://doi.org/10.1016/j.jii.2022.100345>
- Haque, M. S., Nahar, N., & Sayem, S. M. (2021). Industrial water management and sustainability: Development of SIWP tool for textile industries of Bangladesh. *Water Resources and Industry*, 25. <https://doi.org/10.1016/j.wri.2021.100145>
- Hemchandra D W K. (2014). *FACTORS AFFECTING THE ADOPTION DECISION OF VOLUNTARY ENVIRONMENTAL MANAGEMENT SYSTEMS IN THE APPAREL INDUSTRY IN SRI LANKA*.
- Hildebrandt, J., Thrän, D., & Bezama, A. (2021). The circularity of potential bio-textile production routes: Comparing life cycle impacts of bio-based materials used within the manufacturing of selected leather substitutes. *Journal of Cleaner Production*, 287, 125470. <https://doi.org/10.1016/j.jclepro.2020.125470>
- Hossain, L., & Khan, M. S. (2020). Water Footprint Management for Sustainable Growth in the Bangladesh Apparel Sector. *Water*, 12(10), 2760. <https://doi.org/10.3390/w12102760>
- Hynes, N. R. J., Kumar, J. S., Kamyab, H., Sujana, J. A. J., Al-Khashman, O. A., Kuslu, Y., Ene, A., & Suresh Kumar, B. (2020). Modern enabling techniques and adsorbents based dye removal with sustainability concerns in textile industrial sector -A comprehensive review. *Journal of Cleaner Production*, 272, 122636. <https://doi.org/10.1016/j.jclepro.2020.122636>
- Institute of Electrical and Electronics Engineers. (2011). *2011 International Conference on Multimedia Technology : proceedings : (ICMT 2011) July 26-28, 2011, Hangzhou, China*. IEEE.

- Khattak, A., Stringer, C., Benson-Rea, M., & Haworth, N. (2015). Environmental upgrading of apparel firms in global value chains: Evidence from Sri Lanka. *Competition & Change*, 19(4), 317–335. <https://doi.org/10.1177/1024529415581972>
- K. M. Ayatullah Hosne Asif, A. (2017a). An Overview of Sustainability on Apparel Manufacturing Industry in Bangladesh. *Science Journal of Energy Engineering*, 5(1), 1. <https://doi.org/10.11648/j.sjee.20170501.11>
- Liu, X., Yang, Y., Jiang, Y., Fu, Y., Zhong, R. Y., Li, M., & Huang, G. Q. (2023). Data-driven ESG assessment for blockchain services: A comparative study in textiles and apparel industry. *Resources, Conservation and Recycling*, 190, 106837. <https://doi.org/10.1016/j.resconrec.2022.106837>
- Luo, Y., Song, K., Ding, X., & Wu, X. (2021). Environmental sustainability of textiles and apparel: A review of evaluation methods. *Environmental Impact Assessment Review*, 86, 106497. <https://doi.org/10.1016/j.eiar.2020.106497>
- Mohanaraj, R., Dissanayake, H., Iddagoda, A., & Mendis, O. (2023). Development of Sustainability Balanced Scorecard: A Case Study from Apparel Industry Sri Lanka. *HOLISTICA – Journal of Business and Public Administration*, 14(1), 22–38. <https://doi.org/10.2478/hjbpa-2023-0003>
- Mueller, S. A., Carlile, A., Bras, B., Niemann, T. A., Rokosz, S. M., McKenzie, H. L., Chul Kim, H., & Wallington, T. J. (2015). Requirements for water assessment tools: An automotive industry perspective. *Water Resources and Industry*, 9, 30–44. <https://doi.org/10.1016/j.wri.2014.12.001>
- Munasinghe, M., Jayasinghe, P., Ralapanawe, V., & Gajanayake, A. (2016). Supply/value chain analysis of carbon and energy footprint of garment manufacturing in Sri Lanka. *Sustainable Production and Consumption*, 5, 51–64. <https://doi.org/10.1016/j.spc.2015.12.001>
- Munasinghe, P., Druckman, A., & Dissanayake, D. G. K. (2021). A systematic review of the life cycle inventory of clothing. *Journal of Cleaner Production*, 320, 128852. <https://doi.org/10.1016/j.jclepro.2021.128852>
- Muthukumarana, T. T., Karunathilake, H. P., Punchihewa, H. K. G., Manthilake, M. M. I. D., & Hewage, K. N. (2018). Life cycle environmental impacts of the apparel industry in Sri Lanka: Analysis of the energy sources. *Journal of Cleaner Production*, 172, 1346–1357. <https://doi.org/10.1016/j.jclepro.2017.10.261>
- Neri, A., Negri, M., Cagno, E., Franzò, S., Kumar, V., Lampertico, T., & Bassani, C. A. (2023). The role of digital technologies in supporting the implementation of circular economy practices by industrial small and medium enterprises. *Business Strategy and the Environment*, 32(7), 4693–4718. <https://doi.org/10.1002/bse.3388>
- Ozek, H. Z. (2017). Sustainability: Increasing Impact on Textile and Apparel Industry. *Journal of Textile Engineering & Fashion Technology*, 2(5). <https://doi.org/10.15406/jteft.2017.02.00076>
- Perry, P., Wood, S., & Fernie, J. (2015). Corporate Social Responsibility in Garment Sourcing Networks: Factory Management Perspectives on Ethical Trade in Sri Lanka. *Journal of Business Ethics*, 130(3), 737–752. <https://doi.org/10.1007/s10551-014-2252-2>
- Rathore, Dr. B. (2022). Textile Industry 4.0 Transformation for Sustainable Development: Prediction in Manufacturing & Proposed Hybrid Sustainable Practices. *Eduzone: International Peer Reviewed/Refereed Academic Multidisciplinary Journal*, 11(01), 223–241. <https://doi.org/10.56614/eiprmj.v11i1.229>
- Rita Kant. (2012). Textile dyeing industry an environmental hazard. *Natural Science*, 4(1).
- Samanta, K. K., Pandit, P., Samanta, P., & Basak, S. (2019). Water consumption in textile processing and sustainable approaches for its conservation. In *Water in Textiles and Fashion* (pp. 41–59). Elsevier. <https://doi.org/10.1016/B978-0-08-102633-5.00003-8>
- Silva, S. N., Waidyasekara, K. G. A. S., & Dissanayake, D. M. P. P. (2015a). *COMPARATIVE STUDY OF WATER EFFICIENCY IN GREEN AND NON-GREEN BUILDINGS IN APPAREL INDUSTRY IN SRI LANKA*
- Sudeepa N. Silva, K.G.A.S.Waidyasekara, & D.M.P.P. Dissanayake. (2015). *COMPARATIVESTUDYOFWATEREFFICIENCYINGREENAND GREENBUILDINGSINAPPARELINDUSTRYINSRILANKA*.
- Swarnapali, S., & Kumarage, P. (2020, December 30). Real-Time Synchronized Monitoring of Water Consumption and Leak Detection in the Urban Water Supply of Sri Lanka. *Proceedings of IEEE International Conference on Advent Trends in Multidisciplinary Research and Innovation, ICATMRI 2020*. <https://doi.org/10.1109/ICATMRI51801.2020.9398325>

- 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>
- Tsai, W.-H. (2018). Green Production Planning and Control for the Textile Industry by Using Mathematical Programming and Industry 4.0 Techniques. *Energies*, 11(8), 2072. <https://doi.org/10.3390/en11082072>
- Thiry, M. C. (2011). Staying alive: Making textiles sustainable. *AATCC Review*, 11(6), 26–32.
- Turner, C., Oyekan, J., Garn, W., Duggan, C., & Abdou, K. (2022). Industry 5.0 and the Circular Economy: Utilizing LCA with Intelligent Products. *Sustainability*, 14(22), 14847. <https://doi.org/10.3390/su142214847>
- United Nations Environment Program (UNEP). (2020). *38th UN-Water Meeting*.
- Wang, B., Luo, W., Zhang, A., Tian, Z., & Li, Z. (2020). Blockchain-enabled circular supply chain management: A system architecture for fast fashion. *Computers in Industry*, 123, 103324. <https://doi.org/10.1016/j.compind.2020.103324>
- Weerasiri, S. (2012). Attitudes and Awareness towards Environmental Management and its Impact on Environmental Management Practices (EMPs) of SMEs in Sri Lanka. *Journal of Social and Development Sciences*, 3(1), 16–23. <https://doi.org/10.22610/jsds.v3i1.681>
- Yang, Y., He, W., Chen, F., & Wang, L. (2020). Water footprint assessment of silk apparel in China. *Journal of Cleaner Production*, 260, 121050. <https://doi.org/10.1016/j.jclepro.2020.121050>
- Zhanlin Ji, Ganchev, I., & O'Droma, M. (2014). A Generic IoT Architecture for Smart Cities. *25th IET Irish Signals & Systems Conference 2014 and 2014 China-Ireland International Conference on Information and Communities Technologies (ISSC 2014/CIICT 2014)*, 196–199. <https://doi.org/10.1049/cp.2014>.

BEHIND THE WASTE: A SYSTEMATIC REVIEW OF LEADING CAUSES CONTRIBUTING TO OCCUPATIONAL HEALTH AND SAFETY ISSUES AMONG MUNICIPAL SOLID WASTE HANDLERS

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Abstract. Municipal solid waste (MSW) handlers are among the most vulnerable occupational groups, frequently operating in hazardous environments with limited protective measures. Despite increasing awareness of these risks, scientific studies investigating the root causes of occupational health and safety (OHS) issues among MSW handlers remain limited and, in many cases, outdated. A comprehensive synthesis is therefore essential to deepen our understanding of the multifaceted causes contributing to unsafe working conditions in this sector. This study aims to address this gap by systematically synthesising the existing literature on the causes of OHS issues faced by MSW handlers. To achieve this aim, the study is guided by the three objectives: 1) review the overview of the OHS of MSW handlers, 2) review the reasons behind the OHS issues of MSW handlers and 3) explore the next line of research in OHS of MSW handlers. A total of 117 peer-reviewed articles published between 1995 and March 2025 were selected from the Web of Science (WoS) database and analysed using a combination of descriptive and content analysis. The descriptive findings indicate a predominant publication contribution on developing and emerging economies, where OHS issues among waste handlers are particularly acute. The content analysis revealed that the causes of OHS risks can be broadly grouped into three thematic categories: organisational factors (e.g., lack of training, absence of safety protocols, and inadequate provision of personal protective equipment), individual factors (e.g., low awareness of occupational hazards, informal employment, and limited education), and physical factors (e.g., exposure to hazardous waste, extreme weather, and unsanitary work environments). This study makes a significant contribution by not only identifying these core causes but also proposing a structured set of strategies to mitigate OHS risks. It further identifies emerging trends and gaps in the literature, suggesting that future research should focus on context-rich, empirical case studies to evaluate the practical effectiveness of existing and proposed OHS interventions. Key directions for future research include the development of integrated approaches to OHS risk assessment in MSW handling, the enhancement of OHS standards in informal waste sectors, and policy evaluation and implementation studies to assess the impact of regulatory measures. Through this comprehensive synthesis, the study contributes meaningfully to the literature and provides a foundation for policymaking, practice, and academic inquiry aimed at safeguarding the health and dignity of MSW handlers.

Keywords. Occupational Health and Safety (Ohs), Municipal Solid Waste (MSW) Handlers, Municipal Waste, Leading Causes, Occupational Issues, Waste Workers, Systematic Review

1. Introduction

Occupational Health and Safety (OHS) is a multidisciplinary concept aimed at enhancing the safety, health, and well-being of individuals in the workplace (Amponsah-Tawiah & Mensah, 2016). It involves creating safe and healthy working environments by addressing physical, emotional, and mental well-being, preventing work-related accidents and illnesses, and ensuring overall welfare. While there is no universal classification system to define OHS issues, the American Bureau of Labor Statistics (2012), and the Occupational Injury and Illness Classification System (OIICS) are used for effective data collection and analysis, primarily focusing on occupational injuries and illnesses.

Over the past decades, significant global efforts have been made to promote workplace health and safety (International Labour Organisation (ILO), 2020). However, enhancing OHS remains a debated and unresolved issue (Arastoo et al., 2015). Work-related injuries and illnesses continue to pose serious problems worldwide, varying across occupations and sectors (Gizaw et al., 2014; McDonald et al., 2000; Parejo-Moscoso et al., 2013). For instance, solid waste management is ranked as the sixth most hazardous occupation, with an incident rate of 35.5 per 100,000, following fisheries, logging, aviation, iron and steel work, and farming (Gizaw et al., 2014). Given this context, this study focuses on OHS issues in the Municipal Solid Waste (MSW) sector.

MSW refers to solid waste generated from households, commercial, industrial, institutional (including hospitals), market, and public areas (Sarkar, 2003; Turan et al., 2016), which is typically collected and treated by municipalities (Ertz et al., 2016). It comprises diverse materials such as plastics, metals, food waste, wood, and paper (Farmanbordar et al., 2018). Globally, MSW generation is increasing (Dharmasiri, 2019), leading to challenges such as weakened public health, ecological degradation, and reduced quality of life (Karak et al., 2012).

Improper MSW management contributes to economic losses and poses significant risks to public health and the environment (Abduli et al., 2013). According to Alam & Ahmade, (2013), various groups are adversely affected by poor waste management, including residents without access to treatment facilities, children, waste handlers, and communities near waste dumps. Among these, waste handlers are especially vulnerable due to their consistent exposure to hazardous waste (Shazwin & Nakagoshi, 2010).

These waste handlers commonly suffer from a range of health issues, including respiratory and gastrointestinal disorders, musculoskeletal problems, skin diseases, eye infections, headaches, and mental health challenges such as stress and depression (Cointreau, 2006; Englehardt et al., 2003; Gutberlet et al., 2013; Krajewski et al., 2002; Kuijer et al., 2010; Poulsen et al., 1995; Rachiotis et al., 2016; Salve et al., 2017; Schibye et al., 2001). OHS issues are more prevalent in developing countries, where waste handlers are at greater risk due to limited protection and support systems (Athanasidou et al., 2010; Gizaw et al., 2014; Passeti et al., 2014). For example, in Sri Lanka specifically, MSW handlers are often afflicted by back pain, slips and falls, knee pain, and migraines due to the demanding nature of their work (Thisakya & Dissanayake, 2022).

Nearly 4,000 occupational accidents are reported annually in Sri Lanka, resulting in an estimated 600,000 lost working days (ILO, 2013). In Sri Lankan Ministry of Health, (2011) noted that approximately 15% of all admissions to the Colombo National Hospital were due to occupational injuries. Although specific data for MSW handlers is limited, it is well acknowledged that this group faces significant OHS challenges (Mudalige & Dharmathilake, 2000). Despite the recognition of these issues, scientific studies on the causes behind OHS problems among MSW handlers in Sri Lanka are scarce and outdated. Therefore, a comprehensive synthesis is necessary to better understand the underlying causes of these occupational issues. This study aims to synthesise the existing literature on exploring the causes behind the OHS issues in MSW handlers. Therefore, the current study intends to fulfil three objectives.

1. Review the overview of the OHS of MSW handlers.
2. Review the reasons behind the OHS issues of MSW handlers.
3. Explore the next line of research in OHS of MSW handlers.

The next section discusses the research methodology used to meet the aforementioned research objectives.

2. Research Methodology

This study employed a systematic literature review (SLR) as its methodological approach to identify, analyse, and synthesise existing evidence on the causes of OHS issues among MSW handlers. The decision to use an SLR is grounded in the objective of this study: 1) Review the overview of the OHS of MSW handlers, 2) Review the reasons behind the OHS issues of MSW handlers and 3) Explore the next line of research in OHS of MSW handlers. Unlike narrative reviews, the systematic approach ensures transparency, replicability, and methodological rigour by following a predefined protocol for identifying, selecting, and analysing relevant studies (Azarian et al., 2023).

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used as the guideline for the study, which is widely accepted as a standard procedure for doing SLRs. PRISMA assists in planning the study in a way to improve the transparency, accuracy, quality and completeness of the review (Moher et al., 2009). The current study follows the process model adopted by Mayring & Fenzl, (2019) and the following sections explain each phase more comprehensively.

2.1. MATERIAL COLLECTION

The systematic search starts with selecting search engines and keywords to find articles. After considering several research databases (Emerald Insight, Web of Science (WoS), Scopus, Science Direct and Taylor & Francis), it was found that Scopus and WoS had the highest number of relevant results. This is because they include a wide range of social science-based articles. The relevant literature was identified for review using the Scopus database. The rationale behind this decision was that Scopus contains a significantly greater volume of published papers compared to other databases (Aghimien et al., 2020). One search string with several keywords was used to search for articles. A search string was developed by combining the keywords using the Boolean operators, "AND" and "OR" as follows: (*"Municipal solid waste" OR "MSW" OR "solid waste" OR "municipal waste" AND "Occupational health and safety" OR "OHS" OR "occupational issue" OR "occupational injury*" OR "occupational illness*" OR "occupational accident*" OR "occupational hazard*" AND "Waste worker" OR "waste handler" OR "waste picker*"*).

The asterisk (*) symbol was used as a wildcard character to broaden the scope of the search by capturing alternative endings for the keywords. This search string enabled capturing studies that focused on OHS associated with MSW handlers, as evidenced through the primary database search. The timeline for the search was set from 1995 to March 2025, at which point the search was carried out. According to the qualitative meta-analysis done by Ncube et al., (2017) the publications related to OHS in MSW handlers appeared around the year 1995. Thus, the time horizon for the search for articles was set from 1995 to 2025. Accordingly, the initial search resulted in 455 articles. Figure 1 illustrates the methodological process followed in the study.

To further limit the sample size, the introduction and conclusion sections of each article were examined. Herein, 93 articles were excluded from the review since they were duplicates and not related to the topic under study. It includes 18 inaccessible articles. Consequently, 139 articles were included for the subsequent exhaustive examination. Next, a comprehensive examination of the 97 articles was carried out. After the full document review, 22 articles were excluded as a result of final quality screening. Under this final quality screening, the articles were checked to assess their association regarding the topic, methods, findings and contribution to the knowledge (Schwandt, 1996). Consequently, a total of 117 articles were subjected to the final full document review.

2.2. ANALYSIS OF LITERATURE

Informed by Grant and Booth, (2009) the results of this SLR are reported under two categories: a descriptive analysis and a content analysis. The descriptive analysis of the articles provides a robust basis for subsequent content analysis (Vaismoradi et al., 2013). In this step, the bibliographic details of the articles were presented. Herein, the articles were tabulated based on their year of publication, location of data collection and occurrences of keywords. Alternatively, content analysis reveals key themes in existing literature and associations among them (Fereday & Muir-Cochrane, 2006) which in this case are leading causes behind the OHS issues of MSW handlers and precautionary practices. In this step, the authors organised the selected articles into categories that were already established in previous research. Specifically, a similar categorisation of causes was done in a recent study by Ziae, Choobineth, Abdoli-Eramaki and

Ghaem (2018), where they used proper naming of these categories, namely organisational, individual and physical.

2.3. MATERIAL EVALUATION

In content analysis, researchers could be able to be biased and make various decisions about the content of the paper (Bailis, 1996). Such a risk can be lessened by incorporating two or more researchers to search and analyse literature findings. Thus, two researchers were included to reduce the potential of developing prejudice. Herein, the first researcher evaluated and analysed the findings of the review. Subsequently, any ambiguities that arose were resolved by involving the other researcher. A similar procedure was adopted by Prajapati et al., (2019) to improve the reliability and quality of the content analysis.

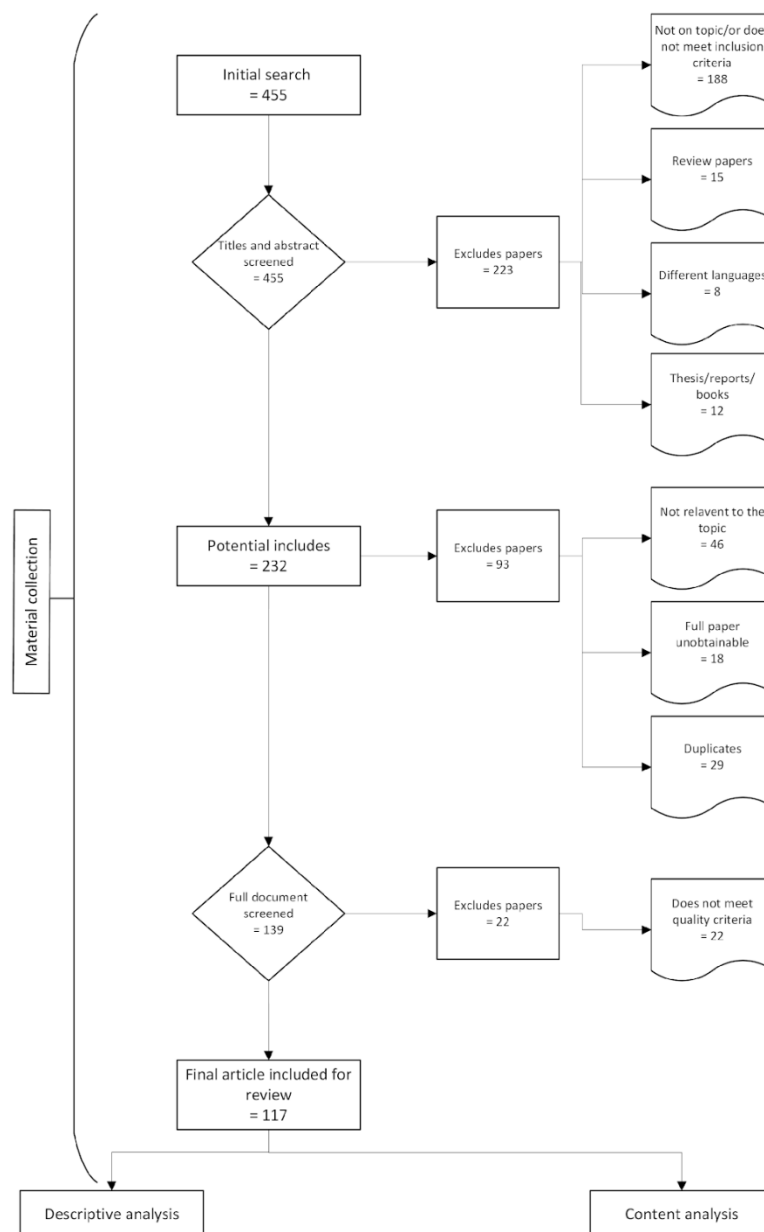


Figure 1: The methodological process followed in the study

Adopted from (Ali et al., 2017)

3. Results of the Descriptive Analysis

This section provides an overview of the aspects and findings of the descriptive analysis conducted for this study. The following sections entail publication per year, publication per country, and keyword analysis.

3.1. PUBLICATION PER YEAR

Among the 117 extracted articles, Figure 2 represents the distribution of articles based on their publication year. Even though the studies on OHS in MSW handlers started to emerge around 1995 (Ncube et al., 2017) Notably, none of the articles published in that year related to the domain of the current study. Interestingly, there is a dip in publications between 2004 and 2011. However, a surge in publications is evident after 2021, with the highest number of publications per year at 22 being recorded in 2023 and 2024. While 2025 has seen eight publications so far, the number of articles for the year 2025 can be higher since the search was limited to articles published till the end of March 2025, at which point the literature search was carried out.

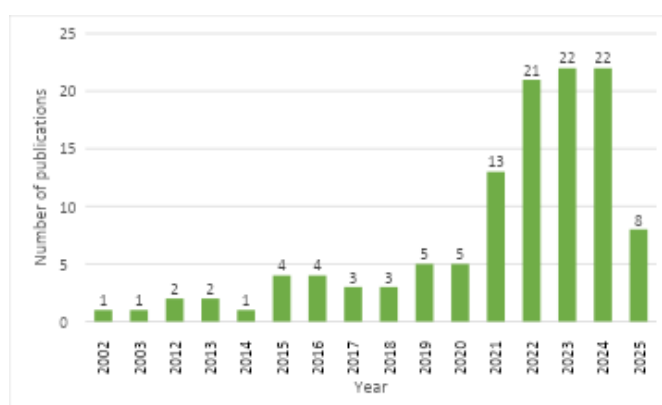


Figure 2: Distribution of articles based on the year of publication

3.2. PUBLICATION PER COUNTRY

Twenty-one countries contributed a total of 117 documents to this field of research. Figure. Figure 3 displays the countries that have a minimum of two articles and three citations.

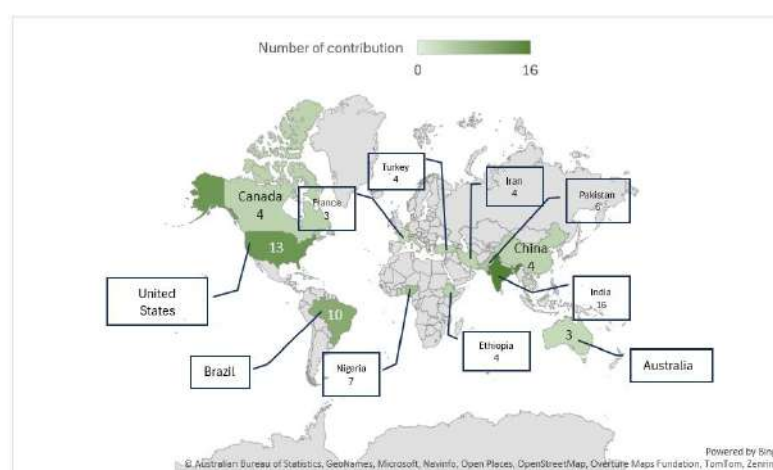


Figure 3: Distribution of articles based on geographic locations

According to Figure 3, the map uses varying shades of green to represent the number of contributions from each country, with darker shades indicating a higher number of articles. India stands out as the leading contributor with 16 articles, reflecting a significant body of research

on the topic, possibly due to the country's growing urban population, waste generation challenges, and associated health concerns (Srivastava et al., 2015). The United States follows with 13 articles, suggesting a strong research presence from a developed country perspective. Brazil also demonstrates considerable involvement, contributing 10 articles, likely due to its well-documented informal waste sector and evolving waste management strategies.

Other notable contributors include Nigeria with 7 articles and Pakistan and China with 6 and 5 articles, respectively, highlighting a growing interest in these regions, which face similar environmental and occupational health challenges in the context of solid waste management. Moderate contributions are also observed from countries such as Canada, Iran, Turkey, and Ethiopia, each contributing 4 articles, as well as France and Australia with 3 articles each. Overall, the map reflects a broad global interest in the topic, with contributions spanning Asia, Africa, the Americas, Europe, and Oceania. However, there appears to be a particularly strong focus on developing and emerging economies.

3.3. KEY-WORD ANALYSIS

A total of 68 keywords were retrieved from the 117 articles using VOSviewer software. The selection of these keywords was based on their occurrence in a minimum of three publications. The frequency of a keyword in a document reflects its overall scope, while co-occurrence highlights how often two keywords appear together in a title, abstract, or keyword list. The findings of this study are depicted in Figure 4 using a minimum requirement of four keywords. The illustration shows the frequency of co-occurring terms in the publications through the size of the nodes. The thickness of the linking lines represents the strength of relationships. The proximity of nodes in the figure shows a strong linkage between them. According to the visual network map, these keywords may be categorised into four clusters.

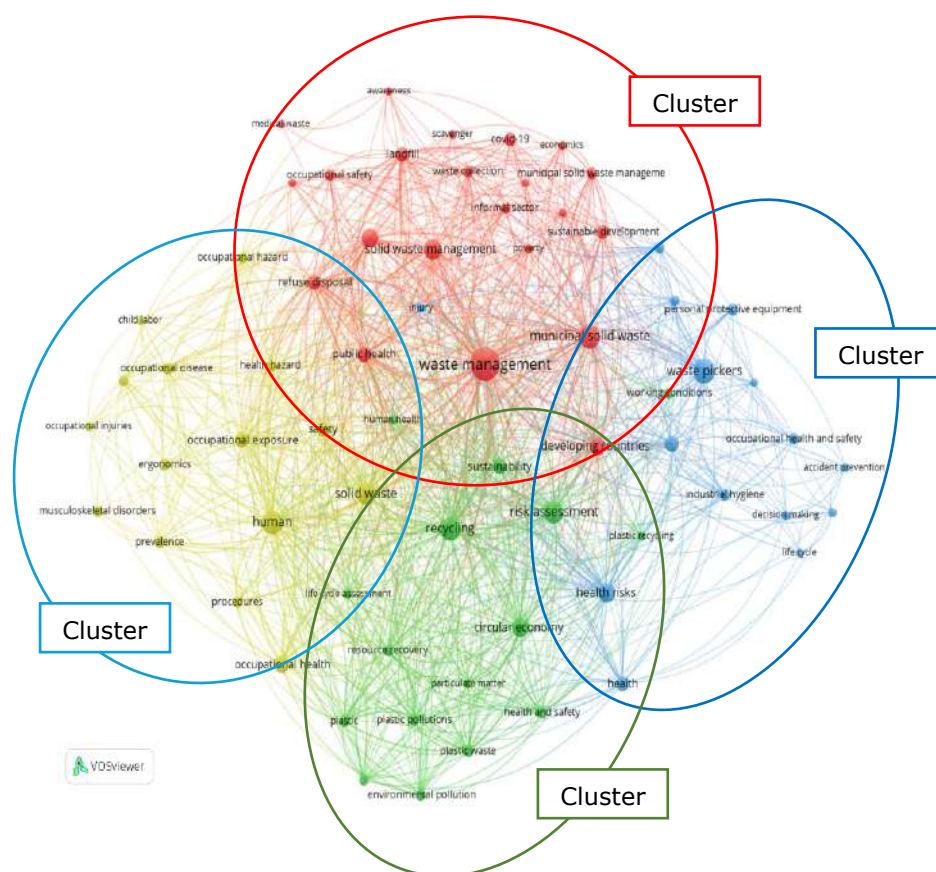


Figure 4: Co-occurrence of keywords in the literature

According to Figure 4, there are terms associated with the solid waste management and governance issues, which are indicated in cluster 1 (red). This cluster is focused on waste governance, urban infrastructure, and policy-level issues related to managing MSW. It includes both formal systems (e.g., landfills, municipal services) and informal actors (e.g., scavengers, informal sector). It often overlaps with socio-economic and institutional concerns. Cluster 2 (blue) highlighted the keywords related to OHS of waste handlers since this cluster is centred on worker-level safety and health protection. It deals with challenges faced by waste handlers, especially in developing countries, touching on OHS frameworks, safety gear, and working conditions. Cluster 3 (green) focuses on environmental sustainability, waste valorisation, and the circular economy model. It includes themes like pollution control, material recovery, and lifecycle assessments, emphasising ecological impacts and economic reuse of waste materials. The final cluster (yellow) relates to health consequences of waste handling — especially physical and biological risks faced by waste handlers. It overlaps with medical and ergonomic concerns and tends to align with epidemiological studies or occupational medicine research. Accordingly, Table 1 tabulates the cluster naming summary, most representative keywords and focus area.

Table 1: Cluster naming summary, representative keywords and focus area

Cluster	Cluster name	Representative keywords	Focus area
Cluster 1	Waste Governance & Management Systems	waste management, municipal solid waste, solid waste management, landfill, refuse disposal, scavenger, informal sector, sustainable development, poverty, awareness	Municipal waste systems, landfill, informal sector
Cluster 2	Occupational Health & Safety of Waste handlers	waste handlers, occupational health and safety, personal protective equipment, accident prevention, working conditions, industrial hygiene, decision making	Waste handlers, safety equipment, work conditions
Cluster 3	Environmental Impact & Circular Economy	recycling, circular economy, plastic, pollution, environmental pollution, plastic waste, plastic recycling, resource recovery, life cycle assessment	Recycling, pollution, circular economy, LCA
Cluster 4	Human Health Risks & Occupational Exposure	human, health hazard, occupational exposure, ergonomics, musculoskeletal disorders, prevalence, occupational injuries, occupational disease	Health issues, ergonomics, occupational diseases

4. Results of the Content Analysis

In the subsequent step, the selected articles were examined, synthesised, and organised into predefined categories, including the underlying causes of OHS issues among MSW handlers, as well as the practices implemented to address these challenges. The following sections provide an in-depth discussion of each category.

4.1. REASONS BEHIND THE OCCUPATIONAL HEALTH AND SAFETY (OHS) ISSUES OF MUNICIPAL SOLID WASTE (MSW) HANDLERS

OHS issues of MSW handlers can happen due to several reasons. According to Robson et al. (2012), causes for OHS issues of the MSW handlers can be classified into three categories as unsafe employee behaviour, the working environment, and management practices. Further, a similar categorisation of causes was done in a recent study by Ziaei et al. (2018), where they

used proper naming of these categories, namely organisational, individual and physical. The authors have derived these categories through researching and expounding on the risk factors for musculoskeletal disorders among municipal solid waste collectors in Shiraz, Iran.

Thus, the following sub-sections are descriptively reviewed aforementioned three categories by exploring the different causes under each category.

4.1.1. Organisational category

The organisational category can be identified as the characteristics of the organisation that influence handlers' behaviour, such as training, top management support, etc. (Ling et al., 2013). The organisational category greatly affects the OHS issues of MSW handlers (Thormar et al., 2013). Hence, Table 2 summarises the literature findings on causes under the organisational category that influence OHS issues of MSW handlers.

Table 2: Causes under the organisational category which influence OHS issues of MSW handlers

Cause	References										
	A	B	C	D	E	F	G	H	I	J	K
• Poor working environment	x					x					
• Poor quality of Personal Protective Equipment (PPE)	x		x		x		x	x	x		x
• Lack of training and instruction		x	x	x	x	x	x			x	
• Lack of supervision									x	x	
• Lack of routine medical checkup programs				x					x	x	
A:(Bleck & Wettberg, 2012), B:(Bogale et al., 2014), C:(Diniz et al., 2019), D:(Ewis et al., 2013), E:(Gebremedhin, 2016), F:(Gizaw et al., 2014), G:(Jerie, 2016), H:(Kandasamy et al., 2013), I:(Thakur et al., 2018), J:(Salazar et al., 2001), K:(Wilson et al., 2006)											

As shown in Table 2, most previous studies argue that poor quality has highly impacted adverse health. A study based in Nigeria disclosed that about 73.6% of MSW handlers were disappointed about the quality of the PPE. This implied that their protective equipment was not to the right quality and not suitable for the tasks (Inyang, 2007). As a result, a lack of safety intervention with the provision of PPE may increase the number of occupational hazards associated with the collection and disposal of solid waste (Jerie, 2016).

Other than the PPE, many preceding research pieces have emphasised that a lack of training and instruction from the organisation could also be another vital reason that causes adverse health effects. The training of waste handlers on OHS issues has also been an important part of improving working conditions (Bogale et al., 2014). The research was done by Ewis et al. (2013), revealed, among the 138 respondents from Egypt, none of them reported training before employment. However, in the end, lack of training, practice, instruction, and supervision will have a positive relationship with adverse OHS problems since waste handlers may not have been given proper guidance (Diniz et al., 2019).

Despite a lack of more discussion, it appears that the working environment influences all hazards, and Bleck & Wettberg, (2012) provide the examples of restricted workspace, slippery surface, and dim lighting enhance mechanical risks such as slipping, falling, cutting, and insufficient hygienic behaviour, often due to a lack of facilities, which increases exposure to biological agents. Additionally, it seems that the provision to provide routing medical checkup

programs was also discussed by a few authors. Accordingly, most MSW handlers were never medically examined in Egypt (Ewis et al., 2013). When it comes to a developing country like India, there is no difference in the situation. Most MSW handlers are deprived of medical facilities and, therefore, are unsatisfied with their job (Thakur et al., 2018).

Most importantly, it could be argued that some of the causes revealed even in the first half of this century are still unresolved.

4.1.2. Individual category

The individual category focuses on the handler's mix of skills, knowledge, experience, attitudes, motivations, habits, and personality, as well as their demographic characteristics (Athanasidou et al., 2010) such as sex and age of handlers, and the level of education (Gizaw et al., 2014). Salminen, Simo ; Gyekye, Seth Ayim ; Ojajärvi (2013), discovered that the individual category has more impact than the organisational category. Literature findings on the causes under individual categories that influence OHS issues of MSW handlers are listed in Table 3.

Table 3: Causes under the individual category which influence OHS issues of MSW handlers

Cause	References														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Inadequate skills and knowledge of the MSW handler					x	x	x	x	x	x	x				x
Gender of the MSW handler	x					x	x	x	x	x		x	x	x	
Age level of the MSW handler	x					x	x	x	x	x		x	x	x	
Poor educational level	x		x			x	x	x	x	x		x	x	x	
Insufficient income				x			x								
Negligence in the use of PPE	x				x		x	x			x				
Lack of sleep		x		x	x		x								
Work experiences				x	x				x	x					
A:(Bogale et al., 2014), B:(Bulduk, 2019), C:(Bunn et al., 2011), D:(Eskezia et al., 2016), E:(Ewis et al., 2013), F:(Gebremedhin, 2016), G:(Gizaw et al., 2014), H:(Hoefel et al., 2013), I:(Inyang, 2007), J:(Jeong et al., 2016), K:(Kandasamy et al., 2013), L:(Mehrdad et al., 2008), M:(Salve et al., 2017), N:(Thakur et al., 2018), O:(Wilson et al., 2006)															

As shown in Table 3, the years of education, age, the overall level of knowledge and duration of work experience were the most important variables impacting the overall OHS of MSW handlers (Gebremedhin, 2016). Jeong et al. (2016) proved that a total of 41.7% of the illnesses occurred in handlers with 5-10 years of experience in Korea. Nevertheless, a different study conducted in Ethiopia argued that the likelihood of occupational injury was significantly higher among handlers with three or fewer service years (Eskezia et al., 2016). However, there is minimal variance in the accident rate based on work experience because this job may not involve specialised procedures or techniques (Jeong et al., 2016). More precisely, Gizaw et al. (2014) revealed that handlers aged ≥ 30 years were 1.834 times more likely to be injured than handlers aged < 30 years. However, it implies that elderly handlers are more vulnerable to accidents since they must constantly move around, work on their feet all day, and carry heavy plastic waste bags. These result in frustration and a loss of concentration (Jeong et al., 2016). Moreover, Hoefel et al. (2013), highlighted that those accidents are more severe among women in Brazil. Hence, it seems gender is also a significant variable to the degree of the impact. The impact of the low educational level of MSW handlers towards the adverse OHS problems is also disclosed in

previous research. As an example, it was proved that 60.3% of handlers do not have any formal education in Nigeria (Gebremedhin, 2016).

Despite the criticality of OHS issues that MSW handlers are experienced with, their usage of PPE is low (Gebremedhin, 2016). According to a study conducted in Addis Ababa, 43.6% of solid waste collectors used PPE at all times while on duty, which might result in the possibility of occupational health concerns (Bogale et al., 2014). Thakur et al. (2018), convinced by their study, also that 6.67% of MSW handlers denied getting any type of protective gear. The argument was similar to the result of an Egyptian survey done by Ewis et al. (2013), who also statistically proved that MSW handlers are not using protective devices such as face masks, goggles, gumboots or gloves while working. By reasoning, Gebremedhin (2016), showed that 21.5% and 8.3% of handlers did not wear PPE because of discomfort and to save their time, respectively. Similarly, Bogale et al. (2014) also emphasised that the main reasons for not wearing PPE are discomfort (25.6%), saving time (12.8%), and not having access (83.7%). Other than that, Jerie (2017) disclosed, lack of awareness and their low social status are also caused by not using PPE even when MSW handlers are supplied. Consequently, MSW handlers who were not using protective devices were 2.6 times more likely to get injured (Bogale et al., 2014). However, since they do not use safety precautions, they may contact with pathogens/allergens through skin and inhalation (Kandasamy et al., 2013). For example, approximately 13.8% of street sweepers reported skin irritations, which could be explained by direct contact with waste while wearing no protective equipment (Ewis et al., 2013). Moreover, among the MSW handlers, the likelihood of occupational injury was 2.57 times higher among those who reported sleeping disturbance as compared to their counterparts (Eskezia et al., 2016).

4.1.3. Physical category

The physical category focuses on the different variables of the handler's specific job or task that influence their safety-related behaviour, including the nature of the work, duration of exposure, workload, etc. (Mélan & Cascino, 2014). Matching the job to the person will ensure that they are not overloaded and that the most effective contribution to the organisation results (Ziaei et al., 2019). Accordingly, Table 4 discloses the literature findings on causes under the physical category which influence OHS issues of MSW handlers.

Table 4: Causes under the physical category which influence OHS issues of MSW handlers

Causes	References									
	A	B	C	D	E	F	G	H	I	J
Highly intensive physical activities	x		x		x	x		x		x
Excessive workload	x				x					x
Weather conditions					x					
Long duration of work exposure		x	x	x	x			x	x	x
Manual handling of solid waste					x		x			
A: (Abou-ElWafa et al., 2012), B: (Bleck & Wettberg, 2012), C: (Bogale et al., 2014), D: (Bulduk, 2019), E: (Gizaw et al., 2014), F: (Jerie, 2017), G: (Kandasamy et al., 2013), H: (Mehrdad et al., 2008), I: (Salazar et al., 2001), J: (Salve et al., 2017)										

As shown in Table 4, it could be argued that many studies conducted with waste collectors revealed that the nature of the work is highly subject to OHS risks. Moreover, they have a higher probability of developing musculoskeletal disorders as compared to the general population due to the nature of their work (Abou-ElWafa et al., 2012; Mehrdad et al., 2008). Similarly, handlers who are repeatedly exposed to lifting, bending, pushing, and pulling for more prolonged periods have also been recognised as having a higher risk of developing musculoskeletal problems

(Schibye et al., 2001). The situation is significantly worse in developing countries, where waste management is mainly done manually (Marimuthu et al., 2021).

Considering the above-identified causes, it is evident that OHS problems can occur with MSW handlers under any circumstances. Hence, those causes can be eliminated by espousing precautionary methods. Therefore, the next section of the chapter discusses the literature findings of precautionary practices.

4.2. PRECAUTIONARY PRACTICES TO MITIGATE THE OCCUPATIONAL HEALTH AND SAFETY ISSUES OF MUNICIPAL SOLID WASTE HANDLERS

Having strong precautionary measures created a thriving safety culture for MSW handlers. Accordingly, many studies discovered a series of precautionary practices in order to minimise the causes discussed in this section. Basically, handlers need to have adequate training and information before starting their job in order to be able to understand the severity of the job and protect their health (Gebremedhin, 2016). The training should deal with the knowledge of the subjective area, equipment, and tools; recognised hazards in the operations and how to control these hazards; potential health concerns; hygiene requirements; background of incidents and accidents, and wearing and use of PPE (Bogale et al., 2014). PPE should also be provided and managed by the responsible authorities (Ewis et al., 2013). Job rotation among work components, improvement of employees' income, job-specific guidelines for maximum production limitations, and replacement of bags and bins with wheeled containers are also expected to make the situation better (Eskezia et al., 2016). Further, the government should make provisions for regular medical checkups and a separate medical allowance to detect early signs of work-related complaints and monitor workability (Eskezia et al., 2016; Thakur et al., 2018).

Moreover, improving the working conditions helps reduce the times the waste handlers come into direct contact with the waste (Diniz et al., 2019). For example, after the age of 40, senior handlers' eyesight begins to deteriorate, with their field of vision narrowing and contracting, unable to transmit as much light as previously (Jeong et al., 2016). Therefore, the previous study further elaborated that MSW handlers should be provided with lighting equipment, and waste-collecting vehicles should be outfitted with lighting capabilities to ensure enough visibility to prevent injuries. On the other hand, since musculoskeletal disorders are common, awkward postures can be reduced by improving appropriate work methods or ergonomically designed work tools (Fewster et al., 2020; Gallagher, 2005).

Thakur et al. (2018), pointed out that the appointment of safety managers is vital to make all altogether practices above. It was further revealed that to improve the work culture of MSW handlers, safety managers ensure that handlers are safe, including providing protective equipment to all types of MSW handlers to avoid exposure to occupational health hazards initially. Moreover, the development and establishment of documentation systems of occupational injuries and illnesses will in minimising future occurrences (Gizaw et al., 2014).

Figure 5 illustrates a summary of precautionary measures extracted from the reviewed literature within this study.

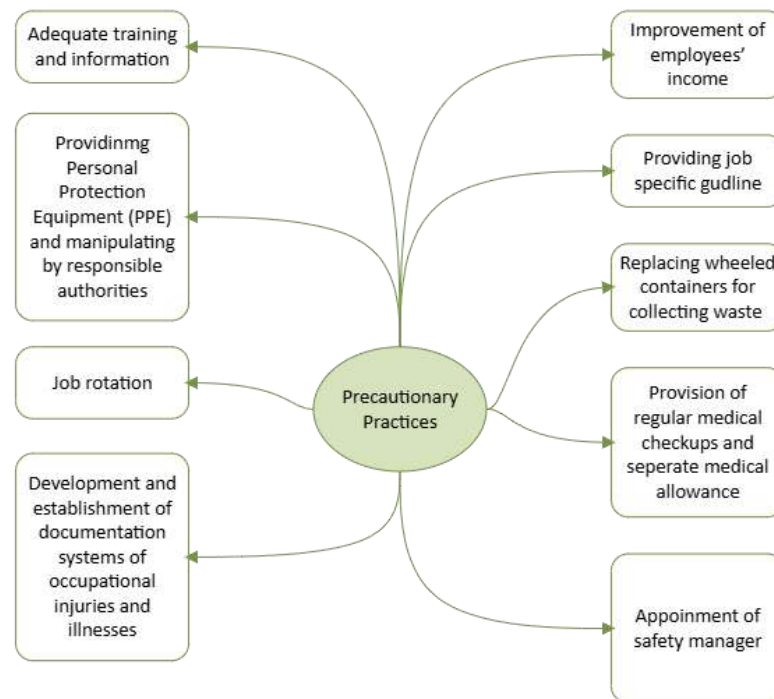


Figure 5: Precautionary practices to mitigate the occupational health and safety issues of the municipal solid waste handlers

5. Future Research Directions

Sections 4.1 and 4.2 outline both the primary factors contributing to OHS issues among MSW handlers and the existing measures implemented to mitigate these issues. The review underscores the critical role of identifying these underlying causes in fostering a safer working environment for MSW handlers, while also highlighting the necessity of linking this understanding to the development and implementation of effective preventive practices. Based on these insights, the following pragmatic future research directions are proposed to further advance our knowledge of OHS within this sector.

5.1 INTEGRATED APPROACHES TO UNDERSTANDING OHS RISKS IN MSW HANDLING

The existing body of research largely isolates occupational health risks from broader systemic issues such as socio-economic status, informal employment, or governance structures. Although many studies have identified individual risks such as musculoskeletal disorders, exposure to toxic substances, or lack of protective equipment (Diniz et al., 2019; Kandasamy et al., 2013), few have taken an integrative approach that considers how these factors intersect (Gizaw et al., 2014; Hoefel et al., 2013). Future research could adopt systems thinking or socio-ecological frameworks to explore how environmental, organisational, and individual factors interact to shape OHS outcomes. Such an approach would help design more holistic interventions tailored to complex real-world contexts.

5.2 ENHANCING OHS IN INFORMAL WASTE SECTORS

Most existing research disproportionately focuses on formal waste management systems, overlooking the large proportion of waste handlers in informal sectors (outside of government-regulated or formally organised waste management systems)—particularly in low- and middle-income countries—who face heightened OHS vulnerabilities due to lack of regulation, job security, and access to healthcare. Future research should prioritise the informal sector, including

ethnographic studies, community-based participatory research, and policy analyses to develop inclusive and context-sensitive strategies that do not inadvertently marginalise these handlers.

5.3 POLICY EVALUATION AND IMPLEMENTATION RESEARCH

Although numerous guidelines and frameworks for improving OHS in waste handling exist, there is limited evidence on their implementation effectiveness or policy uptake (Kandasamy et al., 2013; Thakur et al., 2018). Future work should focus on evaluative research to determine which interventions are working, under what conditions, and for whom. Comparative studies between countries with differing regulatory environments may help identify best practices that can be adapted and scaled. Furthermore, research should explore the role of institutional capacity, governance quality, and multi-stakeholder collaboration in shaping policy outcomes.

6. Discussion

The findings of this study reveal that the causes behind OHS issues among MSW handlers can be grouped into three broad categories: organisational, individual, and environmental/physical factors. These findings align with and expand upon prior studies in the field. Poor provision of PPE, lack of regular training, and weak enforcement of OHS policies were recurring themes in the reviewed literature. These organisational shortcomings mirror the findings of Tshivhase et al. (2022), who reported inadequate PPE and poor adherence to safety guidelines as primary hazards facing MSW handlers in a South African municipality. The current study reinforces the systemic nature of these issues, suggesting they are not isolated but widespread across similar low- and middle-income country (LMIC) contexts.

Similarly, Tolera et al. (2023) in their global systematic review emphasise that institutional deficiencies—such as limited OHS monitoring mechanisms and fragmented policy implementation—are key contributors to adverse safety outcomes among sanitation and hygiene workers. Findings of current study further illustrate how these institutional weaknesses manifest at the ground level, resulting in both acute injuries and long-term health risks among MSW handlers. The study identified several individual-level determinants, including lack of awareness, risk-taking behaviour, and low levels of education or training. These personal factors were found to compound organisational failings, especially when waste handlers are unaware of the health implications of unsafe practices or are compelled to take shortcuts due to productivity demands. Tolera et al. (2023), in their review of cross-sectional studies, also highlight behavioural and cognitive dimensions—such as safety attitudes and risk perceptions—as significant predictors of health outcomes among sanitation workers. This convergence underscores the need for behaviourally informed interventions, including targeted safety education and behavioural nudges, to reinforce safety compliance. Unhygienic working environments, extreme weather exposure, and handling of hazardous waste without segregation were common environmental hazards identified in this review. These findings echo those of Tshivhase et al. (2022), who noted that workers were often exposed to dangerous waste types, including sharps and biomedical waste, due to the absence of pre-collection segregation. Moreover, the findings point to widespread environmental risks exacerbated by poor urban infrastructure and informal work arrangements.

Taken together, this study confirms that OHS outcomes among MSW handlers result from an interplay of systemic, behavioural, and contextual factors. The thematic categories identified here correspond closely with the risk domains emphasised in the global literature. However, the current review contributes a more granular understanding of how these categories intersect in LMIC contexts, especially where informal employment and under-resourced municipal systems prevail.

7. Conclusion and recommendations

This study provides a comprehensive thematic synthesis of the reasons underlying OHS issues faced by MSW handlers. The analysis, which spans literature published from 1995 to 2025 March, identifies a complex interplay of organisational, individual, and physical factors that contribute to unsafe working conditions for MSW handlers. Organisational factors such as the lack of OHS training, inadequate provision of PPE, absence of clear safety policies, and inefficient waste management practices significantly compromise worker safety. Individual-level factors, including low educational backgrounds, poor awareness of occupational risks, and negligence in using PPE, further exacerbate vulnerability to injury and illness. In parallel, physical factors — ranging from exposure to hazardous waste, heat, and dust to poor sanitation and unsanitary work environments — directly threaten the health of waste handlers.

The review also uncovers a general trend of systemic neglect regarding OHS in the waste management sector. Institutional accountability appears minimal, with weak enforcement of existing safety regulations and limited inclusion of MSW handlers, especially those in informal sectors, in OHS planning. Overcoming these challenges requires a multidimensional approach that extends beyond technical interventions. It demands a stakeholder-inclusive framework that acknowledges and responds to the broader socio-political and institutional contexts shaping the everyday realities of MSW handlers. The recurrence of similar OHS issues over nearly three decades of literature underscores the urgency for integrated, context-sensitive policy responses and sustained action from municipal authorities, public health institutions, and civil society organisations.

While this review has discussed the causes of OHS issues and precautionary practices to mitigate them, it also highlights a critical gap in the literature: the lack of focus on the interrelationship between specific causes and targeted mitigation strategies. Most studies tend to address these dimensions in isolation, rather than examining how particular causes can be directly matched with context-appropriate precautionary measures. Future research should thus explore integrated approaches to understanding OHS risks in MSW handling, enhance knowledge and protections within informal waste sectors, and undertake policy evaluation and implementation research to assess the effectiveness of existing interventions and frameworks.

However, this review is not without limitations. It is restricted to English-language publications, which may exclude relevant research conducted and published in other languages, particularly from regions with significant informal waste management activities. Additionally, the analysis is primarily based on secondary data and therefore lacks direct empirical validation through real-world case studies. As such, future research should aim to bridge this gap by conducting in-depth, context-rich case studies that can offer practical insights into the application and effectiveness of OHS interventions in diverse municipal settings.

Despite these limitations, the findings offer a robust foundation for informing research, practice, and policy. The study allows policymakers to strengthen national and municipal OHS regulations with clear standards tailored to the waste sector. Formalise informal waste workforces through legal inclusion and social protection. Allocate targeted investments in infrastructure, training, and waste segregation systems. Industry practitioners, including municipal authorities and private waste management companies, must ensure the consistent provision and monitoring of PPE, implement regular training programs, and foster a culture of safety through participatory planning and transparent reporting mechanisms. Academic researchers have a crucial role to play in addressing the identified knowledge gaps by undertaking longitudinal and mixed-methods research that explores the causal linkages between specific hazards and mitigation strategies.

Therefore, ensuring the health and safety of MSW handlers is a shared responsibility that requires integrated action. Collaborative efforts among governments, industry stakeholders, and

researchers are vital to crafting inclusive, evidence-based, and sustainable solutions. The knowledge synthesised through this review offers valuable direction for advancing OHS in waste management systems and upholding the dignity of those who sustain them.

8. References

- Abduli, M. A., Tavakolli, H., & Azari, A. (2013). Alternatives for solid waste management in Isfahan, Iran: A case study. *Waste Management and Research*, 31(5), 532–537. <https://doi.org/10.1177/0734242X13477718>
- Abou-ElWafa, H. S., El-Bestar, S. F., El-Gilany, A. H., & Awad, E. E. S. (2012). Musculoskeletal disorders among municipal solid waste collectors in Mansoura, Egypt: A cross-sectional study. *BMJ Open*, 2(5), e001338. <https://doi.org/10.1136/bmjopen-2012-001338>
- Aghimien, D. O., Aigbavboa, C. O., Oke, A. E., & Thwala, W. D. (2020). Mapping out research focus for robotics and automation research in construction-related studies: A bibliometric approach. *Journal of Engineering, Design and Technology*, 18(5), 1063–1079. <https://doi.org/10.1108/JEDT-09-2019-0237>
- Alam, P., & Ahmade, K. (2013). Impact of Solid Waste on Health and the Environment. *International Journal of Sustainable Development and ...*, 2(1), 165–168. http://irnet.sg/irnet_journal/IJSDGE/IJSDGE_doc/IJSDGE_V2I1,2_papers/31.pdf
- Ali, A., Mahfouz, A., & Arisha, A. (2017). Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. *Supply Chain Management*, 22(1), 16–39. <https://doi.org/10.1108/SCM-06-2016-0197>
- American Bureau of Labor Statistics. (2012). *Occupational Injury and Illness Classification Manual Version 2.01*.
- Amponsah-Tawiah, K., & Mensah, J. (2016). Occupational Health and Safety and Organizational Commitment: Evidence from the Ghanaian Mining Industry. *Safety and Health at Work*, 7(3), 225–230. <https://doi.org/10.1016/j.shaw.2016.01.002>
- Arastoo, H., Azimov, P. H., & Esfandiarpour, S. (2015). Assessment of barriers to establish OSH: A country report. *Industrial Health*, 53(4), 378–384. <https://doi.org/10.2486/indhealth.2013-0234>
- Athanasiou, M., Makrynos, G., & Dounias, G. (2010). Respiratory health of municipal solid waste workers. *Occupational Medicine*, 60(8), 618–623. <https://doi.org/10.1093/occmed/kqq127>
- Azarian, M., Yu, H., Shiferaw, A. T., & Stevik, T. K. (2023). Do We Perform Systematic Literature Review Right? A Scientific Mapping and Methodological Assessment. *Logistics*, 7(4), 89. <https://doi.org/10.3390/logistics7040089>
- Bailis, D. S. (1996). Estimating liability risks with the media as your guide: A content analysis of media coverage of tort litigation. *Law and Human Behavior*, 20(4), 419–429. <https://doi.org/10.1007/BF01498978>
- Bleck, D., & Wettberg, W. (2012). Waste collection in developing countries - Tackling occupational safety and health hazards at their source. *Waste Management*, 32(11), 2009–2017. <https://doi.org/10.1016/j.wasman.2012.03.025>
- Bogale, D., Kumie, A., & Tefera, W. (2014). Assessment of occupational injuries among Addis Ababa city municipal solid waste collectors: A cross-sectional study. *BMC Public Health*, 14(1), 169. <https://doi.org/10.1186/1471-2458-14-169>
- Bulduk, E. Ö. (2019). Work-related stress levels and musculoskeletal disorders among municipal solid waste collectors in Ankara. *Work*, 63(3), 427–433. <https://doi.org/10.3233/WOR-192949>
- Bunn, T. L., Slavova, S., & Tang, M. (2011). Injuries among solid waste collectors in the private versus public sectors. *Waste Management and Research*, 29(10), 1043–1052. <https://doi.org/10.1177/0734242X11410115>
- Cointreau, S. (2006). Occupational and environmental health issues of solid waste management. *Urban Papers*, 2, 57.
- Dharmasiri, L. M. (2019). Waste Management in Sri Lanka: Challenges and Opportunities. *Sri Lanka Journal of Advanced Social Studies*, 9(1), 72. <https://doi.org/10.4038/sljass.v9i1.7149>

- Diniz, N., Castro, P., Lago, E., da Cruz, F., Zlatar, T., Wasnievski, D., Pereira, A., & Junior, B. B. (2019). Work-related accidents in urban solid waste collection. In *Studies in Systems, Decision and Control* (Vol. 202, pp. 43–51). https://doi.org/10.1007/978-3-030-14730-3_5
- Englehardt, J. D., An, H., Fleming, L. E., & Bean, J. A. (2003). Analytical predictive bayesian assessment of occupational injury risk: Municipal solid waste collectors. *Risk Analysis*, 23(5), 917–927. <https://doi.org/10.1111/1539-6924.00369>
- Ertz, M., Karakas, F., & Sarigöllü, E. (2016). Exploring pro-environmental behaviors of consumers: An analysis of contextual factors, attitude, and behaviors. *Journal of Business Research*, 69(10), 3971–3980. <https://doi.org/10.1016/j.jbusres.2016.06.010>
- Eskezia, D., Aderaw, Z., Ahmed, K. Y., & Tadese, F. (2016). Prevalence and associated factors of occupational injuries among municipal solid waste collectors in four zones of Amhara region, Northwest Ethiopia. *BMC Public Health*, 16(1), 862. <https://doi.org/10.1186/s12889-016-3483-1>
- Ewis, A., Mohamad, E. ., Rahma, M. ., Hifnawy, T. ., & Arafa, A. . (2013). Occupational Health-Related Morbidities Among Street Sweepers and Waste Collectors At Beni-Suef, Egypt. *Egyptian Journal of Occupational Medicine*, 37(1), 79–94. <https://doi.org/10.21608/ejom.2013.773>
- Farmanbordar, S., Karimi, K., & Amiri, H. (2018). Municipal solid waste as a suitable substrate for butanol production as an advanced biofuel. *Energy Conversion and Management*, 157, 396–408. <https://doi.org/10.1016/j.enconman.2017.12.020>
- Fereday, J., & Muir-Cochrane, E. (2006). Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development. *International Journal of Qualitative Methods*, 5(1), 80–92. <https://doi.org/10.1177/160940690600500107>
- Fewster, K. M., Gallagher, K. M., Howarth, S. H., & Callaghan, J. P. (2020). Low back pain development differentially influences centre of pressure regularity following prolonged standing. *Gait and Posture*, 78, e1–e6. <https://doi.org/10.1016/j.gaitpost.2017.06.005>
- Gallagher, S. (2005). Physical limitations and musculoskeletal complaints associated with work in unusual or restricted postures: A literature review. *Journal of Safety Research*, 36(1), 51–61. <https://doi.org/10.1016/j.jsr.2004.12.001>
- Gebremedhin, F. (2016). Assessment of Knowledge, Attitude and Practices Among Solid Waste Collectors in Lideta Sub-city on Prevention of Occupational Health Hazards, Addis Ababa, Ethiopia. *Science Journal of Public Health*, 4(1), 49. <https://doi.org/10.11648/j.sjph.20160401.17>
- Gizaw, Z., Gebrehiwot, M., Teka, Z., & Molla, M. (2014). Assessment of occupational injury and associated factors among municipal solid waste management workers in Gondar town and Bahir Dar City, northwest Ethiopia, 2012. *International Research Journal of Medicine and Medical Sciences*, 05(09), 181–192. <https://doi.org/10.14303/jmms.2014.103>
- Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal*, 26(2), 91–108. <https://doi.org/10.1111/j.1471-1842.2009.00848.x>
- Gutberlet, J., Baeder, A. M., Pontuschka, N. N., Felipe, S. M. N., & dos Santos, T. L. F. (2013). Participatory research revealing the work and occupational health hazards of cooperative recyclers in Brazil. *International Journal of Environmental Research and Public Health*, 10(10), 4607–4627. <https://doi.org/10.3390/ijerph10104607>
- Hoefel, M. da G., Carneiro, F. F., Santos, L. M. P., Gubert, M. B., Amate, E. M., & Santos, W. dos. (2013). Accidents at work and living conditions among solid waste segregators in the open dump of Distrito Federal. *Revista Brasileira de Epidemiologia*, 16(3), 774–785. <https://doi.org/10.1590/S1415-790X2013000300020>
- ILO. (2013). *Safety and health at work in Sri Lanka and the Maldives (ILO in Sri Lanka)*. Decent Work Country Programme for Sri Lanka. <https://www.ilo.org/colombo/areasofwork/safety-and-health-at-work/lang--en/index.htm>
- International Labour Organisation (ILO). (2020). *Safety and health at work*.
- Inyang, M. P. (2007). Health and Safety Risks Amongst the Municipal Solid Waste Collectors in Port Harcourt Metropolis Of the Niger Delta Region Of Nigeria. *International Conference "Waste Management, Environmental Geotechnology and Global Sustainable Development"*, 57, 58.

- Jeong, B. Y., Lee, S., & Lee, J. D. (2016). Workplace Accidents and Work-related Illnesses of Household Waste Collectors. *Safety and Health at Work*, 7(2), 138–142. <https://doi.org/10.1016/j.shaw.2015.11.008>
- Jerie, S. (2016). Occupational risks associated with solid waste management in the informal sector of Gweru, Zimbabwe. *Journal of Environmental and Public Health*, 2016, 1–14. <https://doi.org/10.1155/2016/9024160>
- Jerie, S. (2017). Prevalence of Adverse Health Effects among Municipal Solid Waste Workers, Southern Thailand. *International Journal of Occupational Hygiene*, 9(4), 186–191. <https://doi.org/10.1155/2016/9024160>
- Kandasamy, S. P., Akolkar, A. B., Manoharan, A., & Paranj, S. (2013). Municipal solid waste management at Chennai in southern India - An occupational health perspective. *International Journal of Health Promotion and Education*, 51(1), 50–61. <https://doi.org/10.1080/14635240.2012.750068>
- Karak, T., Bhagat, R. M., & Bhattacharyya, P. (2012). Municipal solid waste generation, composition, and management: The world scenario. *Critical Reviews in Environmental Science and Technology*, 42(15), 1509–1630. <https://doi.org/10.1080/10643389.2011.569871>
- Krajewski, J. A., Tarkowski, S., Cyprowski, M., Szarapińska-Kwaszewska, J., & Dudkiewicz, B. (2002). Occupational exposure to organic dust associated with municipal waste collection and management. *International Journal of Occupational Medicine and Environmental Health*, 15(3), 289–301.
- Kuijjer, P. P. F. M., Sluiter, J. K., & Frings-Dresen, M. H. W. (2010). Health and safety in waste collection: Towards evidence-based worker health surveillance. *American Journal of Industrial Medicine*, 53(10), 1040–1064. <https://doi.org/10.1002/ajim.20870>
- Ling, T. C., Poon, C. S., & Wong, H. W. (2013). Management and recycling of waste glass in concrete products: Current situations in Hong Kong. *Resources, Conservation and Recycling*, 70, 25–31. <https://doi.org/10.1016/j.resconrec.2012.10.006>
- Marimuthu, R., Shanthi, M., Aramvith, S., & Sivaranjani, S. (2021). Smart Waste Management Model for Effective Disposal of Waste Management Through Technology. In *EAI/Springer Innovations in Communication and Computing* (pp. 213–229). https://doi.org/10.1007/978-3-030-70183-3_9
- Mayring, P., & Fenzl, T. (2019). Qualitative Inhaltsanalyse. In *Handbuch Methoden der empirischen Sozialforschung* (pp. 633–648). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-21308-4_42
- McDonald, N., Corrigan, S., Daly, C., & Cromie, S. (2000). Safety management systems and safety culture in aircraft maintenance organisations. *Safety Science*, 34(1–3), 151–176. [https://doi.org/10.1016/S0925-7535\(00\)00011-4](https://doi.org/10.1016/S0925-7535(00)00011-4)
- Mehrdad, R., Majlessi-Nasr, M., Aminian, O., Sharifian, S. A., & Malekhamadi, F. (2008). Musculoskeletal disorders among municipal solid waste workers. *Acta Medica Iranica*, 46(3), 233–238.
- Mélan, C., & Cascino, N. (2014). A multidisciplinary approach of workload assessment in real-job situations: Investigation in the field of aerospace activities. *Frontiers in Psychology*, 5(AUG). <https://doi.org/10.3389/fpsyg.2014.00964>
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Altman, D., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D’Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., ... Tugwell, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement (Chinese edition). *Journal of Chinese Integrative Medicine*, 7(9), 889–896. <https://doi.org/10.3736/jcim20090918>
- Mudalige, O. M. D. C., & Dharmathilake, A. . (2000). Health problems among Colombo Municipal Council workers. *IneFaculty of Medic*, 15–20.
- Ncube, F., Ncube, E. J., & Voyi, K. (2017). A systematic critical review of epidemiological studies on public health concerns of municipal solid waste handling. *Perspectives in Public Health*, 137(2), 102–108. <https://doi.org/10.1177/1757913916639077>
- Parejo-Moscoso, J. M., Rubio-Romero, J. C., Pérez-Canto, S., & Soriano-Serrano, M. (2013). Health and safety management in olive oil mills in Spain. *Safety Science*, 51(1), 101–108. <https://doi.org/10.1016/j.ssci.2012.06.015>
- Passetti, E., Battaglia, M., & Frey, M. (2014). *Investing in safety in the environmental hygiene sector*. <https://books.google.com.br/books?hl=pt-BR&lr=&id=THL->

- CQAAQBAJ&oi=fnd&pg=PA5&dq=investing+in+safety+in+the+environmental+hygiene+sector&ots=rh4jBj6OJ2&sig=mdfmatQKMaf9qeywc6DJh1rhISI#v=onepage&q=investing in safety in the environmental hygiene sector&f=fa
- Poulsen, O. M., Breum, N. O., Ebbelhøj, N., Hansen, Å. M., Ivens, U. I., van Lelieveld, D., Malmros, P., Mathiasen, L., Nielsen, B. H., Nielsen, E. M., Schibye, B., Skov, T., Stenbaek, E. I., & Wilkins, C. K. (1995). Collection of domestic waste. Review of occupational health problems and their possible causes. *Science of the Total Environment*, 170(1–2), 1–19. [https://doi.org/10.1016/0048-9697\(95\)04524-5](https://doi.org/10.1016/0048-9697(95)04524-5)
- Prajapati, H., Kant, R., & Shankar, R. (2019). Bequeath life to death: State-of-art review on reverse logistics. *Journal of Cleaner Production*, 211, 503–520. <https://doi.org/10.1016/j.jclepro.2018.11.187>
- Rachiotis, G., Tsovili, E., Papagiannis, D., Markaki, A., & Hadjichristodoulou, C. (2016). Are municipal solid waste collectors at increased risk of Hepatitis A Virus infection? A Greek cross-sectional study. *Infezioni in Medicina*, 24(4), 299–303.
- 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>
- Salazar, M. K., Connon, C., Takaro, T. K., Beaudet, N., & Barnhart, S. (2001). An evaluation of factors affecting hazardous waste workers' use of respiratory protective equipment. *American Industrial Hygiene Association Journal*, 62(2), 236–245. <https://doi.org/10.1080/15298660108984627>
- Salminen, Simo ; Gyekye, Seth Ayim ; Ojajärvi, A. (2013). Individual and organizational factors of safe behaviour among Ghanaian industrial workers. *Engineering Management Research*, 98–110.
- Salve, P., Chokhandre, P., & Bansod, D. (2017). Assessing musculoskeletal disorders among municipal waste loaders of Mumbai, India. *International Journal of Occupational Medicine and Environmental Health*, 30(6), 875–886. <https://doi.org/10.13075/ijomeh.1896.01049>
- Sarkar, P. (2003). Solid Waste Management In Delhi-A Social Vulnerability Study. *International Conference on Environment and Health*, 451–464.
- Schibye, B., Søgaaard, K., Martinsen, D., & Klausen, K. (2001). Mechanical load on the low back and shoulders during pushing and pulling of two-wheeled waste containers compared with lifting and carrying of bags and bins. *Clinical Biomechanics*, 16(7), 549–559. [https://doi.org/10.1016/S0268-0033\(01\)00039-0](https://doi.org/10.1016/S0268-0033(01)00039-0)
- Schwandt, T. A. (1996). Qualitative data analysis: An expanded sourcebook. In *Evaluation and Program Planning* (Vol. 19, Issue 1). sage. [https://doi.org/10.1016/0149-7189\(96\)88232-2](https://doi.org/10.1016/0149-7189(96)88232-2)
- Shazwin, T., & Nakagoshi, N. (2010). Sustainable Waste Management through International Cooperation : Review of Comprehensive Waste Management Technique 2 Training Course. *Sustainable Waste Management through International Cooperation: Review of Comprehensive Waste Management Technique 2 Training Course*, 16(1), 23–33.
- Sri Lankan Minstry of Health. (2011). *Yearly report*.
- Srivastava, V., Ismail, S. A., Singh, P., & Singh, R. P. (2015). Urban solid waste management in the developing world with emphasis on India: challenges and opportunities. *Reviews in Environmental Science and Biotechnology*, 14(2), 317–337. <https://doi.org/10.1007/s11157-014-9352-4>
- Thakur, P., Ganguly, R., & Dhulia, A. (2018). Occupational Health Hazard Exposure among municipal solid waste workers in Himachal Pradesh, India. *Waste Management*, 78, 483–489. <https://doi.org/10.1016/j.wasman.2018.06.020>
- Thisakya, P. G., & Dissanayake, D. M. P. P. (2022). Occupational health and safety of municipal solid waste handlers in Sri Lanka. *15th International Research Conference - FARU 2022*, 238–247. <https://doi.org/10.31705/faru.2022.27>
- Thormar, S. B., Gersons, B. P. R., Juen, B., Djakababa, M. N., Karlsson, T., & Olff, M. (2013). Organizational factors and mental health in community volunteers. The role of exposure, preparation, training, tasks assigned, and support. *Anxiety, Stress and Coping*, 26(6), 624–642. <https://doi.org/10.1080/10615806.2012.743021>

- Tolera, S. T., Temesgen, S., Mulat Endalew, S., Alamirew, T. S., & Temesgen, L. M. (2023). Global systematic review of occupational health and safety outcomes among sanitation and hygiene workers. *Frontiers in Public Health*, 11, 1304977. <https://doi.org/10.3389/fpubh.2023.1304977>
- Tshivhase, S. E., Mashau, N. S., Ngobeni, T., & Ramathuba, D. U. (2022). Occupational health and safety hazards among solid waste handlers at a selected municipality South Africa. *Health SA Gesondheid*, 27, 1978. <https://doi.org/10.4102/hsag.v27i0.1978>
- Turan, N. G., Baki, O. G., & Ergun, O. N. (2016). Municipal solid waste characteristics and management in Sinop, Turkey. *Environmental Engineering and Management Journal*, 15(1), 13–18. <https://doi.org/10.30638/eemj.2016.002>
- Vaismoradi, M., Turunen, H., & Bondas, T. (2013). Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. *Nursing and Health Sciences*, 15(3), 398–405. <https://doi.org/10.1111/nhs.12048>
- Wilson, D. C., Velis, C., & Cheeseman, C. (2006). Role of informal sector recycling in waste management in developing countries. *Habitat International*, 30(4), 797–808. <https://doi.org/10.1016/j.habitatint.2005.09.005>
- Ziaei, M., Choobineh, A., Abdoli-Eramaki, M., & Ghaem, H. (2018). Individual, physical, and organizational risk factors for musculoskeletal disorders among municipality solid waste collectors in Shiraz, Iran. *Industrial Health*, 56(4), 308–319. <https://doi.org/10.2486/indhealth.2018-0011>
- Ziaei, M., Choobineh, A., Abdoli-Eramaki, M., Ghaem, H., & Jaber, O. (2019). Psychological and physical job demands, decision latitude, and work-related social support among Iranian waste collectors. *Waste Management*, 95, 377–387. <https://doi.org/10.1016/j.wasman.2019.06.031>

DIGITALISED FACILITIES ASSET MANAGEMENT: A CASE STUDY

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Abstract. Building assets constitute a substantial financial investment, often amounting to millions of dollars in business accounts. Effective management of these assets is essential, as their deterioration or failure can disrupt core facility operations and lead to significant repair and replacement costs. Digital tools have become integral to optimizing asset conditions, ensuring safety, and enhancing serviceability. In recent years, there has been a trend where condition assessment (CA) practices are relied on software applications to streamline their processes. This paper examines the impact of digitalizing CA processes, which is one of the core functions of asset management in buildings, through a computerized system using a real-world case study. The CA system was implemented in a university building as a demonstration case to assess the efficiency and cost-effectiveness of the digital process. The findings from this study aim to equip asset managers with the knowledge and confidence to transition to digital asset management systems, ultimately improving operational efficiency and overall asset performance

Keywords. Asset Management, Condition Assessment, Digital, Computerised Systems

1. Introduction

Building assets represent a significant financial investment, often valued at millions of dollars in the business accounts (International Infrastructure Management Manual (IIMM), 2021). These assets require substantial effort for maintenance, with annual maintenance costs accounting for approximately 50% of total expenditures (Ismail, 2019). The management of building assets is crucial, as their failure or deterioration can significantly disrupt the core functions of a facility and leading to increased repair and replacement costs. Besides, ensuring the long-term performance of assets is vital for sustainable operation. However, despite its critical importance, asset management (AM) regularly receives insufficient attention in many organizations.

AM is a complex and systematic process particularly when managing the built assets or buildings., AM involves planning, controlling, and optimizing asset-related activities to maintain operational efficiency and extend asset lifespan (Al-Kasasbeh et al., 2021). It is a systematic process of developing, operating, maintaining, upgrading, servicing, and disposing of assets cost-effectively (International Organisation for Standardisation (ISO),2014). Many strategies are being developed to optimise the AM process. The effective AM strategies are designed to achieve the required level of service while minimizing the cost of operation (IIMM, 2021). Besides, This process is fundamentally to oversee the assets throughout their entire lifecycle, rather during their initial phase or usage.

Nevertheless, AM encompass multidisciplinary activities within the lifecycle of the assets that is devised to optimise the performance of the asset/facility. Condition assessment (CA) of assets is one of the core functions of AM that focuses on securing the long lifespan of the assets and its performance (Moretti et al., 2021). Maintenance, financial and future planning are other functions that are integral part of this role.. In present, CA process is often implemented within organizations but is not actually incorporated with strategic-level decisions to achieve proactive benefits. Conventional AM approaches have been widely complained for their inefficiencies, particularly results in frequent defects, increased reactive maintenance and high maintenance costs (Ismail, 2019). Most CA activities are currently performed manually and have not been digitalized. Additionally, the absence of a centralized and real time database with whole lifecycle asset information poses a significant challenge, for asset related decisions such as maintenance, condition, and performance prediction (Al-Kasasbeh et al., 2021). The dependence on manual

and semi-automated approaches has constrained the efficiency of the process, highlighting the need for a shift toward digital or computerized solutions.

In recent years, AM in particular CA has been relied on digital applications to enhance its processes. CA are supported by various digital tools such as AM systems, Building Information Modelling (BIM), Digital Twins (DT), and Artificial Intelligence (AI) (Wijeratne et al., 2024). These tools play a crucial role in optimizing asset conditions, ensuring safety, and improving serviceability (Salem & Elwakil, 2023). By leveraging real-time data and digitalization, modern CA process provide more accurate and timely asset evaluations than traditional manual methods. Various digital platforms not only facilitate inform decisions and data storage but also integrated with maintenance and financial process thereby reducing the likelihood of unexpected failures, reducing associated costs and enhancing the efficiency (Re Cecconi et al., 2017). Despite the increasing availability of software solutions, there are limited studies on a standardized approach for implementing digital Asset Management System (AMS) to perform the CA of the assets within the building. Thereby, this paper aims to explores the impact of digitalizing CA processes through AMS. A digital CA system is introduced and implemented as a demonstration to an educational building. This enabled the evaluation of the impact of digital solutions compared to the manual approach. The study enhances the efficiency of CA methods and contributes to improved asset performance and sustainability. The paper is structured as follows: first, a literature review on the digitalization of AM practices is provided, followed by the research methodology. The findings are then analyzed and discussed, leading to the conclusion. The study's outcomes aim to empower asset managers with the confidence to digitalize their AM processes, enhancing efficiency and effectiveness.

2. Digitalised Asset Management Systems

2.1 ASSET MANAGEMENT

The AM is the systematic and coordinated practices of an organisation to aimed at optimally and sustainably achieving its objectives through the cost-effective management of assets throughout their lifecycle (IIMM, 2021). ISO 55001 is the designated standard for AM and has been published in three documents for overall assets in an entity. ISO defines AM *"as a systematic and coordinated activity through which an organization realizes value from its assets in delivering its objectives"* (ISO 2014). It emphasizes the importance of integrating AM into strategic planning to ensure efficiency, sustainability, and long-term performance of assets. IIMM (2021) highlighted key principles of AM as 1) providing a defined level of services that meets stakeholders needs, monitoring performance in relation to those level of services, 2) managing the impact of demand changes through demand management, infrastructure investment and other strategies 3) taking a lifecycle approach to developing cost-effective management strategies for the long term that meet that defined level of services 4) identifying, assessing and appropriately controlling risks and 5) a long term financial. In the building, AM is more complex due to the management of large number of complex and diversified assets and their component: element to the detail level.

The functions of AM encompass a range of activities aimed at enhancing asset performance, minimizing risks, and ensuring long-term value creation. Key functions include: (ISO 55000, 2014, Campbell et al. (2016), IIMM,2021,(Matos et al., 2022), (Salem & Elwakil, 2023)

1. Asset Lifecycle Management – Managing assets from acquisition to disposal, ensuring their optimal use throughout their lifecycle
2. Condition assessment: Assets were rated on a predefined scale to determine their current condition and predict their useful life

3. Maintenance and Reliability Management – Implementing preventive and predictive maintenance strategies to enhance asset longevity and reduce failures
4. Strategic Planning and Decision-Making – Aligning asset management with organizational objectives to support long-term value creation
5. Risk Management – Identifying, assessing, and mitigating risks associated with asset performance, reliability, and sustainability
6. Performance Monitoring and Optimization – Using real-time data, key performance indicators (KPIs), and predictive analytics to improve asset efficiency
7. Financial and Cost Management – Ensuring cost-effective investments, budgeting, and resource allocation for asset operations
8. Data and Information Management – Developing centralized and reliable databases to store historical as-built information for better decision-making

AM is an interdisciplinary field that has been developed to enhance and optimize the management of assets throughout their lifecycle. However, this study mainly focuses on the CA process. The CA process is typically physical inspection conducted to assess the current state of a building and estimate the extent of its deterioration (Faqih & Zayed, 2021). The assessment typically begins at the component level, where each element is rated using a predefined scale, and then an overall building condition value is derived (Lupășteanu et al., 2022). Visual inspection is the primary tool used in this process, although several other testing methods are employed to rank the condition of building elements. Finally, a report is generated that integrates the expected lifespan of each building element along with financial planning and other relevant considerations (Faqih & Zayed, 2021). In general, CA is conducted every 2 to 3 years and mostly a manual process. CA generates and requires vast amounts of data and relies on real-time information for informed decision-making on asset lifecycle (Al-Kasasbeh et al., 2021). Given the frequent handling of large datasets, it is important to use computerised methods to ensure efficiency, accuracy, and consistency in the assessment process. However, with technological advancements, many have transitioned to a digital approach.

2.2 DIGITALISED AM APPLICATIONS

Asset managers have transitioned from manual systems to computerized systems and, more recently, into a complete digitalized environment. Most AM functions now employed computerized systems, enhancing the operation. In catering to this demand, several commercialized software solutions have been introduced in the field to support AM functions. Here, the computerised systems related to both AM and FM functions are identified as both terms are generally used interchangeably. The most common digital and computerised platforms widely used in the practice are Computerized Asset Management systems (CAMS), Computerized Maintenance Management Systems (CMMS), Computerized Facilities Management (CFM) systems, and Computer-Aided Facilities Management (CAFM) systems. The CFM and CAFM are included as AM falls within the broader scope of FM.

CMMS was introduced in the 1960s and later reevaluated with many features. This is one of the key software applications that acts as a repository of information or data related to maintenance concepts, asset counts, spare parts, personnel information and planning methods (Mohd Noor et al., 2021). CMMS captures, stores, retrieves and transmits data and information related to maintenance procedures for equipment, plant and infrastructure (Amadi-Echendu & de Wit, 2015). CMMS helps in better management of the maintenance activities (Ismail, 2019). CMMS includes functions such as equipment data management, maintenance preventive/predictive, human resource, work order and complaint system, maintenance scheduling and planning,

inventory management, procurement, financials (Campbell et al., 2016; Mohd Noor et al., 2021). These applications help in optimising the AM activities and make informed decisions. Mainly CMMS support in reducing downtime and frequency of failures of the machines by improving the efficiency and effectiveness of the maintenance force (Ismail, 2019).

Similarly, computer-aided facilities management (CAFM) has emerged to improve the usability of the activities. CAFM systems gather and archive information on buildings facilities, creating a comprehensive database of asset information (Tuan Ibrahim & Mariah, 2022). CAFM offers functions such as reactive maintenance, planned preventative maintenance management, space and move management, resource scheduling (Wong et al., 2018). Wijeratne et al. (2024) highlighted that FM platforms including CAFM and CMMS, provides functions such as asset life cycle and maintenance management and provide greater efficiencies for asset maintenance and replacement scheduling, OPEX and CAPEX predictions via better data availability, Forming work order, Assimilating energy use with the building performance and Hazards management and disaster review. CMMS and CAFM software applications help in manage and record information of daily operations of an organization as in database. This helps in analyzing the current trend and predicting future aspects of the asset performances.

Salem and Elwakil (2023) prioritised that digital tools have been assisted in asset inspections, fund allocation and asset prioritization decisions. The authors noted that most of these systems are simple condition monitoring criteria based on the current condition of the assets. As Al-Kasasbeh et al. (2021), an accurate and well-developed building inventory serves as a powerful tool for asset condition monitoring, enabling proactive maintenance strategies and informed decision-making. By maintaining comprehensive and up-to-date asset records, organizations can enhance efficiency, extend asset lifespan, and optimize resource allocation. Computerized Asset Management (CAM) tools enable data-driven decision-making and, more importantly, provide a centralized database to organize all asset related information. This structured approach enhances decision making processes, improves asset performance tracking, and supports proactive maintenance strategies. Further, IIMM (2021) described AM information system as a computer-based tool which supports AM functions. The system enabled to store large quantities of asset data coupled with complex analysis and reporting functions. According the IIMM (2021), this provides functions such as asset register, performance management, financial management, maintenance management, strategic planning, risk management, capital investment planning and project management requirement. Similarly, CAM systems has assisted in many ways to perform the CA of the assets while these applications embedded with various features.

Building Information Modeling (BIM) has been widely proposed as a technology to support AM in various ways. Numerous studies have explored the integration of BIM with AM functions, demonstrating its potential to enhance asset performance by improving data accessibility, streamlining maintenance processes, and enabling more efficient decision-making throughout the asset lifecycle. Ismail (2019) proposed a model for integrating BIM technology for defect diagnosis, reduce maintenance requirement by identifying condition index and provide details in the best course required for maintenance and in the selection of materials and methods for the repair of IBS. Re Cecconi et al. (2017) proposed a BIM integration to leveraging space management, management of rooms occupancy, management of mechanical equipment status; qualitative condition assessment of buildings; and appraisal of the service life of building components. Al-Kasasbeh et al. (2021) proposed BIM based AM for strategic decision making including a wide range of functionalities, including the accurate acquisition, storage, processing, and reporting of asset information promptly. It has also increased operational efficiency by aiding in the planning, execution, and coordination of maintenance operations. BIM plays an important role, once it facilitate multi-disciplinary coordination, gather information and enable information accessibility, which can be used to support AM (Matos et al., 2022). Despite the BIM, industry 4.0 technologies such as internet of things (IoT), Digital Twin (DT), Augmented reality (AR),

Virtual reality (VR) and Artificial intelligence (AI) has been integrated into the AM applications creating more digital platforms for better AM functions.

However, in practice, most available tools are not delivering a holistic software solution covering all AM functions. Most tools are implemented for maintenance management of the facility. Ismail (2019) observed that many maintenance management systems place little emphasis on decision-making and asset defect diagnosis. It is also argued that the full functionality of CAMMS is not being utilized in practice. Majority of the CA software applications offers ratings options for building elements and the overall asset, facilitating data storages and a limited analysis that go beyond predicting service life and cost. Accordingly, many facilities implement these systems but fail to leverage their advanced capabilities, limiting their potential benefits in optimizing asset performance and decision-making (Campbell et al., 2016). Similarly, Wong et al. (2018) highlighted that while many FM software applications share similar asset and maintenance management functions, they often fail to address the full diversity of the requirements. Furthermore, the impact of technology implementation on the overall efficiency of the system has not been clearly identified. While various digital tools for CA functions have been introduced, there is limited research on how effectively these technologies contribute to optimizing workflows, improving decision-making, and enhancing overall asset performance. This gap highlights the need for further studies to assess the real-world benefits and challenges of integrating technology into asset and facilities management

3. Methodology

This study employs a case study approach to examine the implementation of a computerised digital Asset Management (AM) system in a university facility. Case study research is particularly useful for investigating real-world applications within their contextual settings, allowing for an in-depth analysis of CA challenges and the impact of digital solutions (Yin, 2018). A state university with a 25-acre physical footprint, six faculties, 35 departments, and nine centers was selected as the case institution. The university's facilities management team currently oversees CA process.

The CA is performed to a four-storey building in the university premises. The assessment specifically focuses on ten rooms located on the third and fourth floors of the building given its complexity. These rooms represent diverse functional areas, encompassing administrative spaces, teaching facilities, and communal areas. The selected rooms on the third floor include the Department Office (Room 1), AV Studio (Room 2), Graphic Design Studio (Room 3), Computer Lab 01 (Room 4), and the Corridor (Room 5). These spaces serve academic and operational purposes, making them suitable for assessing asset management efficiency across different functions. On the fourth floor, the Auditorium (Room 6), Staffroom 1 (Room 7), Staffroom 2 (Room 8), Common Classroom (Room 9), and Corridor (Room 10) were selected. These rooms accommodate both educational and administrative activities, making their condition and performance critical to the building's overall functionality.

3.1 DATA COLLECTION TECHNIQUE AND ANALYSIS

The primary data collection technique used in this study is visual inspection observation, a method widely employed in CA practices to assess infrastructure conditions and maintenance needs (Patton, 2015). Observations were conducted to evaluate the general condition of the building, with a focus on identifying critical defects that require immediate attention and developing predictive insights for long-term maintenance and budget planning. The implementation of the digital AM system followed a structured process to ensure systematic asset inspection, data entry, analysis, and reporting. The process began with introducing the system to the data collection team (five members), providing training on asset entry, inspection protocols, and report generation. A comprehensive asset inspection was conducted within

selected rooms on the third and fourth floors, assessing existing defects and maintenance needs. Asset details were then entered into the system, where each asset was assigned a unique identification (ID) for tracking. The team identify the severity and condition of each building components according to the set instructions. The instructions were defined in the computerised systems. A severity rating (1–3 scale) was used to categorize asset conditions, while a defect level rating (1–4 scale) was assigned based on expert assessments. Images of defects were captured and uploaded for documentation. Finally, the system generated detailed reports highlighting asset conditions, maintenance priorities, and recommendations for predictive maintenance and budget planning. This structured approach enhanced asset tracking, defect identification, and long-term efficiency of Assets. The collected data was analysed to generate detailed reports on the current asset conditions, maintenance requirements, and potential risk areas. Descriptive statistics and qualitative assessments were applied to interpret asset conditions, prioritise urgent repairs, and recommend strategies for sustainable asset management.

4. Data Analysis and Discussions

A digital platform was introduced for CA process that involves asset information recording, inspection, asset of condition, predicting budget, cost and maintenance within buildings on the university premises. This study focuses on the initial introduction of the digitalized system as a demonstration case on one of the buildings in university premises. Initially, the system was deployed solely to assess the condition of a limited set of building elements. While the system is designed to manage over 25 components/elements such as assets associated with electrical, finishes, superstructure, fire service etc. The implemented digital system is designed to optimize CA function in the built environment. This system offers a range of advanced capabilities, including asset inspection, condition assessment, and predictive analysis for estimating costs and determining the useful life of assets over time. Additionally, it facilitates efficient data storage, enabling the seamless organization and retrieval of historical records. A key feature of the system is real-time data capturing, which enhances decision-making by providing up-to-date and accurate information. These functionalities collectively improve asset management, ensuring sustainability and long-term operational efficiency.

4.1 CONDITION ASSESSMENT

As highlighted in the methodology section, a detailed and systematic approach was undertaken to assess the condition of building assets and their components, enabling informed decision-making. When asset details, including their condition, are input into the system, it generates multiple reports relevant to evaluating asset conditions and supporting decision-making processes. These reports include assessments of individual assets and the overall condition of the building, estimated replacement costs for asset elements based on the replacement need over a period, projected useful life of building components, and specific replacement and maintenance requirements.

Figure 1 visually represents the results of the condition assessment. As shown in Figure 1(a), the overall CA of ten rooms was shown. The findings indicated that most rooms are in condition categories 1 and 2, signifying a relatively good state. However, Rooms 5 and 10 were identified as being in critical condition, requiring immediate attention. To gain a more comprehensive understanding, it is vital to analyse the condition based on individual building components. Figure 1(b) provides a breakdown of the condition of different building elements, with an average condition rating assigned to each category. The results reveal that finishes, special features, and the superstructure exhibit varied condition types and defects, suggesting inconsistencies in maintenance and potential structural concerns. On average, air conditioning and electrical systems were rated at condition 2, indicating they are generally in fair condition but may require

periodic maintenance. However, the fire protection system was rated as condition 3, which is critical and necessitates urgent intervention to ensure safety and its operation. The inspections overall identified 39 defect types across 100 inspection points. Among these, 35% of the elements were found to be in excellent condition, 45% in good condition, 13% in average condition, and only 5% in poor condition. These findings highlighted that while most assets are well-maintained, certain critical areas require immediate attention to prevent further deterioration.

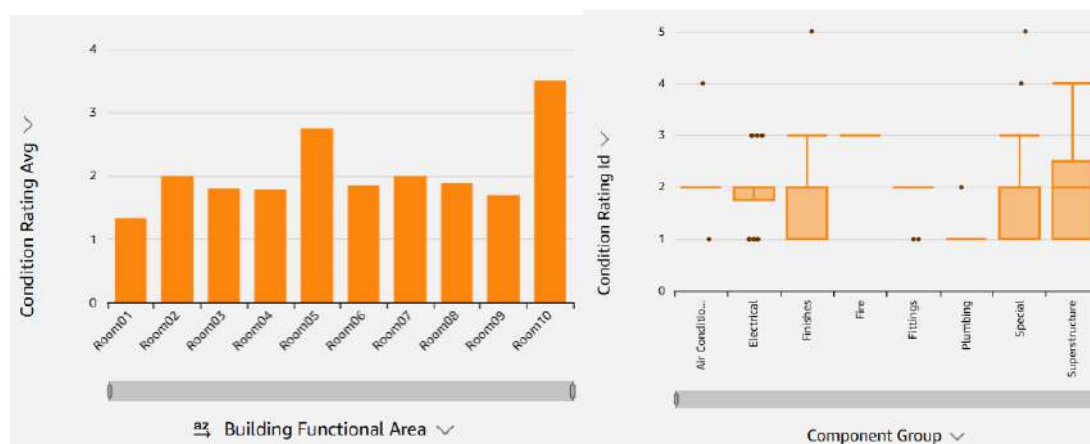


Figure 1 (a): Condition of the rooms

Figure 1 (b): Condition of the assets

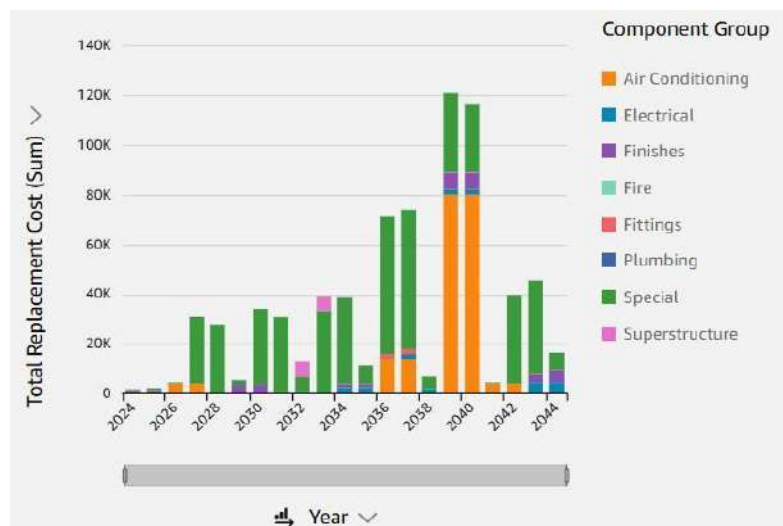


Figure 2: Replacement of the assets

The system also estimates the cost of replacing building elements over a 20-year period, providing valuable insights for long-term financial planning. Figure 2 illustrates the projected expenditures required for these elements over the next two decades. The analysis indicates that in the immediate future, financial resources should be allocated primarily to the "special category" elements such as, as they are expected to require significant investment in the next few years. However, by the year 2040, a substantial portion of the budget will need to be directed toward the replacement and maintenance of the air conditioning system, highlighting its

anticipated wear and lifecycle costs. This report plays a crucial role in asset management and budget planning, enabling decision-makers to proactively allocate funds and schedule maintenance. By understanding future financial demands, institutions can implement a strategic approach to resource distribution, ensuring the safety and functionality of critical building components while minimizing unexpected financial burdens.

4.2 MANUAL VS. DIGITALIZED ASSET MANAGEMENT PROCESS

This section aims to discuss the feasibility of transition to digitalised system. The process of manual and digital approach for CA can be documented with distinct workflows and operational efficiencies. The university is currently following the manual process which is illustrated in Figure 4. In this process, defect reporting, work order management, and asset updates rely on manual documentation and communication. In contrast, 5 depicts the digitalized approach, which leverages automation to streamline defect logging, work order assignment, and real-time updates. The below section outlines each process.

As seen in Figure 4, the manual process begins when a defect is identified and recorded on paper or a spreadsheet. The inspector then compiles defect records into a report, which is sent to the maintenance team for review. The maintenance team assesses the defect details, determines priority, and then raises a work order manually. Once approved, the work order is assigned to a contractor through email, phone, or printed documents. The contractor receives the work order, schedules the repair, and executes the task, updating the maintenance team as necessary. If additional materials, approvals, or clarifications are required, the contractor may need to communicate back and forth with the maintenance team, resulting in multiple interactions before work is finalized. Once the work is completed, the contractor submits a completion report manually, which the facility team verifies before updating the asset's condition in records. If any follow-up work is required, a new work order is generated, restarting the process.

As seen in Figure 5, the digital approach for CA begins when a defect is logged directly into a digital system via a mobile application. The system automatically compiles and stores the defect details, making them immediately available to the maintenance team. Upon review, the maintenance team raises a work order in the system, which is automatically assigned to a contractor based on predefined criteria. The contractor receives a real-time notification and can accept, schedule, and update work progress directly within the system. Any additional approvals, material requests, or clarifications are processed within digital platform, eliminating the need for separate communication channels. Work updates are logged in real-time, and once the repair is completed, the contractor submits a digital completion report, which the maintenance team reviews and verifies within the system. The system then automatically updates the asset condition in the records. If further work is required, a new work order can be generated within the same workflow.

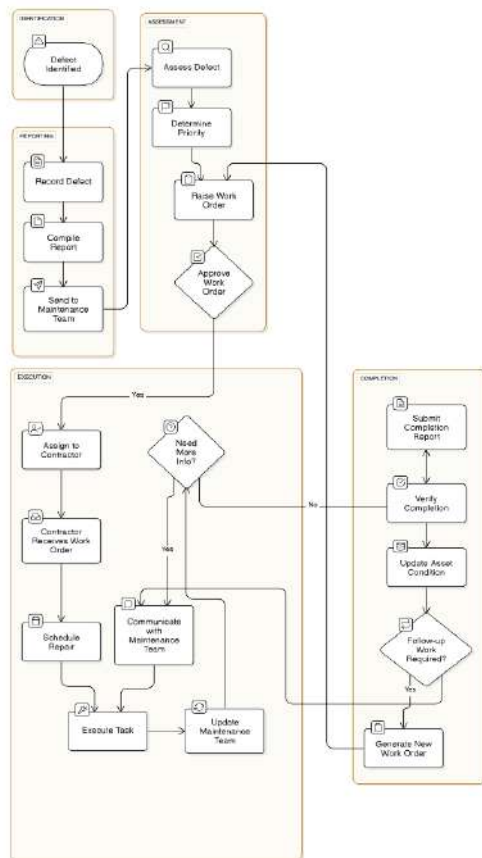


Figure 4: Manual process

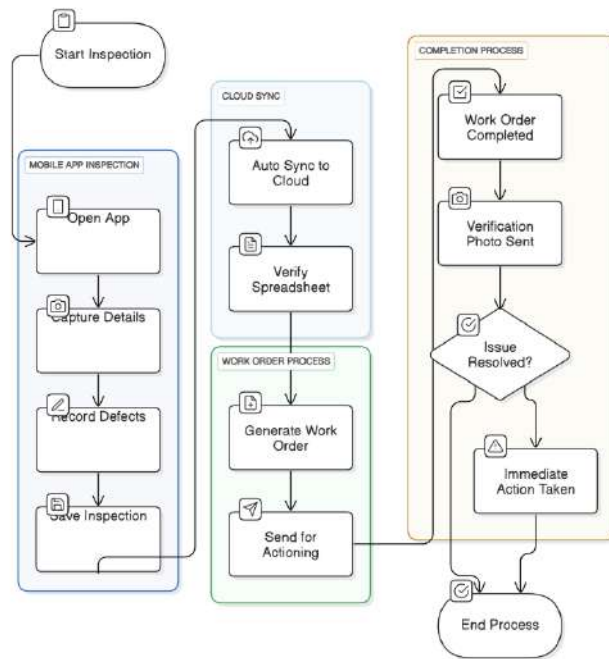


Figure 5: Digital process

4.3. DATA-DRIVEN COMPARATIVE ANALYSIS: MANUAL VS. DIGITALIZED ASSET MANAGEMENT

The comparative evaluation of manual and digitalized asset management systems is grounded in the ability to monitor asset performance and maintenance efficiency through quantifiable metrics. A key advantage of digitalized AM is its ability to collect, process, and analyse data systematically, enabling the identification of trends and performance deviations over time. Unlike manual record-keeping, which relies on static documentation and subjective assessments, digitalized systems facilitate real-time monitoring of asset conditions, defect occurrences, and maintenance interventions. The integration of automated tracking mechanisms ensures the continuous capture of asset degradation patterns, providing actionable insights into optimal maintenance scheduling and resource allocation.

To evaluate the practical advantages of digitalized CA compared to traditional manual methods, various metrics were employed to quantify its benefits. Key measurable factors employed in this study are defect identification rates, defect reporting times, resolution times and cost. Furthermore, non-quantifiable benefits were also recognized. The quantitative benefits were identified and estimated based on data availability. The observations in manual process and the average timestamps recorded in the digital system were also collected to quantify several metrics for both manual and digital process.

One of the key metrics analysed was defect reporting time and response time. Figure 6 presents a comparative analysis of the time required to document defects using manual and digital system. The defect reporting time includes the duration from site inspection to defect identification and formal documentation before initiating corrective action. The data from the

case study indicated that paper-based approaches require significantly more time compared to digitalized processes. On average, the manual reporting process takes approximately seven minutes per defect, whereas the digital system enables near-instantaneous recording and uploading of defect data. This improvement greatly enhances operational efficiency. Furthermore, the results reveal that digitalized tracking systems identified a significantly higher number of defects over the observation period, ensuring a more comprehensive approach to AM. Further, this ensures the standard record keeping of the data.

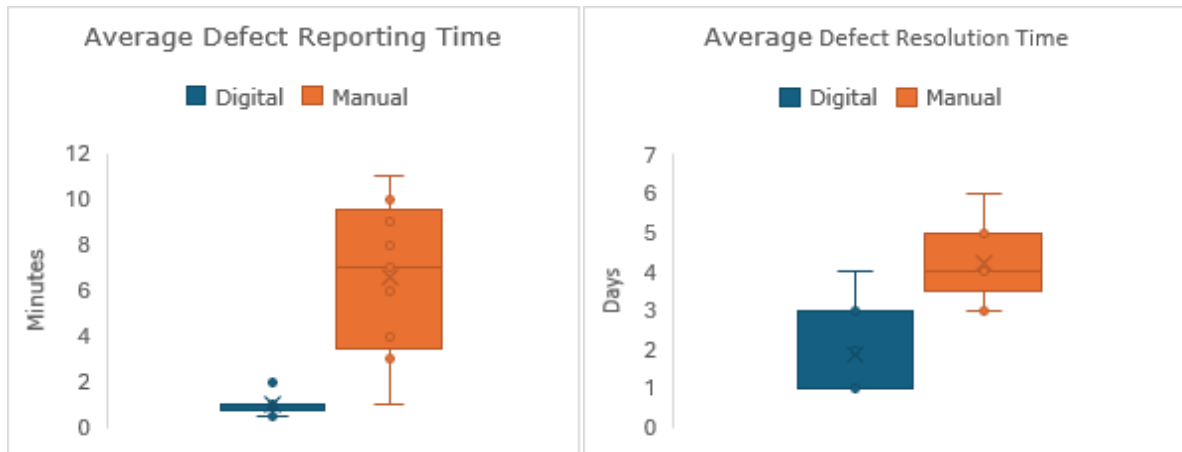


Figure 6: Average defect reporting time and defect resolution time

The maintenance efficiency was further evaluated by analyzing the time taken to address identified defects. Figure 5 illustrates the comparative response times for assets managed manually versus those tracked using digitalized systems. The findings indicated that digital AM systems significantly reduce the time required to resolve maintenance issues. This efficiency gain is largely attributed to the automation of defect logging, which eliminates delays associated with manual data entry, physical report submission, and maintenance task prioritization. The response times not only enhance the operational efficiency but also translate into cost savings by reducing labour hours. Additionally, the ability to identify defects more effectively allows for better maintenance planning, minimizing costs associated with reactive maintenance. The digitalized systems facilitate cost reductions by shifting from reactive to predictive maintenance strategies. The capability to analyse historical data and predict asset degradation trends enables proactive interventions, thereby reducing unplanned maintenance and extending the lifespan of critical assets. In contrast, manual CA relies heavily on reactive maintenance, often leading to higher costs due to emergency repairs and premature asset replacements—issues that could have been mitigated through early detection and planned maintenance strategies. By integrating digital AM, organizations can optimize maintenance operations, enhance defect identification accuracy, and implement cost-effective strategies that contribute to the long-term sustainability of building assets.

5. Discussion and Conclusions

AM information plays an important role in data-driven decision-making. Of them CA is a critical function that led safe and effective management of assets over its lifecycle. Timely storage and updating of asset information enhance decision-making processes, reducing downtime and failures while extending asset lifespan. Consequently, AM is closely linked with maintenance management, ensuring a safer and more efficient workplace. The comparative analysis of manual versus digitalized asset management has demonstrated significant differences in defect identification, maintenance response efficiency, and cost-effectiveness. By systematically monitoring asset conditions and tracking maintenance interventions, digitalized systems offer

quantifiable improvements over traditional manual record-keeping. The findings provide strong evidence for the benefits of transitioning toward a data-driven approach in asset management.

The study found that digitalized AM identified more defects compared to manual inspections over a six-month period. This discrepancy is primarily due to the structured and standardized nature of digital inspections, which ensure that assets are assessed systematically. In contrast, manual inspections were more prone to oversight, particularly for minor defects that could evolve into major failures if left unaddressed. The increased defect detection rate highlights the importance of automated monitoring in mitigating long-term maintenance risks. Maintenance response times also demonstrated a stark contrast between manual and digitalized asset tracking. On average, defects logged in the digitalized system were addressed within 48 hours, while those recorded manually required an average of 96 hours before intervention. The delay in manual processing can be attributed to the reliance on paper records and administrative bottlenecks, whereas digitalized systems facilitated instantaneous logging and automated prioritization of repairs. Faster response times have direct implications for asset longevity, as timely interventions prevent further deterioration and reduce the likelihood of unplanned downtime. From a financial perspective, cost analyses indicate that digitalized AM resulted in an average cost reduction over 6 months compared to manual methods. The ability to forecast asset degradation allowed for early intervention and preventative maintenance, reducing the occurrence of emergency repairs, which are typically more expensive and carries a higher risk to the organisation. In contrast, manual tracking led to a higher percentage of reactive maintenance expenditures, with 62% of total maintenance costs attributed to urgent repairs, compared to only 40% under the digitalized system. These findings suggest that predictive maintenance strategies facilitated by digitalized asset tracking improve financial planning and resource allocation.

While digitalized systems present clear advantages in terms of accuracy, efficiency, and cost control, it is important to acknowledge potential challenges associated with their implementation. Initial setup costs, staff training requirements, and simple reluctance to change existing processors may pose barriers to adoption. However, the long-term benefits of reduced maintenance costs and improved asset reliability outweigh these initial investments. Furthermore, digitalization enables the integration of emerging technologies such as machine learning for predictive analytics and Internet of Things (IoT) sensors for real-time monitoring, which could further enhance asset performance management. In summary, the results of this study indicate that transitioning from manual to digitalized asset management yields substantial benefits in defect identification, maintenance efficiency, and cost savings. While challenges exist, the long-term advantages make a compelling case for adopting digital solutions in facilities management. Future research should focus on refining predictive maintenance models and exploring the integration of automated asset condition monitoring to further enhance decision-making in asset lifecycle management.

5. References

- Al-Kasasbeh, M., Abudayyeh, O., & Liu, H. (2021). An integrated decision support system for building asset management based on BIM and Work Breakdown Structure. *Journal of Building Engineering*, 34, 101959. <https://doi.org/https://doi.org/10.1016/j.jobee.2020.101959>
- Amadi-Echendu, J. E., & de Wit, F. C. P. (2015). Technology adoption: A study on post-implementation perceptions and acceptance of computerised maintenance management systems. *Technology in Society*, 43, 209-218. <https://doi.org/https://doi.org/10.1016/j.techsoc.2015.09.001>
- Campbell, J. D., Jardine, A. K. S., & McGlynn, J. (2016). *Asset Management Excellence: Optimizing Equipment Life-Cycle Decisions*, Second Edition. CRC Press. <https://books.google.com.au/books?id=W96qu5XqM50C>
- Faqih, F., & Zayed, T. (2021). Defect-based building condition assessment. *Building and Environment*, 191, 107575. <https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107575>

- Ismail, Z.-A. (2019). An Integrated Computerised Maintenance Management System (I-CMMS) for IBS building maintenance. *International Journal of Building Pathology and Adaptation*, 37(3), 326-343. <https://doi.org/10.1108/IJBPA-10-2017-0049>
- International infrastructure management manual (IIMM) (2020) International infrastructure management manual.* (6th edition.). National Asset Management Steering NAMS Group.
- Lupășteanu, V., Lupășteanu, R., & Chingălată, C. (2022). Condition assessment of buildings in Romania: A proposed method and case study. *Journal of Building Engineering*, 47, 103814. <https://doi.org/https://doi.org/10.1016/j.jobee.2021.103814>
- Matos, R., Rodrigues, H., Costa, A., & Rodrigues, F. (2022). Building Condition Indicators Analysis for BIM-FM Integration. *Archives of Computational Methods in Engineering*, 29(6), 3919-3942. <https://doi.org/10.1007/s11831-022-09719-6>
- Mohd Noor, H., Mazlan, S. A., & Amrin, A. (2021). Computerized Maintenance Management System in IR4.0 Adaptation - A State of Implementation Review and Perspective. *IOP Conference Series: Materials Science and Engineering*, 1051(1), 012019. <https://doi.org/10.1088/1757-899X/1051/1/012019>
- Moretti, N., Ellul, C., Re Cecconi, F., Papapesios, N., & Dejacco, M. C. (2021). GeoBIM for built environment condition assessment supporting asset management decision making. *Automation in Construction*, 130, 103859. <https://doi.org/https://doi.org/10.1016/j.autcon.2021.103859>
- Re Cecconi, F., Maltese, S., & Dejacco, M. C. (2017). Leveraging BIM for digital built environment asset management. *Innovative Infrastructure Solutions*, 2(1), 14. <https://doi.org/10.1007/s41062-017-0061-z>
- Salem, D., & Elwakil, E. (2023). Asset condition assessment model for healthcare facilities. *International Journal of Construction Management*, 23(1), 182-203. <https://doi.org/10.1080/15623599.2020.1857002>
- Tuan Ibrahim, T. N. N., & Mariah, A. (2022). Assessing The Implementation of Computer Aided Facility Management (CAFM) In Malaysia Industry. *Progress in Engineering Application and Technology*, 3(2), 307-315. <https://publisher.uthm.edu.my/periodicals/index.php/peat/article/view/7891>
- Wijeratne, P. U., Gunarathna, C., Yang, R. J., Wu, P., Hampson, K., & Shemery, A. (2024). BIM enabler for facilities management: a review of 33 cases. *International Journal of Construction Management*, 24(3), 251-260. <https://doi.org/10.1080/15623599.2023.2222962>
- Wong, J. K. W., Ge, J., & He, S. X. (2018). Digitisation in facilities management: A literature review and future research directions. *Automation in Construction*, 92, 312-326. <https://doi.org/https://doi.org/10.1016/j.autcon.2018.04.006>

TECHNICAL PAPERS

ENHANCING SAFETY IN FACILITIES MANAGEMENT: A BID MANAGEMENT APPROACH

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Abstract. Safety in Facilities Management (FM) is a fundamental pillar that ensures the well-being of occupants and protects assets while maintaining operational efficiency. In the bid management process, embedding safety into FM contracts not only strengthens compliance but also adds value by fostering a safety-first culture. Bid management plays a crucial role in ensuring that safety is prioritized from the outset of FM contracts. This paper examines how to integrate safety requirements into bid proposals and offers best practices for ensuring safety in the FM bidding process. The findings of this study highlight the importance of integrating safety early in the FM bidding process to ensure regulatory compliance and enhance the reputation of FM service providers (FMSPs). By prioritizing safety at every stage of the bidding process, FMSPs can boost competitiveness, mitigate risks, and foster safer environments.

Keywords. Facilities Management, Safety, Bid Management, UAE

1. Introduction

Safety is a critical priority in facilities such as industrial plants, healthcare institutions, and large commercial properties, where even minor lapses can have significant consequences. Facilities Management (FM) encompasses a broad spectrum of activities that directly impact both occupants and building assets, making safety a fundamental pillar of effective FM operations (Pilbeam, 2024; Wetzel & Thabet, 2016). A comprehensive FM safety strategy not only minimizes workplace incidents, but also ensures regulatory compliance, enhances operational efficiency, and fosters a culture of safety and well-being within the built (Gustin, 2020 & Hinks & Puybaraud, 1999). Safety is an essential factor, requiring adherence to local regulations, as well as international standards, which set the framework for workplace safety and risk mitigation (Gallant, 2007; Wang et al., 2022).

Prioritizing safety in bid management ensures proper resource allocation for safety programs, personal protective equipment (PPE), and workforce training, leading to a safer FM contract. Furthermore, a strong commitment to safety contributes to higher workforce retention, as employees are more likely to remain with an organization that prioritizes their well-being. Safety is a competitive advantage in FM bids, as clients prefer FM Service Providers (FMSPs) with strong HSE records and certifications, showcasing professionalism and reliability (Dahanayake & Sumanarathna, 2022; Talamo & Atta, 2019).

Safety is recognized as a fundamental requirement of FM, particularly in ensuring occupant well-being and asset protection. Existing literature largely focuses on post-contract safety measures, with limited attention given to how safety is embedded at the pre-contractual stage—specifically during the formulation and evaluation of FM bids. A key area that is underexplored is the integration of safety during the bid management, which is crucial for defining operational standards and risk mitigation strategies in FM contracts (Dahanayake & Sumanarathna, 2022; Mawed, 2024). This study aims to address this research gap by exploring the potential for integrating safety into the bid management process. Bridging this gap is key to promoting safety-oriented bidding that boosts competitiveness and fosters a safety-first FM culture. This paper examines how safety is integrated into FM bidding, highlights the challenges into bids, and suggests best practices to incorporate safety in FM bids.

2. Methodology

The methodology is based on the authors' viewpoint derived from their industry experience in managing FM bids. This paper is in alignment with the methodological precedent set by Edwards and Holt (2010) and Sumanarathna et al. (2024), who employed expert-based authorial viewpoints to examine under-researched domains. While existing literature addresses FM safety standards and operational safety practices, the specific integration of safety considerations into the bid management process remains underexplored. The authors offer over 10 years of experience in FM and bid management, providing a practice-informed methodological approach in an under-researched area. Authors offer a localized perspective on the challenges and strategies for integrating safety into bid proposals, which are essential for successful contract execution. While this study adopts a practice-informed approach, the authors engaged in a systematic reflection process, drawing on multiple bid case examples across different FM contexts to ensure consistency and reduce anecdotal bias. Relevant academic literature is incorporated throughout the paper to contextualize, support, and critically reflect upon the authors' perspectives. The study is positioned as a preliminary investigation with the intention of conducting future research on incorporating safety within FM bid strategies.

3. Embedding Safety into Bid Management

In the UAE, safety in FM is not just a regulatory requirement but a vital component of project success. The FM sector plays a key role in upholding these safety standards. Embedding safety into the bidding process is essential to ensuring compliance with UAE laws and international best practices including UAE Ministry of Labour and Social Affairs, Occupational Safety and Health Abu Dhabi (OSHAD) regulations, and ISO 45001:2018, the global standard for occupational health and safety management. Non-compliance can result in significant penalties and damage to an FMSPs' reputation, making the incorporation of safety into the bidding process a non-negotiable aspect of FM contract management.

3.1 THE ROLE OF SAFETY IN THE FM BIDDING PROCESS

This section summarizes the role of safety in each stage of the bidding process.

3.1.1 Pre-qualification stage

In the UAE, the safety in FM bids is evident from the pre-qualification stage, where safety is often a primary evaluation criterion for clients. In many cases, it is mandatory for FM bidders to demonstrate of a robust safety management system that complies with local regulations, industry standards, and international frameworks—such as ISO 45001:2018 and OSHAD. Furthermore, clients frequently require FM bidders to have a proven track record of safety compliance, with no history of safety-related non-compliances or incidents. A strong safety record and compliance with industry standards are critical factors for advancing beyond this stage. Potential bidders are required to confirm the availability of relevant insurance coverage—such as Public Liability, Workers' Compensation and Employer's Liability—during this stage to manage potential liabilities related to accidents or injuries that could arise during the contract execution.

3.1.2 Bidding stage

The bidding stage is an opportunity to set the tone for the safety culture within the facility. Bidders who prioritize safety in their proposals communicate their commitment to a safe work environment which can enhance their reputation and help build trust with the client. One of the most pressing reasons for emphasizing safety during the FM bidding stage is the potential for accidents, injuries, and hazards that may arise during the operation and maintenance of a facility. Proper safety protocols and planning during the bidding process help mitigate these risks,

reducing the likelihood of costly incidents. FMSPs should conduct thorough assessments of potential safety hazards specific to the facility in bid. Moreover, failure to adhere safety requirements—such as occupational safety laws, fire safety codes, building codes—during the bidding process can lead to non-compliance, resulting in fines, penalties, or even the revocation of operating licenses. Additionally, the bidders are typically required to submit detailed safety management plans, procedures, policies, and processes as part of the bids—such as. emergency procedures, risk assessments, employee training, and equipment safety standards— to ensure safety on the job site. Bidders are typically required to submit proof of relevant insurances as part of their bid.

3.1.3 Bid evaluation stage

In the evaluation stage of FM proposal, safety is a key factor that cannot be overlooked. By evaluating FMSPs' proposed safety plans, past performance, and overall safety culture, the clients make informed decisions that prioritize both worker well-being and facility operational stability. The commitment towards safety significantly enhances bidder's competitiveness, credibility and the overall win probability. Ultimately, the importance of safety in FM bid evaluation lies in its ability to secure the contract award while reducing long-term risks, ensure compliance, and create a safer, more efficient environment for all.

3.2. INTEGRATING SAFETY INTO BID PROPOSALS

The first step is to understand and incorporate safety requirements from the RFP, Law, industry standards, and ethical responsibilities. The RFP outlines client's safety, risk mitigation, and compliance expectations. Moreover, ensuring compliance with all relevant legal and regulatory standards—depending on the type of facility, its location, and the specific services being provided—is crucial in bid proposals. FMSPs should also incorporate industry best practices, even if not legally binding, to enhance credibility and safety. Ethical responsibility is equally important, ensuring a safe environment for workers, the public, and client assets beyond mere compliance. Safety is a fundamental responsibility that cannot be compromised.



Figure 1: Integrating Safety into Bid Proposals

A thorough understanding of the facility's unique risks is also crucial. FMSPs should conduct site visits and closely review the scope of work (SOW) along with Service Level Agreements (SLAs)/Key Performance Indicators (KPIs). A detailed understanding of specific safety hazards enables FM bidders to propose targeted safety measures that will reduce hazards throughout the contract period.

The FM bid proposal should also consider a well-staffed, well-supervised team for creating a safety-conscious working environment. This includes ensuring that there are qualified staff who can safely perform the tasks, enough personnel to cover the specific needs of the facility and

the supervision to ensure that tasks are being completed safely and that workers are adhering to safety protocols. In addition, dedicated safety personnel may be required to ensure safety protocols across all tasks in compliance with regulatory safety standards, especially in larger or more complex facilities. In some cases, support from a FMSP's centralized safety team would be sufficient.

Safety is also about having the right tools and equipment for the job—for example, electrical work demands insulated tools and circuit testers, while high-level cleaning and hard-to-reach tasks require suitable scaffolding, ladders, and fall protection systems. The bid should not only estimate the tools and machinery required, but also account for how they will be maintained and tested to ensure they are safe to use. Bidders should also ensure that workers are equipped with appropriate PPE. The bid should account for these factors, also considering seasonal requirements and replenishments. No matter how well-equipped or well-staffed the project is, a safety plan will only be as effective as the training provided to personnel. Ensuring that safety trainings—such as IOSH (Institution of Occupational Safety and Health)/NEBOSH (National Examination Board in Occupational Safety and Health) for key personnel, fire warden training, task-specific training, and health and safety inductions—is included in the cost calculation avoids unexpected costs and allows transparency to the investment required to maintain a safe facility.

Technology-driven innovations are essential enabler of safety in FM in the UAE. Advanced solutions help mitigate risks, ensure compliance, and create safer environments. During bidding, integrating relevant key technologies—such as real-time monitoring, and smart safety devices—enhances protocols and reduces incidents. FMSPs should incorporate these innovations to strengthen safety and differentiate their bids.

Other key safety considerations such as site-specific safety plans, risk mitigation, monitoring, reporting, auditing, continuous improvement, staff well-being, FMSP safety culture, subcontractor safety management should also be integrated into the bid proposal.

4. Integrating Safety in FM Bids: Challenges and Best Practices

The key challenges in integrating safety into FM bids, and corresponding mitigation strategies, are presented in Table 1. These are drawn from the authors' extensive professional experience, developed over a decade of reviewing RFPs and preparing bid proposals across diverse sectors in the UAE FM market.

Table 1: Challenges and Best Practices

No	Challenge	Mitigation Strategies/Best Practices
1	<i>Budget Constraints: Balancing safety investment vs. competitive pricing</i>	
1.1	Integrating safety, particularly in complex FM bids, requires significant financial investment for resources, training, compliance and ongoing safety management. In competitive bidding, FMSPs may feel pressured to lower costs, potentially compromising safety by cutting corners on experienced staff, staff training etc. Some bidders may exclude safety-related costs to seem more competitive, but encounter safety risks, reputational damage, and financial fallouts in the long run.	FMSPs should educate clients on the long-term benefits of prioritizing safety over short-term cost savings by highlighting the potential financial and reputational risks of accidents to justify the initial investment in safety measures. Safety should be positioned as a key differentiator in the bid proposal, which can enhance client trust, strengthen reputation, and improve win probability.
1.2	The rapid advancement of safety technologies—such as IoT sensors, drones, robots—can provide significant advantages in managing safety risks. While these technologies can improve safety monitoring, incident reporting, and predictive maintenance, the initial implementation costs can be	Including a detailed breakdown of technological costs within the bid proposal, along with anticipated savings from improved safety and risk mitigation, can help justify the expenditure.

	high. FMSPs may find it challenging to integrate these within their bids, especially if clients are not yet familiar with or do not value innovations.	Including successful case studies can help build trust with clients and prove the return on investment in safety innovation.
2	<i>Absence of a comprehensive risk analysis</i>	
2.1	A lack of thorough risk evaluation in FM bids due to the below can lead to underestimating or overlooking potential risks, which, in turn, can impact the project's safety, financial stability, and long-term success. • Inadequate Risk Analysis – Operational, financial, compliance, environmental, market/external risks may be overlooked or insufficiently assessed. • Limited Data Access – Lack of critical data can hinder a thorough risk assessment. • Unrealistic Bid Timelines – Tight deadlines may force bidders to prioritize speed over comprehensive risk evaluation.	Adopt a structured risk management approach during the bid stage through; • Site Visits & Safety Audits to collect critical data. • Engage SMEs – Consult safety and operations experts. • Collaborate with Clients – Foster transparent and timely data sharing. • Leverage Past Data to identify and mitigate common risks. • Advocate Realistic Timelines to allow a thorough risk analysis. • Extend risk evaluation to subcontractors. • Early Client Engagement to discuss risks upfront to tailor the risk mitigation strategy. • Submit a detailed risk register and a contingency plan.
3	<i>Lack of Specific Safety Metrics in RFPs</i>	
3.1	Some RFPs lack well-defined safety SLAs/KPIs, resulting in varied interpretations by bidders and inconsistent safety standards across proposals. This inconsistency makes it difficult for clients to compare safety performance and select the most qualified FMSPs.	• Define safety metrics in RFP – Include measurable KPIs, compliance requirements, and mandatory training expectations. If the RFP lacks safety SLAs/KPIs, bidders should propose their own safety metrics. • Bidders should showcase safety systems, past performance, and strategies to exceed standards.

5. Conclusions and Implications

This study underscores the importance of integrating safety requirements early in the FM bidding process, as it not only ensures regulatory compliance but also enhances the reputation of FMSPs for delivering secure, high-quality services. By prioritizing safety at every stage, from pre-qualification to bid evaluation, FMSPs can boost competitiveness, reduce risks, and contribute to safer and efficient built environments. Addressing challenges like balancing safety with cost, limited risk analysis, and unclear safety metrics can be achieved by raising awareness of the long-term benefits of safety, adopting structured risk management, and advocating for clear safety metrics. This approach leads to long-term sustainable safety standards for both clients and FMSPs.

This study carries several practical and theoretical implications for the FM sector, particularly in the context of bid management as follows.

- *For FMSPs:* Actionable insights into how safety requirements can be systematically integrated into bid proposals.

- *For Clients:* Valuable insights to enhance procurement specifications, ensuring that safety is considered from the FMSP selection through to service delivery.
- *For the Academic and Research Community:* Needs for future studies to validate and expand upon the findings through structured methodologies.

6. Limitations and Future Work

While this study offers practical insights derived from industry experience, its reliance on expert opinion introduces potential subjectivity. The inherent subjectivity associated with expert-based methodologies is acknowledged. Empirical validation through structured case studies in real-world FM contracts is required to assess the applicability and effectiveness of the findings across diverse organizational settings. The findings of this study are indicative and preliminary; therefore, future studies employing empirical methods—such as surveys, interviews, and case study comparisons—will be conducted to validate these initial insights.

5. References

- Dahanayake, K.C. and Sumanarathna, N. (2022), "IoT-BIM-based digital transformation in facilities management: a conceptual model", *Journal of Facilities Management*, Vol. 20 No. 3, pp. 437-451. <https://doi.org/10.1108/JFM-10-2020-0076>
- Edwards, D.J. and Holt, G.D. (2010), "The case for "3D triangulation" when applied to construction management research", *Construction Innovation*, Vol. 10 No. 1, pp. 25-41. <https://doi.org/10.1108/14714171011018292>
- Gallant, B. J. (2007). *The Facility Manager's Guide to Environmental Health and Safety*. Government Institutes.
- Gustin, J. F. (2020). *Safety management: A guide for facility managers*. River Publishers.
- Hinks, J., & Puybaraud, M. C. (1999). Facilities management and fire safety during alterations, changes-in-use, and the maintenance of building facilities—a management model for debate. *Facilities*, 17(9/10), 377-391.
- Mawed, M. (2024), "Insight into facilities management market in the UAE: trends, drivers, and threats", *Smart and Sustainable Built Environment*, Vol. ahead-of-print No. ahead-of-print. <https://doi.org/10.1108/SASBE-08-2023-0218>
- Pilbeam, C. (2024). Practices and challenges of safety management in outsourced facilities management. *Journal of Safety Research*, 90, 144-162.
- Sumanarathna, N., Dahanayake, K.C. and Adhikari, A., (2024), "Big data analytics in facilities management higher education: a way forward", in Kyrö, R., and Jylhä, T. (Ed.s.), *EuroFM conference 2024*, 10-12 June 2024, London Metropolitan University, pp. 66-76. <https://doi.org/10.5281/zenodo.11658176>.
- Talamo, C., & Atta, N. (2019). Tendering process and facility management agreements: the role of invitation to tender. *Invitations to Tender for Facility Management Services: Process Mapping, Service Specifications and Innovative Scenarios*, 1-32.
- Wang, K. C., Almassy, R., Wei, H. H., & Shohet, I. M. (2022). Integrated building maintenance and safety framework: educational and public facilities case study. *Buildings*, 12(6), 770.
- Wetzel, E. M., & Thabet, W. Y. (2016). Utilizing Six Sigma to develop standard attributes for a Safety for Facilities Management (SFFM) framework. *Safety science*, 89, 355-368.

A STUDY OF HUMAN ERROR FACTORS ON TRANSPORTATION ACCIDENTS IN CONTAINER TERMINALS IN SRI LANKA

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Abstract. Transportation accidents at container terminals often result from human error, a complex and multifaceted issue with significant implications for safety, productivity, and economic efficiency. This study investigates the human error factors influencing transportation-related incidents in Sri Lankan container terminals. Using a mixed-methods case study approach that combines documentation analysis with expert interviews, the study identifies key error-inducing conditions and underlying causes. Findings highlight a lack of training, communication breakdowns, poor supervision, and infrastructural inadequacies as primary contributors to accidents. Recommendations are made for improving training protocols, communication channels, and safety oversight. This research provides insights for policymakers and terminal operators to develop targeted interventions to mitigate human error and enhance operational safety.

Keywords. Human Error, Transportation Accidents, Container Terminals, Sri Lanka, Risk Factors

1. Introduction

Container terminals play a critical role in global logistics and trade, with operational safety being a key concern due to the high-risk nature of terminal activities. Human error is widely acknowledged as a major contributing factor to transportation accidents in these environments. While international studies have examined human error in port operations, there is limited research focusing on the Sri Lankan context, where unique infrastructural, regulatory, and operational challenges exist.

In Sri Lanka, the rapid growth of port activities has intensified safety concerns, particularly at busy container terminals such as Colombo Port. However, despite rising accident rates, there has been a lack of systematic investigation into the human factors contributing to these incidents. This study aims to fill that gap by examining the specific conditions and behaviors that lead to human error in Sri Lanka's container terminals.

1.1 RESEARCH QUESTIONS:

1. What are the primary human error factors contributing to transportation accidents in Sri Lankan container terminals?
2. How can these factors be mitigated through policy and operational interventions?

The study contributes to the literature by contextualizing human error within the Sri Lankan terminal environment and offering actionable recommendations for enhancing safety management practices. Prior studies on human error in transportation and logistics emphasize organizational, psychological, and environmental factors. (WEBER, 1983), for example, illustrates how latent failures and active errors interact to produce accidents. In port operations, factors such as inadequate training, miscommunication, fatigue, and poor supervision have been linked to accidents (Hetherington et al., 2006). However, few studies specifically address these issues in South Asian or Sri Lankan ports. A regional analysis by Perera and Fernando (2018) highlighted infrastructural constraints and limited safety oversight as key challenges in South Asia. This study extends that work by focusing specifically on container terminals in Sri Lanka, using a mixed-methods approach to examine human error in detail.

2. Methods Employed

A single case study method was chosen, following (Noor, 2008), who argues that investigations should be guided by replication rather than sampling rationale. Among the three operational terminals at the Port of Colombo, one container terminal was selected based on accessibility, efficient data collection, and its high handling capacity of 2 million TEUs annually. The unit of analysis in this study focuses on work-related transportation accidents, particularly those related to health and safety. A survey strategy was used to collect data on worker behaviors, perceptions, and experiences (Gomm, 2008). The study conducted semi-structured interviews with key personnel, including the Health, Safety, and Environment Manager, Operations Manager, and Safety Officer, chosen for their industry expertise.

Data collection included both primary and secondary sources. Secondary data was gathered from literature reviews and the Accident Investigation Report (AIR) database at the selected terminal. Primary data was collected through expert interviews, using open-ended and standardized questions to support the findings from quantitative analysis.

2.1 PRIMARY DATA FINDINGS

Transportation accidents in container terminals are largely influenced by human errors, inadequate safety measures, and insufficient training programs. One of the most frequent mistakes made by drivers is misjudging the turning radius of their vehicles, which often results in collisions with obstacles, containers, and terminal infrastructure such as crane ladders, curbs, and signboards. This issue is particularly common among drivers operating prime movers, which require wider turns. Many drivers fail to anticipate this, leading to either excessively sharp or overly wide turns that increase the risk of accidents. The primary causes of these errors include a lack of understanding of vehicle dimensions and improper steering techniques, highlighting gaps in practical training and experience.

Despite having safety protocols and training programs in place, the current measures appear to be theoretically driven rather than hands-on. The organisation conducts safety inductions, leaflet campaigns for external drivers, and defensive driving training. However, while these initiatives help in raising awareness, they do not fully prepare drivers for real-life emergency situations. Theoretical knowledge is necessary but insufficient when practical skills and on-the-job training are not emphasized. Another significant issue is that safety training programs do not evolve with operational changes. Equipment, vehicles, and traffic conditions change over time, yet training materials are not frequently updated to reflect these changes. This lack of periodic training refreshers results in drivers using outdated techniques that may no longer be effective in preventing accidents. Additionally, existing safety measures focus heavily on routine checks and hazard identification rather than on accident prevention strategies. This reactive approach means that while hazards are identified, proactive interventions to mitigate risks are often delayed or overlooked.

A specific accident case highlights the consequences of human error and the importance of strict safety enforcement. In one incident, an internal truck collided with another internal truck at 9:15 a.m. due to unsafe manoeuvring. The driver lost control of the vehicle, resulting in a serious accident where one driver lost two teeth due to the impact. Notably, neither driver was wearing a seatbelt, which could have mitigated the severity of the injuries. This accident prompted the organisation to strictly enforce seatbelt usage and introduce a colour-coded system that allows safety personnel to easily identify drivers who are not wearing seatbelts. Additionally, as an engineering control, the speed limit for all vehicles was reduced to 25 km/h, aiming to minimise the impact of collisions and improve overall traffic safety within the terminal.

Data analysis reveals clear patterns in accident occurrences across different vehicle types, time periods, and terminal locations. Internal trucks have consistently recorded the highest number of accidents, with a notable spike in 2023. The increase in inter-terminal truck incidents over the years also indicates a rising safety concern. Cab-related incidents peaked in 2022, marking the highest level in the last five years. These findings suggest that drivers operating internal and inter-terminal trucks require additional safety training and supervision to reduce accident risks. Accident timing analysis indicates that incidents are most frequent during the busy morning hours, with an unusual spike in early morning and midday in 2022. This suggests that fatigue, high traffic density, and environmental factors contribute to accident risks. Additionally, location-wise data shows that most accidents occur at the Wharf and Back Reach, with higher accident rates near the Gate House. This suggests that traffic congestion, poor visibility, and infrastructure design may be contributing to accident-prone zones within the terminal.

To address these challenges, several safety enhancements and interventions must be implemented. First, hands-on training should be prioritised to ensure drivers gain practical experience in manoeuvring their vehicles safely. The introduction of simulated accident scenarios would help drivers develop better emergency response skills. Second, stricter compliance with seatbelt usage must be enforced through regular monitoring of the newly introduced colour-coded system. Third, traffic management strategies need improvement, including better signage, improved lighting, and controlled traffic flow at accident-prone areas such as the Wharf, Back Reach, and Gate House. Additionally, fatigue management programs should be introduced to address accident spikes during early morning and midday by adjusting work schedules and enforcing rest breaks for drivers. Finally, safety training updates must be conducted periodically to ensure drivers are well-equipped with the latest safety knowledge and best practices.

Lastly, the findings indicate that human error, insufficient practical training, and weak enforcement of safety measures are major contributors to transportation accidents in container terminals. The lack of awareness about vehicle dimensions, improper turning techniques, and inadequate safety training significantly increase the risk of accidents. Accidents are most common during peak hours and at high-traffic locations, such as the Wharf and Back Reach, highlighting the need for enhanced visibility, better traffic management, and stricter enforcement of safety protocols. Addressing these issues through proactive training, improved accident prevention strategies, and stronger compliance measures is crucial for reducing accident rates and improving overall safety standards in container terminal operations.

2.2 SECONDARY DATA FINDINGS

Findings from secondary data reveal Equipment Wise Accidents as shown in Figure 1. The data indicates that Internal Trucks consistently account for the highest number of accidents across all years, with a noticeable increase in 2021, 2022, and 2023. This suggests that internal truck operations pose a significant safety risk and require targeted interventions. Additionally, Cab-related accidents peaked in 2022, marking the highest level in five years, before slightly declining in 2023. The sharp rise in Own Inter-Terminal Truck incidents in 2023 is a major concern, highlighting the need for enhanced safety protocols and stricter enforcement measures in inter-terminal operations.

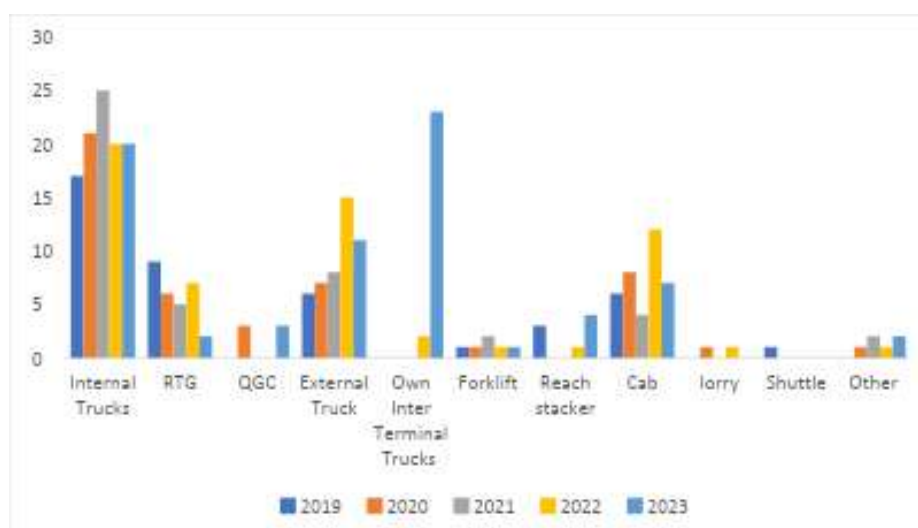


Figure 1: Equipment-Wise Accidents

The analysis also shows that External Trucks have experienced a steady increase in accidents, indicating growing operational risks that need better monitoring and training interventions. On the other hand, accident rates for RTG (Rubber-Tyred Gantry Cranes) (Ding et al., 2021) indicates that Forklifts, and Reach Stackers remain relatively low, suggesting that existing safety measures for these equipment types may be more effective. Equipment categories such as Lorry, Shuttle, and QGC (Quay Gantry Crane) (Premathilaka, 2018) have consistently recorded minimal accidents, indicating lower operational risk.

These findings highlight critical safety challenges within the terminal, particularly for Internal Trucks, Inter-Terminal Trucks, and Cab operations. Addressing these issues through enhanced training, stricter traffic management, improved speed control, and better compliance with safety regulations will be essential in reducing accident rates and improving overall transportation safety in the terminal.

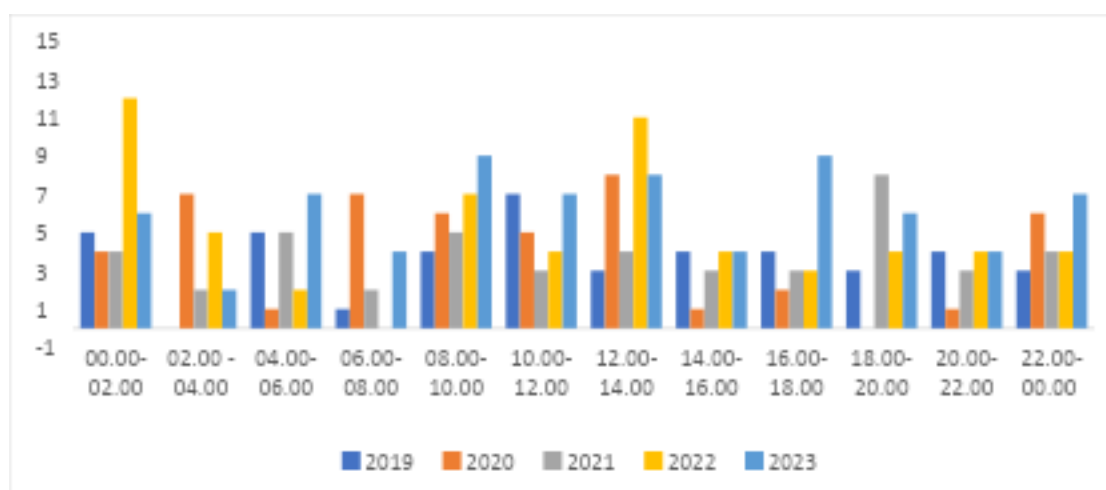


Figure 2: Accident times

Figure 2 illustrates the distribution of accident occurrences over time from 2019 to 2023, identifying peak accident hours and key contributing factors such as traffic density, fatigue, and environmental conditions. The data highlights a notable spike in accidents between 12:00 – 02:00 AM in 2022, likely due to driver fatigue and reduced alertness during night shifts. Another peak between 12:00 – 14:00 in 2022 may be attributed to post-lunch fatigue or increased

operational activity. Across all years, the highest accident frequencies occur between 10:00 AM – 14:00 PM, suggesting that high traffic density, workload pressure, and operational intensity contribute to accident risks. While accident rates decline after 16:00, a spike between 18:00 – 20:00 in 2021 suggests visibility challenges or shift transitions as potential factors.

The accident pattern in 2022 shows extreme variations, whereas 2023 records a generally higher accident count, indicating increased traffic density or systemic safety issues. Years 2019–2021 display a more even distribution with fewer peaks. To mitigate these risks, fatigue management programs, optimized traffic flow, improved visibility with better lighting and signage, and strict speed enforcement are crucial. Better scheduling, enhanced training, and compliance monitoring will help reduce accidents and improve overall safety in Sri Lankan container terminals.

Figure 3 shows the distribution of accidents by location from 2019 to 2023, identifying high-risk zones. The Wharf consistently records the highest number of accidents, peaking in 2023, likely due to heavy traffic and operational complexities. Outside the Terminal and Diesel Point also show significant spikes in 2023, suggesting issues with traffic management and fueling operations. Several turning points, such as 1/2AB, 3/4AB, and 2/3CD, exhibit moderate but consistent accident rates, indicating navigation difficulties and blind spots.

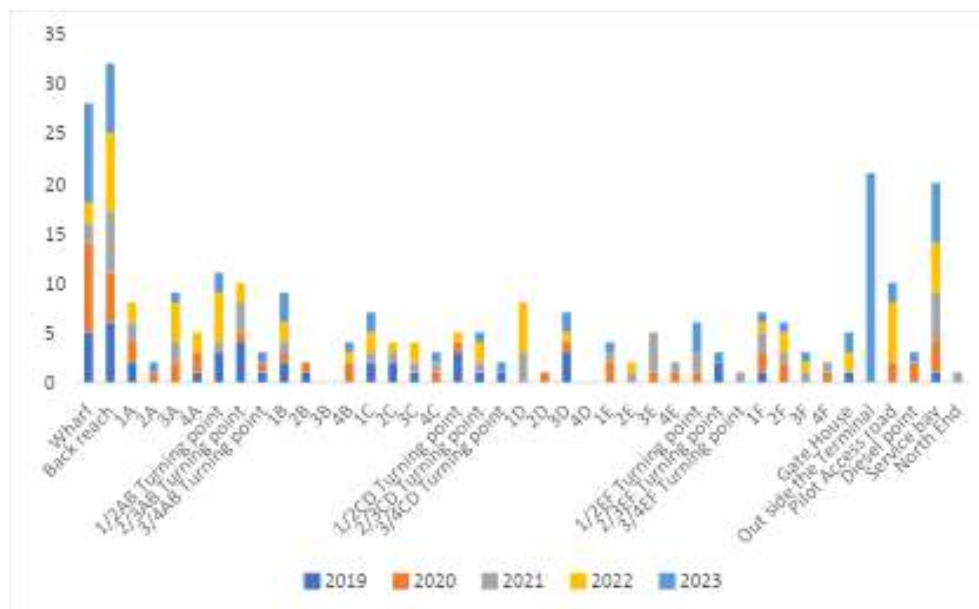


Figure 3: Accidents by location

The increase in accidents at 4F in recent years suggests a growing safety concern. These findings indicate that traffic congestion, operational hazards, and procedural gaps contribute to accident risks. Enhanced traffic regulations, better driver training, improved signage, and stricter enforcement of safety protocols are crucial to mitigating these risks. Addressing these high-risk areas will significantly improve overall terminal safety and operational efficiency.

3. Conclusion

In summary, this study underscores the significant role that human factors and organizational weaknesses play in transportation accidents at Sri Lankan container terminals. To create a safer and more efficient work environment, terminal operators must go beyond surface-level interventions and tackle the root causes—ranging from inadequate training and poor communication to lack of accountability and motivation.

For industry practitioners, the findings point to the urgent need for practical, hands-on training programs that simulate real-world conditions, particularly for internal truck drivers, where accident rates are highest. Strengthening safety enforcement, improving shift scheduling to address fatigue, and introducing structured recognition and feedback systems can motivate employees and encourage safer behaviors. Critical high-risk zones such as the Wharf, Back Reach, and Gate House also require targeted infrastructure improvements and better traffic flow management. For policymakers, the study highlights the necessity of regulatory oversight to ensure consistent safety standards across terminals. This includes mandating minimum training requirements, enforcing clear disciplinary procedures, and incentivizing terminals to adopt proactive safety cultures.

4. Recommendations

To address the critical issue of transportation accidents in Sri Lankan container terminals, this study recommends a multi-pronged approach that acknowledges both the human and systemic dimensions of safety. First, terminal operators must prioritize comprehensive training programs that go beyond theoretical instruction. Simulated, hands-on learning environments—especially tailored for internal truck drivers—can help staff respond more effectively to real-world scenarios and reduce the frequency of human errors. Second, organizational practices need a closer examination. Poor communication, inconsistent shift scheduling, and unclear accountability contribute to both mental fatigue and lapses in safety. Introducing structured feedback systems, clear communication channels, and performance-based recognition can foster a more safety-conscious and motivated workforce.

Furthermore, high-risk zones such as the Wharf, Back Reach, and Gate House demand immediate infrastructural attention. Improvements in traffic design, signage, and lighting can significantly reduce the risk of collisions and near-miss incidents in these congested areas. From a policy standpoint, there is a clear need for stronger regulatory frameworks that enforce uniform safety standards across terminals. Authorities should establish baseline requirements for driver training, implement transparent disciplinary procedures, and provide incentives for terminals that demonstrate measurable safety improvements. Ultimately, fostering a culture that values safety as much as operational efficiency requires collaboration between terminal management, frontline workers, and policymakers. By aligning human-centered strategies with infrastructure and policy reforms, Sri Lanka's container terminals can move toward a safer, more resilient future.

4.1 LIMITATIONS

While this study offers valuable insights into the role of human error in transportation accidents at Sri Lankan container terminals, there are a few limitations to acknowledge. First, the research focused on a single terminal, which may limit how broadly the findings can be applied across other terminals with different operational setups or safety cultures. The insights from interviews, though rich in detail, were gathered from a relatively small group of individuals, which might not fully represent the experiences and views of all employees. Additionally, the study relied on existing accident records, which may not capture every incident accurately—especially minor or unreported ones that could still offer important clues about safety risks.

4.2 FUTURE RESEARCH

Going forward, researchers could expand the scope by studying multiple container terminals to compare practices and identify common patterns or unique challenges. It would also be valuable to explore employee experiences in more depth, perhaps through anonymous surveys or focus groups, to get a broader understanding of day-to-day safety issues. Long-term studies that track the effects of specific safety interventions—such as new training programs or communication

strategies—could help determine what works best in reducing accidents. Finally, future research might also look at how technology, like real-time tracking or automated safety alerts, can support safer operations and reduce the chances of human error.

5. References

- Ding, Y., Yang, Y., Heilig, L., Lalla-Ruiz, E., & Voss, S. (2021). Deployment and retrofit strategy for rubber-tyred gantry cranes considering carbon emissions. *Computers and Industrial Engineering*, 161(April), 107645. <https://doi.org/10.1016/j.cie.2021.107645>
- Gomm, R. (2008). Social Research Methodology. *Social Research Methodology*. <https://doi.org/10.1007/978-0-230-22911-2>
- Hetherington, C., Flin, R., & Mearns, K. (2006). Safety in shipping: The human element. *Journal of Safety Research*, 37(4), 401–411. <https://doi.org/10.1016/j.jsr.2006.04.007>
- Noor, K. (2008). Case Study : A Strategic Research Methodology Khairul Baharein Mohd Noor. *American Journal of Applied Sciences*, 5(11), 1602–1604.
- Perera, L., & Fernando, M. (2018). *Infrastructure Challenges in East and South Asia*
- Premathilaka, W. H. V. (2018). *Determining the factors affecting the turnaround time of container vessels: a case study on Port of Colombo container vessels: a case study on Port of Colombo*. 77. https://commons.wmu.se/all_dissertations/600
- WEBER, L. (1983). European Organization for the Safety of Air Navigation (Eurocontrol). *Regional Cooperation, Organizations and Problems*, 13, 191–194. <https://doi.org/10.1016/b978-0-444-86237-2.50059-7>

