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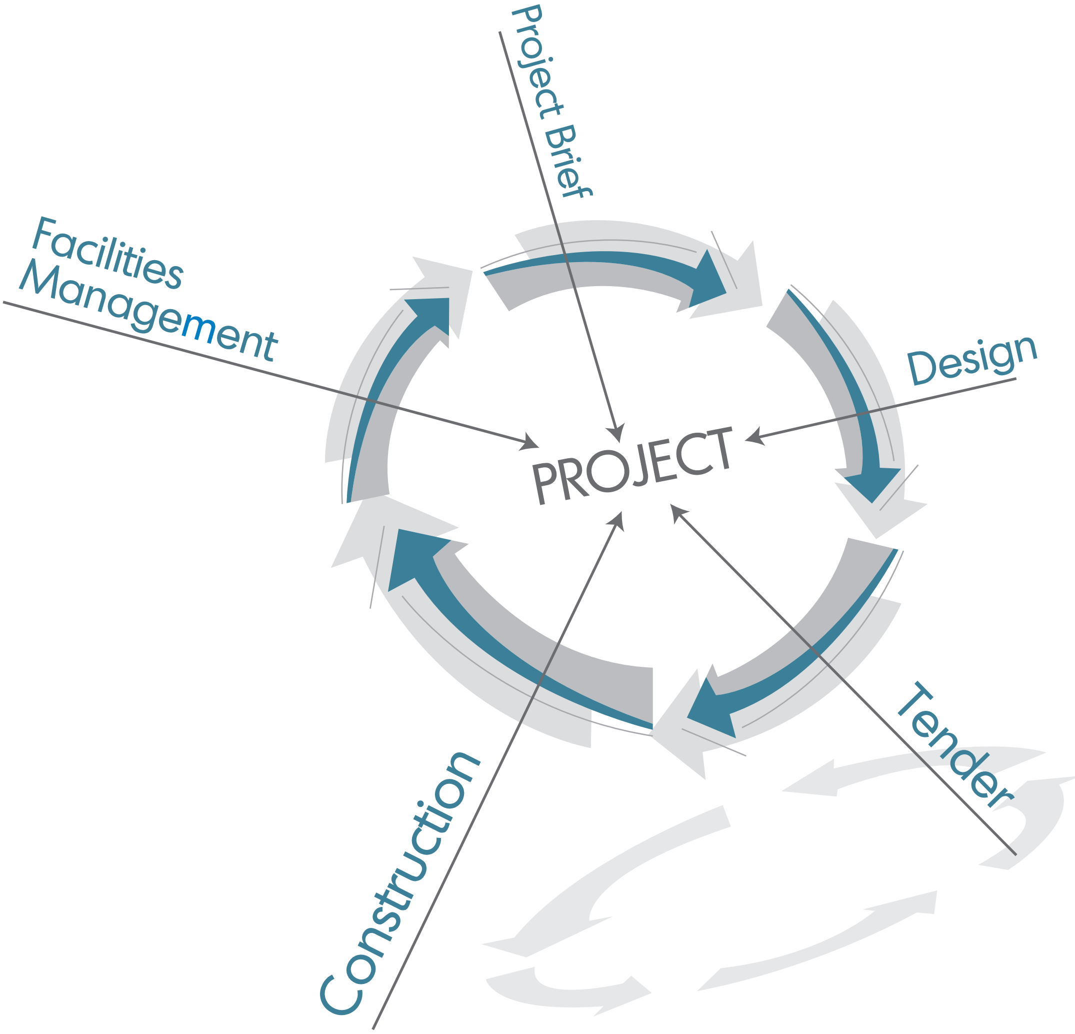

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Editorial

Welcome from the Editors

Welcome to the forty-sixth (46th) issue of Malaysian Construction Research Journal (MCRJ). In this issue, we are pleased to include eight papers that cover a wide range of research areas in the construction industry. The editorial team would like to express our sincere gratitude to all contributing authors and reviewers for their contributions, continuous support and comments.

In this issue:

Nasfiza Mokhtar et al. explored the application of the Bamboo-Geotextile Buoyant System (GEOBAMTILE) as an innovative ground improvement solution, specifically for road embankment reinforcement in areas with soft soil. A key aspect of this research was the integration of fibre optic sensing (FOS) technology, which played a critical role in providing real-time, continuous monitoring of strain and stress distributions within the GEOBAMTILE system. FOS technology allowed for precise tracking of changes in structural performance, revealing that the bamboo geotextile reinforcement significantly mitigated both overall and differential settlement. The results indicated that the GEOBAMTILE system effectively distributed loads, reducing stress on the underlying soft soils and minimising the risk of differential and large settlement. The FOS technology also revealed critical strain and stress areas, particularly at road shoulders, where critical readings were observed, suggesting additional improvements to the GEOBAMTILE system. By leveraging the advantages of FOS, such as immunity to electromagnetic interference, lightweight sensors, and the ability to monitor numerous points over large areas, this study not only enhanced the durability of road infrastructure but also aligned with sustainable engineering practices by utilising renewable materials. The findings highlight the potential of bamboo geotextile systems in infrastructure projects, demonstrating that the incorporation of advanced monitoring technologies, such as FOS, can pave the way for more resilient and environmentally friendly road construction methodologies.

Jahanzeb Asim and Muneera Esa analysed the adoption of Agile methods within Pakistan's construction industry and their anticipated impact on enhancing project flexibility, participation by various stakeholders, and overall efficiency. The research examines the consequences of conventional project management approaches, such as inflexible workflows, procrastination, and unaligned stakeholders, using Scrum and Kanban Agile frameworks, as well as Lean Construction, and its ability to mitigate these problems. This research identified several key barriers to Agile adoption, including resistance to change, regulatory constraints, and budget cuts, through qualitative interviews with industry professionals. The results propose solutions such as phased implementation, Agile training, and hybrid models of Agile. The study contributes to what the authors refer to as a "broader discourse on Agile in developing economies" by providing a strategic roadmap for implementing Agile in Pakistan's construction industry, aiming to enhance project success and adaptability.

AbdulLateef Olanrewaju et al. investigated the potential of digital twin technology in sustainable construction, emphasising its capacity to enhance project performance, construction productivity, and efficiency. Despite its promising advantages, the adoption of digital twin technology remains sluggish. Using a survey questionnaire administered to construction stakeholders, the researchers employed Principal Component Analysis (PCA) to cluster the barriers hindering the adoption of digital twins in sustainable construction. The study identified critical barriers, including clients' reluctance to invest in digital twin services, the high cost of technology implementation for construction firms, a lack of organisational expertise, cultural resistance within construction companies, issues related to data quality, limited collaboration among project stakeholders, challenges with data compatibility, and resistance to change among staff. The findings not only highlight key obstacles but also provide a foundation for future research and the formulation of effective strategies to facilitate the industry's adoption of digital twin technology in pursuit of sustainability goals.

Maria Achieng Akulu et al. conducted a study on the adoption of Artificial Intelligence (AI) in the construction industries of Zambia and Kenya. Using a quantitative research approach, they gathered survey data from industry professionals, employing statistical analysis to evaluate awareness and implementation levels of AI. The findings indicated a high awareness of AI; however, its actual adoption was limited, primarily occurring during the design and planning phases, where specific tools were utilised. More advanced AI applications were found to be underutilised, and there were no significant differences in adoption rates between Zambia and Kenya. The study concluded that targeted interventions, including policy support, capacity building, and investment incentives, are essential for enhancing the integration of AI. By increasing both awareness and accessibility to AI technologies, there is significant potential for improved efficiency, productivity, and innovation in the construction sectors of both countries.

Nadzirah Zainordin et al. exploring in the dynamic realm of construction, the Industrialized Building System (IBS) stands out as a transformative approach, promising a multitude of benefits. This study embarks on a journey to unravel the benefits through a systematic literature review. By synthesizing an extensive array of scholarly works, this research aims to shed light on the range of benefits that IBS implementation brings to the construction industry. The systematic review methodology ensures a rigorous and unbiased exploration, encompassing factors such as cost and finance, sustainability, environmental, safety, social benefit, labor reduction, and construction site. Furthermore, this study delves into the challenges and facilitators associated with IBS adoption, offering a holistic understanding of the intricacies involved. The findings not only underline the significant advantages that IBS presents but also provide invaluable insights for industry practitioners, policymakers, and researchers striving to navigate the terrain of modern construction practices. As the construction industry seeks innovative solutions for sustainable and efficient building, this study's revelations contribute to the ongoing dialogue, fostering awareness and informed decision-making around the potential perks of integrating Industrialized Building Systems.

Sui Lai Khoo et al. have aimed to integrate the digitalisation in the construction industry with a key driver of sustainability, enabling more efficient resource management, and reducing environmental impact. Quantity Surveyors (QS) play a crucial role in ensuring that digital advancements align with sustainable construction practices, particularly in cost management and project efficiency. This study explores the synergy between digitalisation and sustainability from the perspective of Malaysian QS professionals, highlighting the impact, challenges, and opportunities of adopting digital tools in sustainable construction. The research aims to examine how digital technologies such as Building Information Modelling

(BIM), Artificial Intelligence (AI), and blockchain contribute to sustainability, identify the barriers faced by QS professionals in implementing digital solutions, and provide insights into their role in promoting cost efficiency and waste reduction. Findings indicate that while digitalisation enhances sustainability by improving cost forecasting, resource optimisation, and environmental performance, challenges such as high implementation costs, skill gaps, and resistance to change hinder widespread adoption. The study concludes that industry-wide training programs, policy incentives, and collaborative initiatives are essential to support QS professionals in leveraging digitalisation for sustainability. These insights provide valuable implications for policymakers, industry stakeholders, and QS practitioners in driving Malaysia's construction industry towards a more sustainable and digitally integrated future.

Jannatun Naemah Ismam et al. aims to propose a conceptual framework of project managers' competencies toward safety performance in green construction. It highlights recent studies that link higher competency levels with improved safety outcomes and emphasizes the significance of project managers' competence in influencing safety performance within this context. The three (3) competency attributes were developed based on the existing Crawford Integrated Model of Competence, while the five (5) safety performance components were identified using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. The findings reveal three key competency attributes that project managers should possess to achieve safe and sustainable construction practices. These attributes are known as Knowledge, Skills, and Attitudes. Furthermore, five safety performance components were identified, outlining the essential dimensions of safety performance in green construction.

Nur Azrin Ahmad Pakrudin et al. investigates the Critical Success Factors (CSFs) influencing Facilities Management (FM) implementation in the healthcare sector through Interpretive Structural Modelling (ISM) and MICMAC analysis. Fifteen CSFs, identified from prior literature, were evaluated by thirteen FM experts to determine their interrelationships and hierarchical influence. The ISM approach revealed six hierarchical levels, with Knowledge and Competencies and Top Management Commitment and Support serving as foundational drivers. Teamwork Effectiveness, Contract Management, Strategic Decision-Making, Resources and Training, and Customer Focus emerged as key enablers for successful implementation. Strategic Planning and Work Environment were identified as linkage factors connecting the drivers to dependent factors such as Risk Management, Performance Measurement, and Accreditation. The resulting ISM-based model provides a structured framework for prioritizing initiatives to enhance FM implementation effectiveness in healthcare. The study underscores the significance of leadership commitment, knowledge capability, and collaborative culture in driving FM performance, while also offering a transferable model for application across other facility sectors.

Editorial Committee

SUSTAINABLE GROUND IMPROVEMENT USING BAMBOO-GEOTEXTILE REINFORCEMENT AND REAL-TIME MONITORING WITH FIBER OPTIC TECHNOLOGY

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Abstract
Infrastructure projects such as roads, highways, and railways are vital for economic development, but constructing on soft soils, like soft clay or peat, poses significant challenges due to settlement and stability issues. This study explores the application of the Bamboo-Geotextile Buoyant System (GEOBAMTILE) as an innovative ground improvement solution, specifically for road embankment reinforcement in soft soil areas. The research was conducted on a full-scale road construction project in Tanjung Karang, Selangor, where bamboo-geotextile layers were installed beneath the embankment to distribute loads and minimise differential settlement. A comprehensive long-term monitoring program was implemented using fibre optic sensing (FOS) technology, including Fibre Bragg Grating (FBG) sensors and Brillouin Optical Time Domain Analysis (BOTDA) for real-time data acquisition. Results indicated that the GEOBAMTILE system significantly reduced both overall and differential settlement by effectively distributing the stress. The FOS technology revealed that critical strain and stress readings were observed on the road shoulders, where higher traffic loads were concentrated. Overall, the combination of bamboo reinforcement and fibre optic monitoring provides a sustainable and efficient approach to enhancing the performance of road infrastructure on soft ground.

Keywords: *Fiber Optic Sensing; BOTDA; Fiber Bragg Grating; Soft Clay; Bamboo-geotextile*

INTRODUCTION

Infrastructure such as roads, highways, and railways are essential for a country's economy, as they facilitate the smooth movement of goods, services, and people. A strong transportation network reduces travel time, lowers costs, and improves connections between cities and rural areas, thereby supporting trade, tourism, and industry. The safety and reliability of these networks are critical for economic stability, as disruptions can lead to delays and increased expenses (Nikolaeva, 2020). Road construction on very soft ground, such as soft clay or peat, is often avoided due to the challenges and limited engineering solutions available to address the problems related to soil characteristics (Basri et al., 2021; Basri et al., 2020; Zainorabidin et al., 2023). However, road alignment cannot always be adjusted to avoid passing through soft soil areas, which necessitates proper solutions or ground improvement before construction can begin. In recent years, several studies have been conducted to predict and understand soil behaviour, especially using bamboo reinforcement or systems in road construction. The investigation includes laboratory-scale studies (Basri et al., 2018; Wahab et al., 2021), small-scale studies (Asaduzzaman & Islam, 2014; Hegde & Sitharam, 2015; Pinka et al., 2021; Saha & Mandal, 2020; Waruwu et al., 2019), modelling efforts, and even full-scale tests (Deb et al., 2021; Mamatha & Kommu, 2016; Marto et al., 2010; Rahardjo, 2005). These investigations have provided deeper insights into soil behaviour related to road construction on soft soil.

Traditionally, ground monitoring has been conducted using mechanical and electrical sensors, which measure parameters such as displacement and load, transmitting data as electrical signals. While these methods are reliable, they have limitations, including a restricted number of sensing points and susceptibility to environmental interference from nearby construction machinery (Bednarski et al., 2021; Puzrin et al., 2020). Moreover, manually-read sensors require personnel to work in potentially hazardous conditions, and these systems often lack the capability to provide real-time data (Sharon, 2020). Several challenges were encountered during the investigations, including localised readings, broken equipment that caused inaccurate readings, high costs, and a limited number of readings (Sharon, 2020). Without effective geotechnical monitoring, unexpected ground movement or failure may lead to serious issues, including structural damage, road closures, and financial losses. Excessive settlement or embankment failures can result in cracked road surfaces, posing significant safety hazards.

Thus, this study was conducted on a full-scale ground improvement project using GEOBAMTILE, which applied fibre optic technology as an alternative for continuous monitoring. In recent years, FOS has emerged as a superior alternative for ground monitoring, including applications such as GEOBAMTILE. FOS offers several advantages: immunity to electromagnetic and radio frequency interference (Chai et al., 2019), intrinsic safety due to the absence of electrical components, lightweight and compact sensors, real-time automated data acquisition (Pendão & Silva, 2022; Puzrin et al., 2020), and the ability to monitor numerous sensing points over large areas (Ip et al., 2022; Zhang et al., 2020). FOS has been successfully implemented in civil engineering applications such as tunnels, bridges, and embankments, enabling distributed measurements of strain, temperature, and deformation with high spatial resolution (Wijaya et al., 2021).

In combination with the sustainable GEOBAMTILE system, these techniques are particularly effective for enhancing soil stabilisation, drainage, and embankment reinforcement in road construction projects. Thus, incorporating fibre optic sensing along with ground improvement techniques such as GEOBAMTILE provides a sustainable, real-time, and safer approach for monitoring road construction projects, ultimately improving the durability and safety of road infrastructure. This study aims to investigate potential alternatives for continuous monitoring of the GEOBAMTILE system in terms of the structural performance of bamboo within the system, monitor horizontal and longitudinal differential settlement along the road, and observe land subsidence and the influence of depth beneath the GEOBAMTILE system. This comprehensive instrumentation and monitoring plan will enable a detailed evaluation of the system's structural performance and its impact on the surrounding environment.

MATERIALS AND METHODS

Study Location

The study was conducted at Federal Route Trunk 05 (FR05) in Tanjung Karang, Selangor, located at GPS coordinates 3°30'54.1"N, 101°05'45.8"E. Situated on the west coast of Selangor, this road improvement project encompasses parts of the existing roadway which begins at Kg Tengah, approximately 5 km north of Tanjung Karang town, and extends for about 45 km, concluding roughly 2 km before reaching Sabak Bernam town (refer to Figure 1). The project is strategically located alongside built-up areas, ensuring that the upgraded roadway effectively meets the needs of both local traffic and broader connectivity along the West Coast Expressways. A preliminary investigation revealed that the depth of soft clay reach reached up to 20 meters. Therefore, the GEOBAMTILE was installed as a means to distribute the load applied from the road embankment and traffic, thus minimising the imposed stress on the underlain soft subgrade, which results in a significant reduction of differential and total settlement. Long-term monitoring was conducted to investigate the efficiency of the GEOBAMTILE system. Instrumentations were deployed using FBG sensors and BOTDA technology. The primary focus is to monitor the structural integrity of the bamboo in the GEOBAMTILE system, measure horizontal and longitudinal differential settlement along the road, and evaluate land subsidence and influence depth below the system.

Figure 1. Sample Location of U-Turn 5 at Tanjong Karang–Sabak Bernam Upgrading Project

As-Built Instrumentation Setup

The FBG system is used to monitor the load transfer and groundwater pressure below the GEOBAMTILE system, utilising FBG Earth pressure cells and piezometers. These sensors were installed in boreholes and connected to an FBG interrogator, which is used to store and analyse dynamic and static measurements. BOTDA technology is used to monitor strain in the bamboo structure, differential settlement, and vertical land subsidence. Two types of optical cables were utilised, with fibre strain cable (FSC) cables for horizontal strain monitoring on the bamboo and soft strain cable (SSC) cables for vertical land subsidence monitoring. Strain measurements were compared with baseline readings and subsequent data was analysed to determine the strain change and estimate the settlement behaviour. The readings were obtained at intervals of approximately three months to assess the performance and settlement behaviour of the GEOBAMTILE system over time. Figure 2 illustrates the overall methodology flowchart of the study. Figures 3, 4 and 5 show the distributed fibre optic strain sensing cable, the plan view of the top layer of GEOBAMTILE, the plan view of the bottom layer of GEOBAMTILE and the cross-section view, respectively. The figures illustrate the as-built instrumentation setup for the purpose of continuous monitoring of the GEOBAMTILE system.

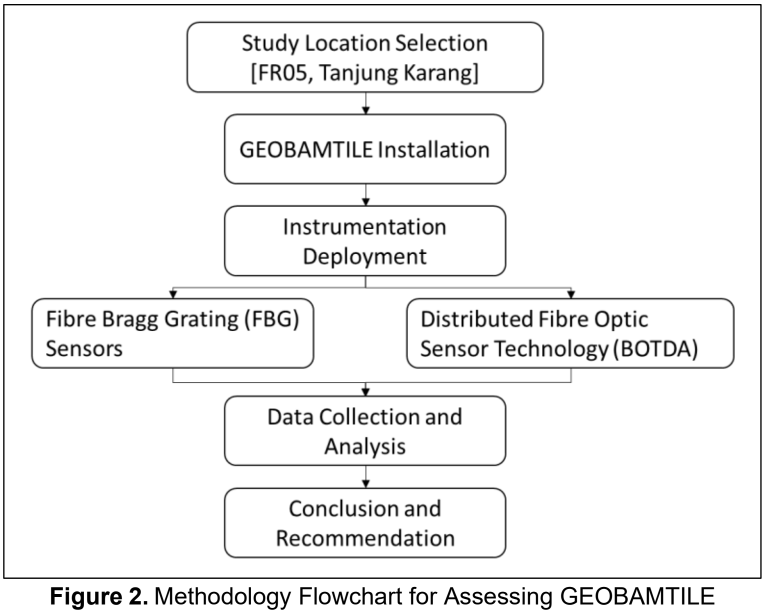


Figure 2. Methodology Flowchart for Assessing GEOBAMTILE

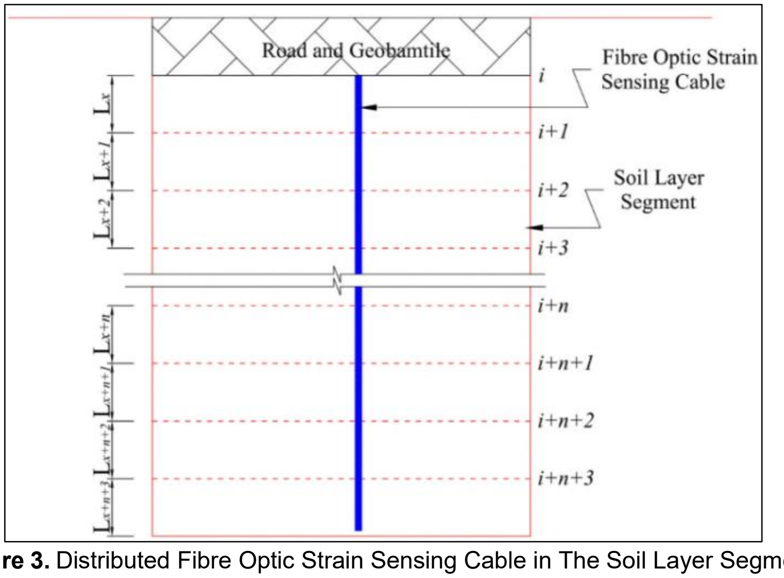
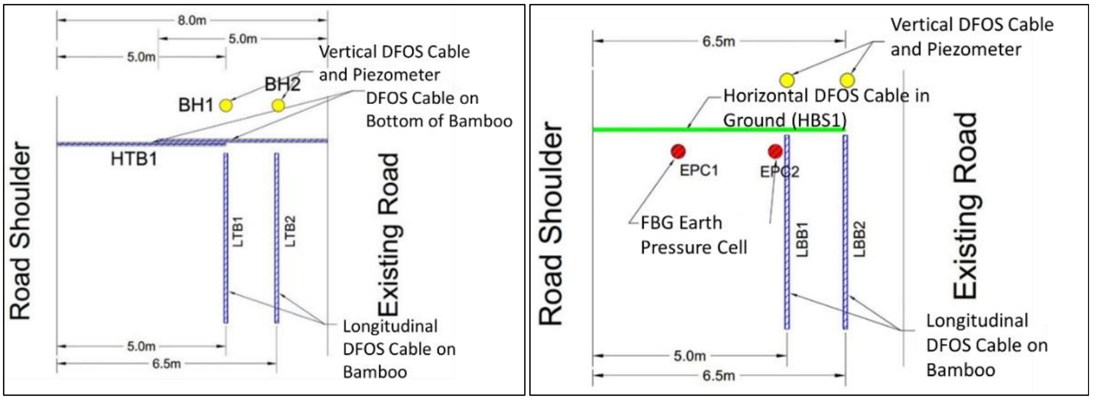


Figure 3. Distributed Fibre Optic Strain Sensing Cable in The Soil Layer Segment



(a) (b)

Figure 4. Plan View of Instrumentation (a) at The Top Layer of The GEOBAMTILE; (b) at The Bottom Layer of The GEOBAMTILE

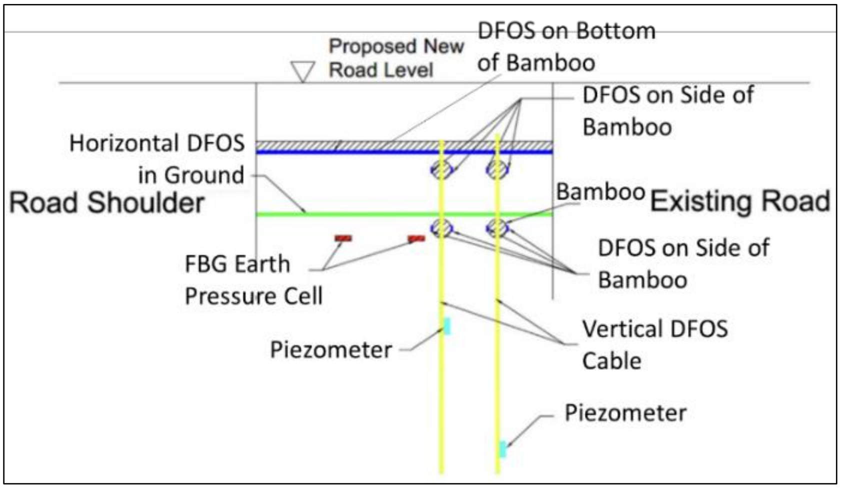


Figure 5. Cross-Section View of Instrumentation at GEOBAMTILE System Across The Road

RESULTS AND DISCUSSION

Strain Reading

Figure 6 shows that in the first meter of the longitudinal top layer 1 (LTB1) fibre optic, a slight variation in strain was observed. During the construction phase (from Day 0 to Day 119), the road exhibited elongation, which is consistent with findings by Glisic and Inaudi (Glisic & Inaudi, 2007), who highlighted that elongation is often associated with the redistribution of loads and soil compaction during construction. However, after opening to traffic (from Day 208 to Day 860), the road experienced shortening, a phenomenon that corresponds to the settlement caused by repeated traffic loads and dynamic stress (Lin, 2019). From 2 to 5 meters, strain readings fluctuated, with peaks and troughs indicating periods of significant elongation or shortening. The strain values ranged from -450 to 450 με, indicating that overall, the road predominantly experienced elongation throughout the monitoring period.

Figure 7 illustrates the strain readings for LTB2, showing a similar pattern throughout the monitoring period. The road primarily experienced elongation, with strain decreasing as the length increased. During the construction period (from Day 0 to Day 14), the strain was higher compared to after the road was opened to traffic (from Day 195 to Day 860). This behaviour is likely due to a reduction in stress distribution to the bamboo as the soil layer densified over time. As mentioned by Lin et al. (Lin, 2019), densification and soil layers significantly reduce strain amplitudes, especially in systems designed for load distribution. The strain ranged from -20 to 410 με.

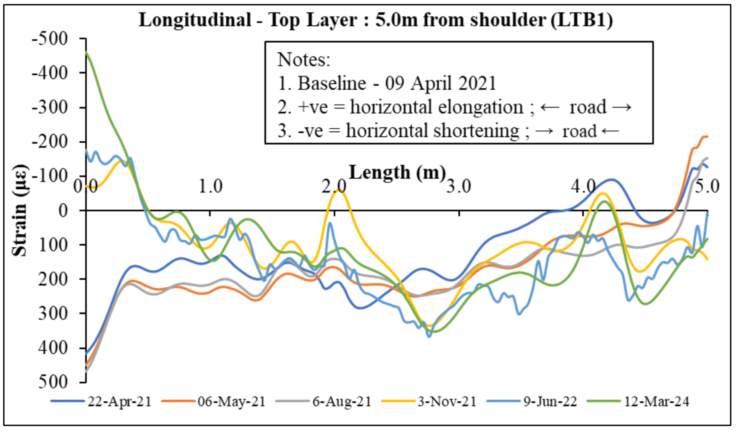


Figure 6. Strain Against Length for LTB1

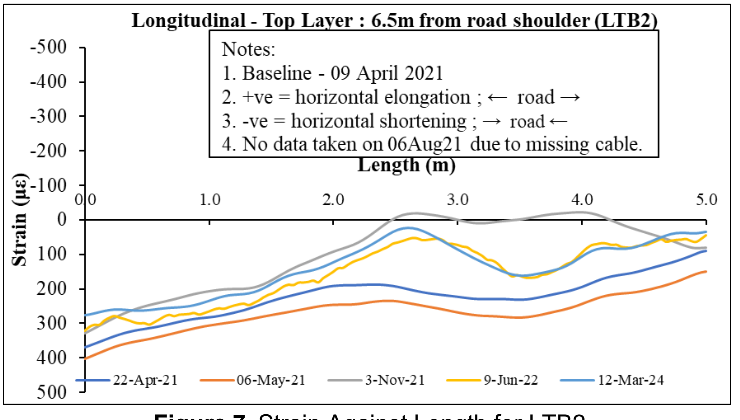


Figure 7. Strain Against Length for LTB2

A significant increase in strain was observed on the first 1 meter upon contact and stabilised throughout the remaining length, suggesting the critical strain reading was on the first 1 meter. This finding was due to the pronounced localised stress concentrations at the contact points in the reinforced systems (Glisic & Inaudi, 2007). From the strain measurement, it can also be observed that the strain decreases over length due to the dissipation of stress governed by the buoyancy effect. Comparison between LTB1 and LTB2 suggests that an area that doesn't come directly in contact with the tyres from the passing traffic shows minimum variations in strain readings, which could be attributed to the ability of the system to distribute the load. As mentioned by Wu et al. (2020), geosynthetic reinforcements can effectively minimise localised stresses and provide uniform load transfer across the system.

The strain readings for the horizontal top layer (HTB1), shown in Figure 8, ranged from -1500 to 1500 με, displaying fluctuations throughout the monitoring period. These variations indicate significant elongation and shortening at different points along the road, mainly influenced by pressure distribution across the fibre optic's position. As load was applied to the bamboo layer, tensile forces caused elongation, while compressive forces led to shortening. This dual behaviour suggests that the bamboo layer experienced both elongation and compression, indicating potential heaving rather than just settling over time. Cyclic loading from traffic could induce alternating tensile and compressive strains in geosynthetic reinforcements, highlighting the dynamic nature of stress distribution (Wu, 2020). Moreover, local variations in load application, such as wheel paths and near the shoulder, could amplify strain fluctuations, contributing to the observed patterns of elongation and compression (Lin, 2019).

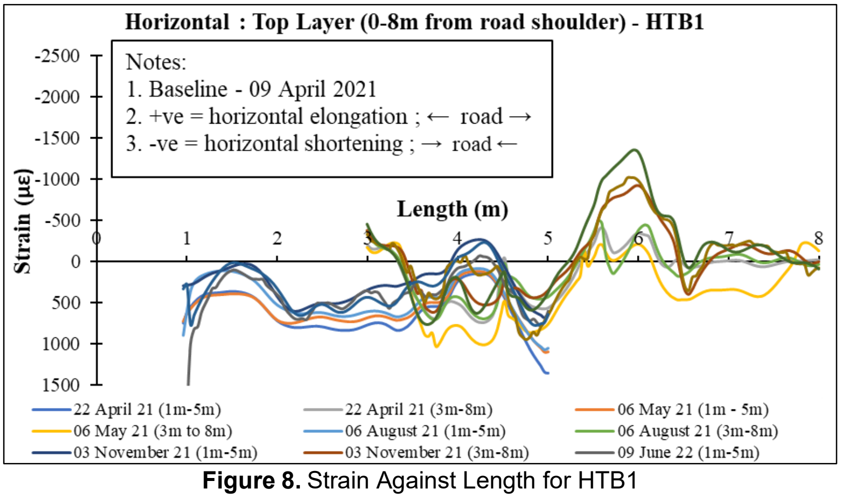


Figure 8. Strain Against Length for HTB1

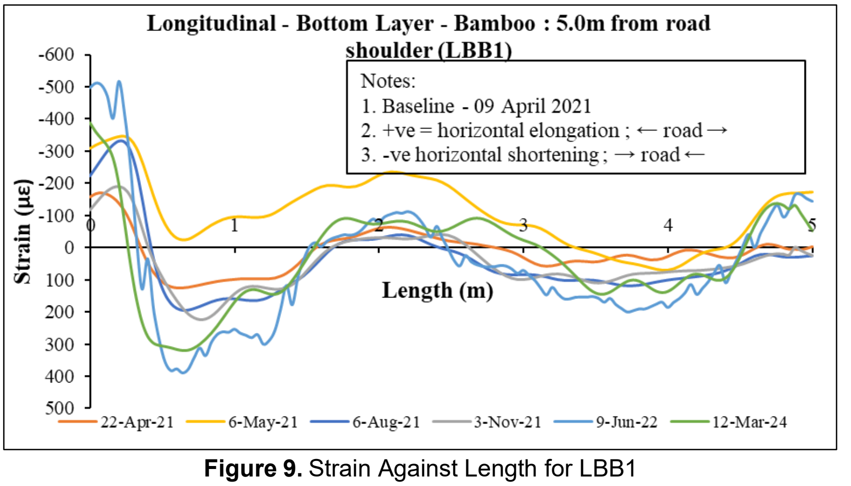


Figure 9. Strain Against Length for LBB1

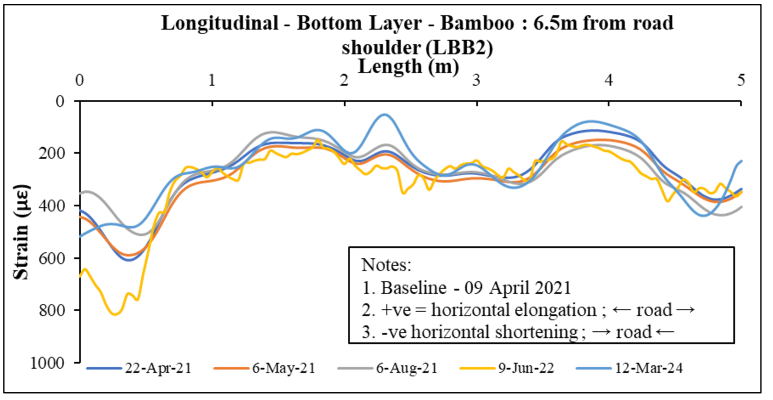


Figure 10. Strain Against Length for LBB2

The strain readings for the bottom layer, represented by longitudinal bottom layer 1 (LBB1) and LBB2, are shown in Figures 9 and 10, respectively. Similar to the top layer, LBB1 exhibited a significant increase of strain on the first 1 meter before fluctuating and stabilising throughout the monitoring period, with notable peaks and troughs indicating significant elongation and shortening at different points between 2 to 5 meters. This behaviour is consistent with findings by Wu et al. (2020), who reported that reinforcement layers often experience localised stress concentrations at their edges, leading to higher strain variability. However, LBB2 only experienced elongation during the same period compared to LBB1, which suffered both elongation and shortening. The strain measurements ranged from -500 to 400 με for LBB1 and from 20 to 810 με for LBB2.

A single fibre optic was installed to monitor soil strain beneath the bamboo layer horizontally, as shown in Figure 11 for the horizontal bottom layer (HBS1). The soil at the bottom of the bamboo layer experienced a strain of up to 3200 με, which is 2 to 3 times higher than the strain observed in the top bamboo layer. This higher strain is attributed to the combined stresses from vehicles, the bamboo layer, and the pavement above. Moreover, the behaviour could be due to the position of the fibre, which maximises contact with the passing vehicles.

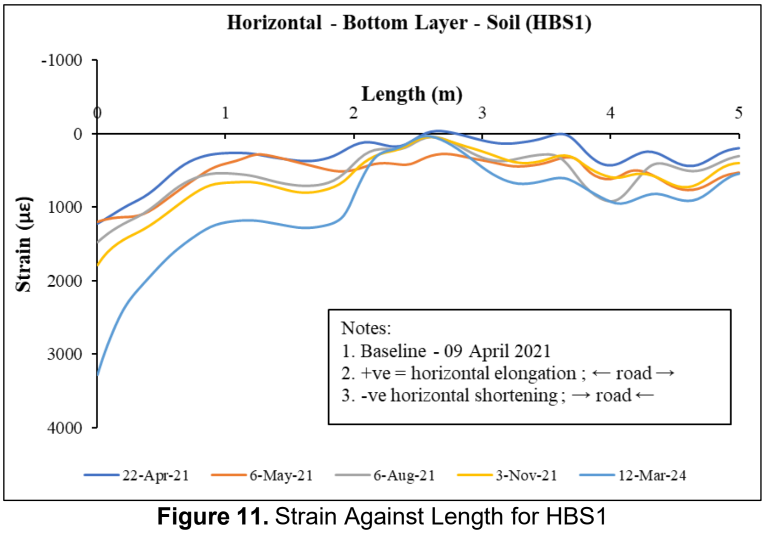
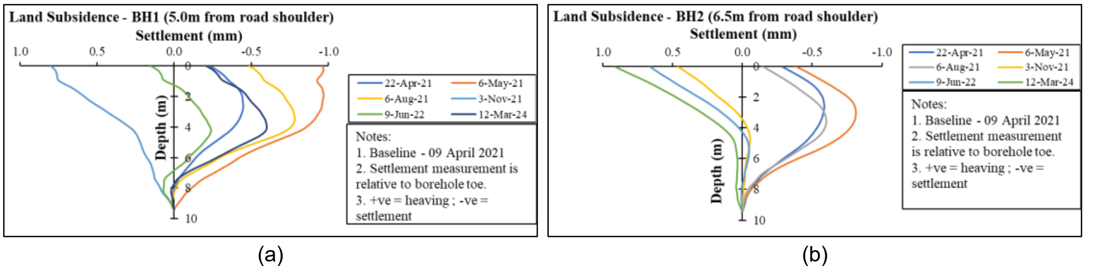


Figure 11. Strain Against Length for HBS1

The strain distribution observed also suggests that higher strain was recorded near the shoulder compared to the middle road. The behaviour could be governed by the heavier vehicles that typically use the left lane, which is near the shoulder, compared to the right lane, which is usually used by the smaller and faster vehicles. This finding suggests that extra attention should be given to the GEOBAMTILE design, especially on the left lane and parts of the road shoulder. As mentioned by Lin et al. (2019), the traffic loads generate dynamic stress up to 2 meters beyond the roadway. Overall, this observation validates the capability of fibre optic sensors to capture dynamic strain changes accurately and in superior resolution compared to conventional methods in monitoring infrastructure performance (Wu, 2020).

Settlement

Settlement measurements were taken from two boreholes, BH1 and BH2, as shown in Figure 12. In BH1, the peak settlement increased significantly from -0.45 mm to -0.97 mm during the early phase of GEOBAMTILE construction (Day 0 to Day 14). From Day 14 to Day 1,051, the settlement gradually decreased to 0.8 mm, with heaving observed between Day 195 and Day 585, likely due to rising groundwater from heavy rainfall. This heaving phenomenon was attributed to the expansion of clay layers combined with bamboo buoyancy effects, as moisture content influences both soil expansion and the buoyancy properties of bamboo in reinforced systems. The finding was consistent with Mekonnen and Mandal (Mekonnen, 2017), who observed that changes in groundwater levels during heavy rainfall can significantly impact the performance of geotechnical reinforcements like bamboo and geogrid systems.



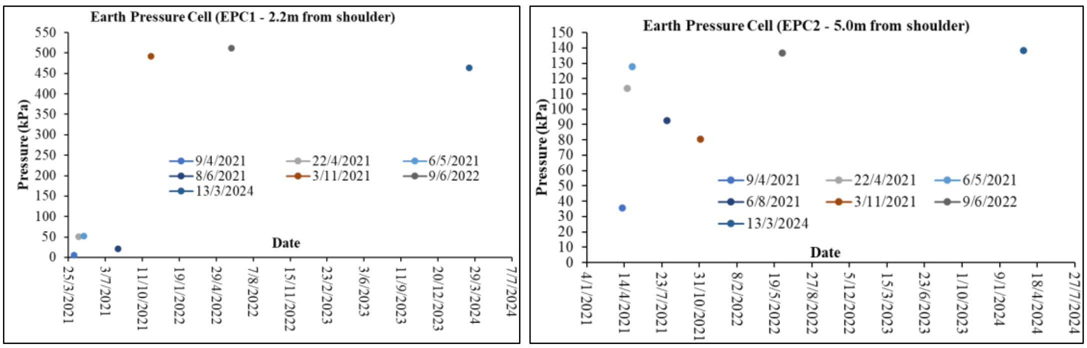
(a) (b)

Figure 12. Land Subsidence at (a) BH1; and (b) BH2

Similarly, BH2 showed an initial settlement increase from -0.59 mm to -0.81 mm (Day 0 to Day 14) before gradually decreasing to 0.92 mm by Day 1,051, with heaving observed between Day 414 and Day 1,051. Overall, settlement increased during the early construction phase but declined as the soil compacted after the road was opened to traffic, providing valuable insights into settlement distribution at different depths. Overall, real-time settlement was observed, providing a reliable estimate of the GEOBAMTILE system's effectiveness in minimising total settlement. However, a challenge persists in determining the total settlement from the measured strain due to the absence of an appropriate theoretical method (Zhang et al., 2020). Moreover, the findings also revealed a significant decrease in the influence of traffic loads on the settlement with an increase in depth. A similar finding was observed by Qi et al. (2022), where the influence of traffic load on settlement decreases significantly with depth.

Soil Stress and Pore Water Pressure (PWP)

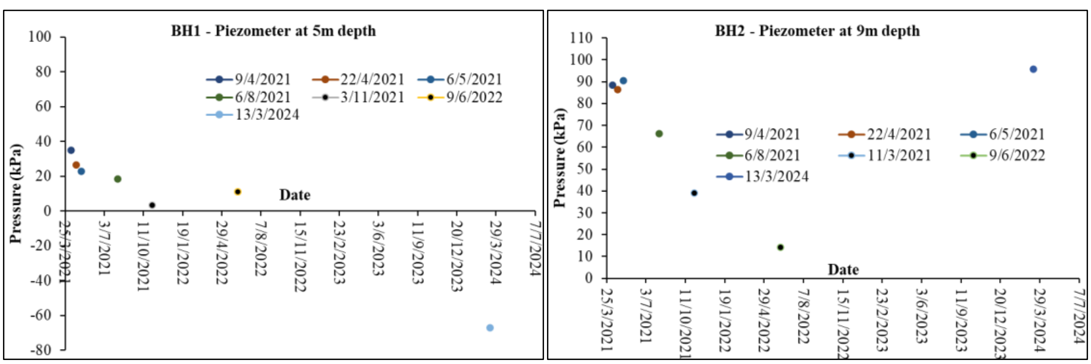
The soil stress and pore water pressure (PWP) were measured using FBG Earth pressure cells and piezometers. Two FBG Earth pressure cells, EPC 1 and EPC 2, were placed 2.2 and 5 meters from the road shoulder, while the FBG piezometers were installed at depths of 5 meters in BH1 and 9 meters in BH2. Phase 1 (construction) data was recorded from Day 0 to Day 60, while Phase 2 (road open for traffic) data was measured from Day 208 to Day 1,130. The results for EPC are illustrated in Figure 13.



(a) (b)

Figure 13. Soil Pressure Reading from (a) EPC1 and (b) EPC2

For EPC 1, soil stress gradually increased from 5.47 to 51.49 kPa during the construction phase (Day 0 to Day 27), then dropped slightly to 21.22 kPa by Day 60. The soil stress fluctuations observed during the construction stage are largely attributed to compaction and load distribution (Garlapati, 2018). After the road was opened for traffic, soil stress surged to 512 kPa by Day 585 before reducing to 463.78 kPa by Day 1,130. Similarly, EPC 2 saw a rise in stress from 35.45 to 127.74 kPa during construction (Day 0 to Day 27), followed by a drop to 80.61 kPa by Day 208. After the road was opened, the stress increased again to 138.31 kPa by Day 1,130. Similar to the strain measurements, the Earth pressure cell also shows similar behaviour where EPC1, which was located closer to the road shoulder, recorded a significantly higher stress level compared to EPC2. The finding was attributed to the traffic-induced dynamics, which led to a notable increase in subgrade pressure, especially in the shoulder regions, causing a significant increase in recorded soil stress (Zhang, 2019).



(a) (b)

Figure 14. Pore Water Pressure Reading from (a) BH1 and (b) BH2

The pore water pressure (PWP) readings from the FBG piezometer are illustrated in Figure 14. In BH1, located at a depth of 5 meters, the PWP decreased from 34.89 to 3.31 kPa between Day 0 and Day 208. The drop could be linked to soil consolidation and the dissipation of excess pore pressures (Sun, 2018).

A slight increase was observed on 9th June 2022, bringing the PWP to 10.93 kPa before dropping further to -67.15 kPa. The increase could be governed by the fluctuating groundwater levels due to the influence of rainfall and groundwater recharge on deeper soil layers (Zhang, 2019). Conversely, the piezometer in BH2, at a depth of 9 meters, showed a consistent decline in PWP from 88.45 to 14.23 kPa until 9th June 2022. Notably, on Day 1,130, the PWP spiked to 95.85 kPa. Overall, PWP recorded at deeper depth was slightly higher compared to the shallow part, which was attributed to the different roles of the pressure head and differential response to external loading (Garlapati, 2018).

CONCLUSIONS

This study demonstrated the effectiveness of the GEOBAMTILE as a sustainable ground improvement solution for road embankments in soft soil conditions. A key aspect of this research was the integration of FOS technology, which played a critical role in providing real-time, continuous monitoring of strain and stress distributions within the GEOBAMTILE system. FOS technology allowed for precise tracking of changes in structural performance, revealing that the bamboo geotextile reinforcement significantly mitigated both overall and differential settlement. The results indicated that the GEOBAMTILE system effectively distributed loads, reducing stress on the underlying soft soils and minimising the risk of differential and large settlement. The FOS technology also revealed the critical strain and stress area, particularly at road shoulders where critical readings were observed, suggesting additional improvement on the GEOBAMTILE system. By leveraging the advantages of FOS, such as immunity to electromagnetic interference, lightweight sensors, and the ability to monitor numerous points over large areas, this study not only enhanced the durability of road infrastructure but also aligned with sustainable engineering practices by utilising renewable materials. Despite the limitations of this study, such as site-specific conditions, material variability, and the need for long-term performance assessments, the results provide valuable insights into the effectiveness of the GEOBAMTILE system. The findings highlight the potential of bamboo geotextile systems in infrastructure projects, demonstrating that the incorporation of advanced monitoring technologies like FOS can pave the way for more resilient and environmentally friendly road construction methodologies. Furthermore, future studies could enhance understanding by investigating the resilient modulus of the subgrade layers with the GEOBAMTILE system under cyclic loading conditions.

ACKNOWLEDGEMENTS

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STRATEGIC AGILITY: NAVIGATING THE PAKISTANI CONSTRUCTION INDUSTRY THROUGH AGILE SOLUTIONS

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Abstract
At present, the construction industry of Pakistan has numerous problems, followed by tight deadlines, increased consumer expectations, and frequent changes in the project scope. These challenges, along with the continuous use of traditional project management practices, have led to delays and limitations on the successful completion of projects. An alternative worth exploring remains Agile project management, which was primarily developed for the IT sector, as it features flexible approaches towards work, aims at customer satisfaction, and uses incremental development techniques. This research examines the impact of Agile practices on construction project performance by exploring the implementation, advantages, and weaknesses of these methods in the sector. Key Agile ideas like flexibility, the scope of changes, efficiency, and stakeholder engagement were looked at through qualitative interviews with construction professionals who have used Agile before. The study results conclude that the application of Agile practices is one of the means of resolving problems facing the construction sector in Pakistan. This creates an opportunity to improve not only the efficiency of the projects but also their performance.

Keywords: *Agile Strategies*; *Project Management; Construction; Project Success; Agile Solutions*

INTRODUCTION

Over the last two decades, Agile methodologies have changed the way projects are managed in many industries, particularly in software development, manufacturing, and service delivery (Pinto, Kerzner, & Cleland, 2023). Agile frameworks prioritise iterative development, stakeholder involvement, constant feedback, and flexibility, resulting in increased project efficiency and responsiveness to change (Rigby, Sutherland, & Takeuchi, 2016). Because agile works so well in these areas, construction and other industries with rigid structures, lots of unknowns, and long project lifecycles are now looking into Agile methods to make projects more flexible and lower risks (Basaif, Al-Ashwal, Rahim, Karim, & Loo, 2020).

While the adoption of Agile for rural development is a relatively new topic, the United States, the United Kingdom, and Germany have already begun integrating Agile methodologies such as Scrum, Kanban, and Lean Construction into more traditional project management practices (Babalola, Ibem, & Ezema, 2019). There has been an improvement in changes in scope as well as increased collaboration and faster project completion in agile construction projects (Bradley, Barbara, Mischke, & Woetzel, 2017).

Agile project management was originally developed for the IT sector, but its flexibility, iterative development, and stakeholder collaboration have made it attractive for construction (Pinto, Kerzner, & Cleland, 2023). Scrum, Kanban, and Lean Construction are the most used Agile frameworks in the construction industry (Rigby, Sutherland, & Takeuchi, 2016).

- Scrum: Focuses on iterative sprints, allowing for incremental progress.
- Kanban: A visual workflow management system that enhances efficiency.
- Lean Construction: Reduces waste and optimises resource use (Albuquerque, Torres, & Berssaneti, 2020).

For instance, a case study in the Netherlands on Agile adoption in urban infrastructure projects noted that citizen and urban regulation feedback was responded to much more efficiently with the Agile adoption (Vrijhoef & Koskela, 2005). Similarly, research on Agile implementation in Singapore's high-rise construction projects revealed that Agile principles enhanced coordination between architects, engineers, and contractors, reducing design errors and accelerating project timelines (Ghosh, Edwards, & Hosseini, 2021). In India, Agile-based Lean Construction techniques used in metro rail projects led to improved efficiency in resource allocation and reduced project delays (Dikert, Paasivaara, & Lassenius, 2016). Such examples provide evidence of the capabilities of failing construction management techniques and processes that could improve productivity and efficiency using Agile methodologies in developing countries (Yaakob et al., 2021).

Research on the adoption of Agile methodologies in construction in Pakistan and other similar developing countries is almost non-existent, despite the international shift towards Agile methodologies in construction (Hayat, Rehman, Arif, Kaa, Wahab 2019). Pakistan's construction sector plays a crucial role in economic development, contributing approximately 2.5% to the national GDP and employing over 7.6% of the labour force (Pakistan Bureau of Statistics, 2023). Rapid urbanisation, growing housing demand, and large-scale infrastructure projects, such as those under the China-Pakistan Economic Corridor (CPEC), have created an urgent need for efficient and adaptive project management approaches (Raza, Tayeh, Aisheh & Maglad, 2023).

However, the industry is plagued by frequent project delays, budget overruns, and inefficient stakeholder collaboration (Sohail & Cavill, 2008). Traditional Waterfall-style project management methods dominate Pakistan's construction sector, emphasising rigid planning, sequential execution, and centralised decision-making (Hayat, Hafeez, Bilal & Shabbir, 2022). These models do not accommodate dynamic project environments, where changes in client expectations, material shortages, and external disruptions frequently occur. Agile methodologies, with their iterative problem-solving, adaptability, and continuous stakeholder engagement, offer a promising alternative to these challenges.

Although there has been some success in adopting Agile principles in construction in developed nations, the attempt poses unique problems in developing countries (Ciric, Lalic, Delic, Gracanin, & Stefanovic, 2022). Key challenges include:

- Inflexible contractual and regulatory environments (Araujo, Piña, Aidar, Coelho, & Carvalho, 2019).
- Cultural resistance to change and hierarchical decision-making structures (Dumrak, Mostafa, & Hadjinicolaou, 2020).
- Limited awareness and training opportunities for Agile methodologies in construction (Zasa, Patrucco, & Pellizzoni, 2020).

Many construction projects in Pakistan, India, and South Africa operate under fixed contracts, making Agile's flexible scope adjustments difficult to implement (Albuquerque, Torres, & Berssaneti, 2020). Additionally, organisations in developing markets often favour hierarchical decision-making structures, which can conflict with Agile's emphasis on team autonomy and collaborative decision-making (Dumrak, Mostafa, & Hadjinicolaou, 2020). In addition, because there are little knowledge of Agile principles and no training opportunities available in construction, Agile methodologies remain largely unadopted in these regions (Zasa, Patrucco, & Pellizzoni, 2020).

A study conducted in Brazil on Agile adoption in public infrastructure projects found that bureaucratic inefficiencies and rigid procurement laws hindered Agile implementation (Patanakul, Shenhar, & Milosevic, 2012). In contrast, Chile's construction sector successfully integrated Agile methodologies by developing hybrid project management models that combined Agile's flexibility with traditional regulatory requirements (Geraldi, Maylor, & Williams, 2011). A study from Turkey on the use of Agile in residential construction projects found that it improved teamwork on-site and cut down on mistakes. However, it was still hard to make Agile principles fit with strict safety and compliance rules (Alaidaros, Omer, & Romli, 2021).

A critical gap in the literature exists regarding the adaptation of Agile methodologies to Pakistan's construction sector. Most studies focus on developed economies, failing to consider cultural, economic, and regulatory factors that impact Agile adoption in developing countries (Arefazar, Nazari, Hafezi, & Maghol, 2022). Moreover, existing research does not sufficiently compare Agile and traditional project management approaches in construction within emerging markets, nor does it explore cultural and organisational barriers to Agile adoption in these regions (Gemino, Horner Reich, & Serrador, 2021).

This study seeks to bridge this knowledge gap by analysing Agile adoption in Pakistan's construction industry and assessing its benefits, challenges, and practical feasibility. By integrating insights from change management literature, this research examines cultural resistance and organisational hurdles, offering a structured roadmap for Agile adoption in Pakistan and other developing economies facing similar challenges.

This study aims to provide a comparative analysis of Agile and traditional project management approaches, highlighting their strengths, limitations, and practical implications for construction projects. It also attempts to determine critical success factors for Agile adoption, leveraging learnings from other sectors and developed economies to formulate a contextualised Agile framework for Pakistan. Using change management principles (Vijayasarathy & Turk, 2008), it also looks at the main things that make it hard to implement Agile, like cultural resistance, legal restrictions, and a lack of skills.

The study ultimately aims to develop a strategic roadmap for Agile integration in Pakistan's construction industry, offering practical recommendations for policymakers, industry leaders, and project managers. By aiming at these goals, this study adds to both theoretical knowledge and practical knowledge by promoting Agile methods to make construction projects in Pakistan and other similar emerging economies more efficient, flexible, and likely to succeed.

Table 1. Results Deduced After Analysing The Interview Data Thematically

Themes	Research Question	Code	Description	Example Quote
Contribution of Agile Methodologies	How Agile methodologies contribute to the management of construction projects	Flexibility in Agile	Refers to the ability to make changes to scope, design, or process as project conditions evolve.	If there is some new space requirement, we can go to the design team. We can make an extension in the building and adapt the plans accordingly.
	How Agile methodologies contribute to the management of construction projects	Team collaboration	Emphasises teamwork and collaboration in achieving project goals through better communication and unity.	Proactiveness, different team leadership, unity, decision-making... these are personal project manager roles which we can fit with.
	How Agile methodologies contribute to the management of construction projects	Time management	Relates to how Agile methodologies reduce time for project completion through iterative cycles.	We can reduce that in time processing and make a better use of technology to ensure timely project execution.
	How Agile methodologies contribute to the management of construction projects	Proactiveness	Highlights the ability to anticipate problems early and take initiative to prevent them.	Agile allows for teams to be proactive by predicting issues and make decisions on important matters ahead of time. This includes developing leadership, cohesion among the team members, and improving the decision-making process to solve the issues effectively.
	How Agile methodologies contribute to the management of construction projects	Stakeholder involvement	Focuses on including stakeholders in feedback loops to achieve project alignment and flexibility.	Because of its continuous improvement and collaboration with stakeholders, Agile is well positioned to deal with the unknowns and constraints of the construction projects.
Barriers to execution	Obstacles associated with implementing Agile in construction	Resistance to change	Talks about how some organisations or cultures don't want to use Agile methods because of their preference for traditional methods.	The resistance from the people's behaviour, team behaviour as they don't accept the changes in our project or in our scope.
	Obstacles associated with implementing Agile in construction	Budget management	Focuses on the efficient allocation and use of financial resources in construction projects.	Budget concerns arise due to resistance from clients when iterative processes require additional resources and changes during the project.
	Obstacles associated with implementing Agile in construction	Iterative process misalignment	Refers to the difficulty in aligning Agile's iterative cycles with the construction industry's linear workflows.	As with any other Agile methodology, the iterative process involves creating first drafts, then getting reviews and subsequently improving those drafts over time. In this case, we can imagine that a design is a variable at the beginning of the project, and over the course of the project, the design undergoes multiple rounds of changes to meet project requirements and stakeholder expectations.

Themes	Research Question	Code	Description	Example Quote
	Obstacles associated with implementing Agile in construction	Stakeholder involvement (challenges)	Misaligned expectations and goals might make it difficult to engage stakeholders on a continual basis in the construction industry.	It has been observed that clients are often the last people to embrace change when it comes to the Agile way of working, as they prefer fixed-end results rather than collaborating in an iterative environment. This mindset often prevents stakeholders from being involved effectively.
Strategies for mitigation	How obstacles can be mitigated or overcome to improve Agile in construction	Team collaboration (solution)	Getting team members to work together can help lower criticism and improve Agile methods and goals.	It takes considerable effort to build an effective team as project managers need to possess the right abilities that drive proactive leadership, promote intrateam cohesion, and allow for timely decision-making. These characteristics help to curb the resistance when introducing the Agile principles and practices into the norm.
	How obstacles can be mitigated or overcome to improve Agile in construction	Flexibility in Agile (solution)	Drawing attention to the benefits of being flexible can help get people on board with Agile methods and lessen resistance.	If there are some new space requirements, we can go to the design team, make an extension in the building and integrate it seamlessly into the plan.
	How obstacles can be mitigated or overcome to improve Agile in construction	Stakeholder involvement (solution)	Improved stakeholder engagement reduces misalignment and fosters collaboration, addressing resistance to Agile.	Continuous improvement and stakeholder collaboration make them well-suited for uncertainties and challenges, ensuring alignment with project goals.
	How obstacles can be mitigated or overcome to improve Agile in construction	Proactiveness (solution)	Proactive planning and addressing issues early mitigate implementation challenges and ensure project continuity.	Proactiveness entails anticipating possible issues in advance and making prompt choices to avoid delays to the project schedule.

METHODOLOGY

This research employs a qualitative research design involving semi-structured interviews to analyse the adoption, benefits, and challenges of Agile approaches in the construction sector. We adopted a qualitative approach to gain a thorough understanding of participants' experiences, viewpoints, and challenges, which are difficult to convey in quantitative designs. Such a methodology is particularly suitable for investigating Agile adoption, where personal experience and differences in context play a crucial role (Poth & Shannon, 2022).

A purposive sample method was used to pick 10 respondents, ensuring that only experts with direct expertise in Agile project management were included. The sample size was determined according to the idea of data saturation when more data fails to provide further insights (Guest, Bunce, & Johnson, 2006). Taking into consideration the qualitative nature of the research, this sample size is enough to capture a variety of viewpoints while yet preserving the depth of replies. The participants were carefully selected from various roles across the construction industry, ranging from project managers and engineers to construction coordinators and top executives. Their combined experiences provided an effective understanding of the deployment of Agile. All participants have a minimum of five years of experience in construction project management and were well-versed in Agile methodology, guaranteeing that their comments were educated and indicative of real industry expertise.

The data was gathered via semi-structured interviews done via video conversations, each lasting 45 to 60 minutes. This approach ensured uniformity in questions while enabling participants to give more information on their experiences. The interviews focused on the extent of Agile adoption in the construction industry, issues faced during the implementation of Agile methodology, perceived advantages, including project flexibility, efficiency, and stakeholder engagement, and solutions to mitigate obstacles to Agile adoption.

Thematic analysis, according to Braun & Clarke's (2019) paradigm, was used to examine the interview data (Figure 1). The procedure began with data familiarisation, where we transcribed and reread interviews repeatedly to gain comprehensive knowledge. Subsequently, basic coding was conducted to identify essential ideas pertaining to Agile adoption, obstacles, and advantages. The codes were then categorised into overarching topics, including flexibility, stakeholder participation, and project efficiency. Themes were meticulously examined to guarantee coherence and relevance prior to their finalisation with explicit definitions. A coding framework was established to systematically classify replies, guaranteeing consistency and reliability in data interpretation.

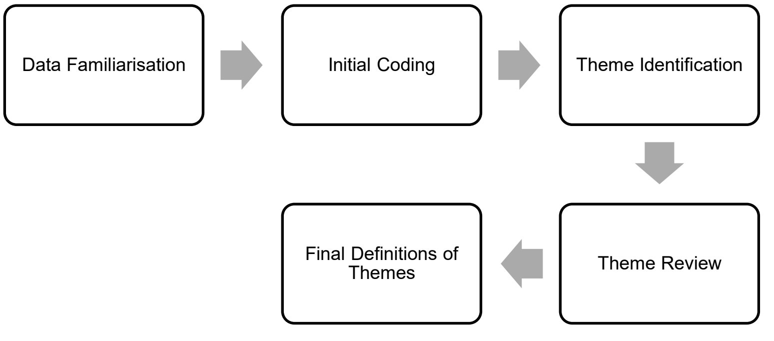

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Figure 1. The Figure Shows The Process of Thematic Analysis

Various measures were used to improve the credibility and reliability of the results by mitigating bias. Triangulation was used by comparing data with existing literature to authenticate opinions. Member verification was performed, whereby participants received a summary of the results to verify the correctness of their replies (Lincoln & Guba, 1985). Furthermore, investigator reflexivity was maintained, with the researcher consciously reflecting on any biases and maintaining neutrality throughout data collection and analysis.

Ethical issues were a fundamental aspect of the study process. All participants were granted informed permission prior to the interviews, confirming their comprehension of the study's goal and scope. Their names remained anonymous, and all replies were anonymous in the final study. By confronting these ethical issues, the study guaranteed openness and integrity in its research methodology.

DATA ANALYSIS

This research examines the use of Agile techniques in the management of construction projects, specifically in relation to dynamic and unexpected situations. The study is directed by three thematic questions that are addressed during the interviews. The study uses thematic analysis of interview transcripts from experts in the construction industry to look into the pros and cons of Agile deployment.

Statistical Analysis

Ten individuals participated in the research. The participants were professionals from several construction industries who had varying levels of expertise in Agile project management. Below is a list of the participant's demographic characteristics. All participants possessed at least a master's degree in a relevant field, ensuring their expertise in Agile project management and related terminology (Figure 2). This educational background illustrates a strong fundamental understanding of the issues being investigated.

Professional Designation: Each participant held a key position within the organisation, enabling them to understand and effectively implement Agile methodologies, thereby improving both their projects and their organisations (Figure 3).

The graph illustrates the total experience of the respondents, showing that the majority (7 out of 10) have 6–10 years of experience in the construction industry, with no participants reporting less than 5 years or more than 25 years of experience (Figure 4).

Each of the respondents had significant expertise in the construction industry, with each respondent having over five years of relevant experience (Figure 5).

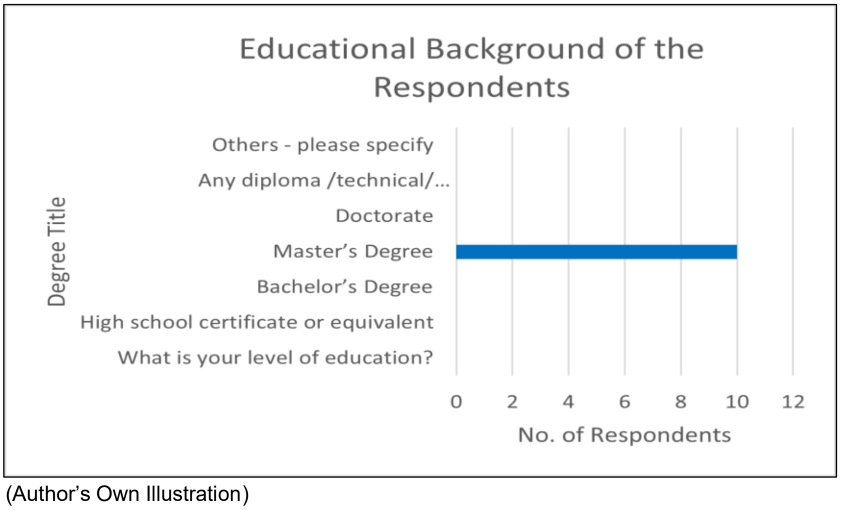

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Figure 2. Segmentation of Respondents by Educational Level from The Data Collected in 2024 in Pakistan

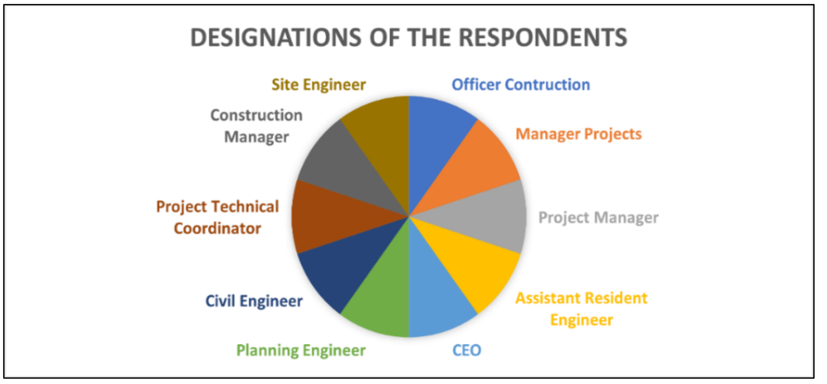

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Figure 3. Sample Division Based on The Designation of The Respondents from The Data Collected in 2024 in Pakistan

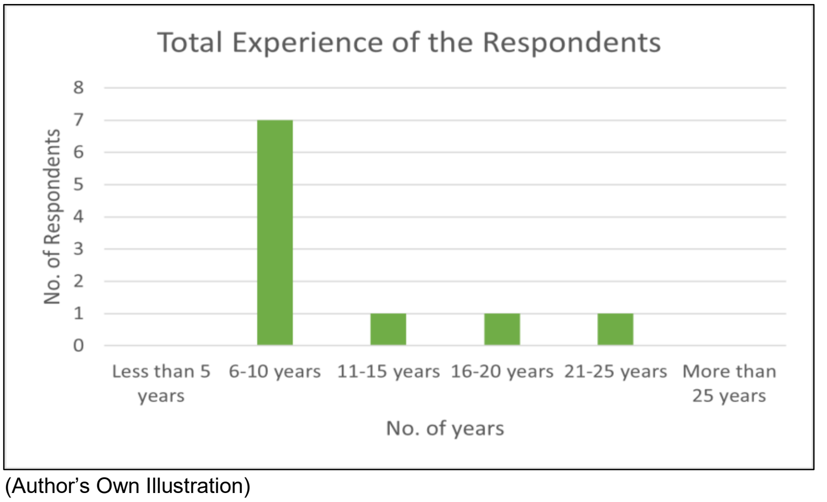

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Figure 4. Graph Showing The Total Experience of Respondents from The Data Collected in 2024 in Pakistan

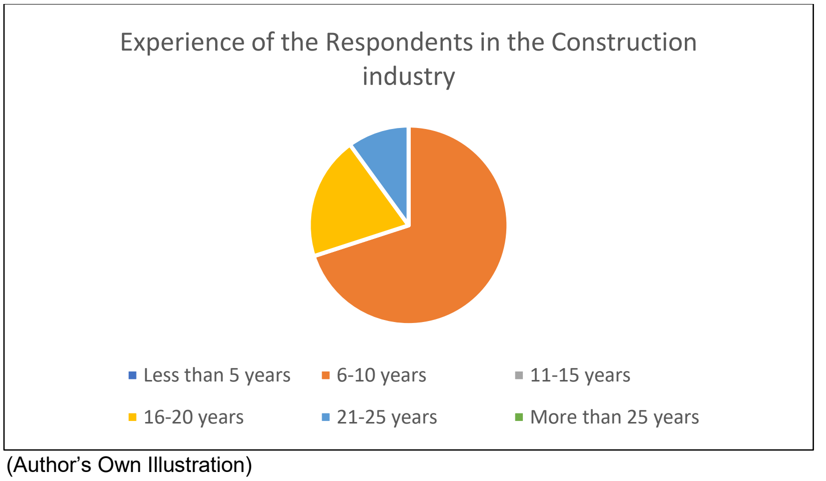

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Figure 5. Sorted Graph of The Sample Showing The Experience of Respondents in The Construction Industry from The Data Collected in 2024 in Pakistan

The number of projects all participants had engaged in served as a measure of their profound comprehension of project management and the many elements of Agile techniques (Figure 6).

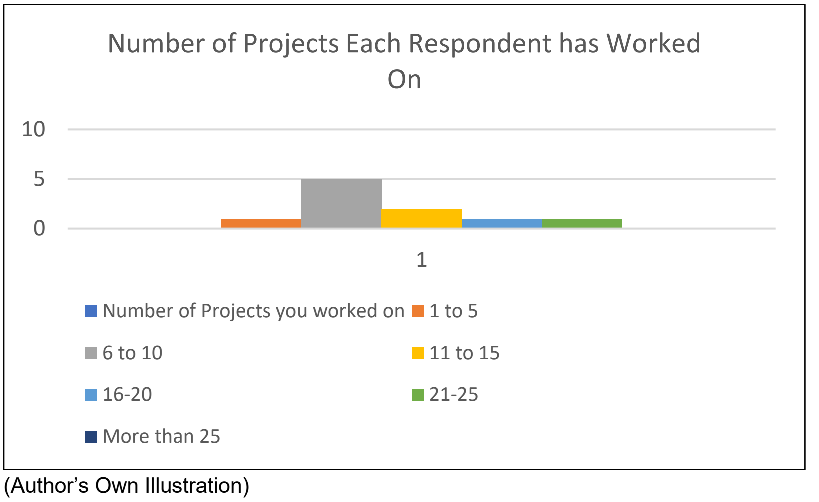

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Figure 6. A Graph Showing The Number of Projects Each Respondent has Worked On in The Construction Industry Based on The Data Collected in 2024 in Pakistan

Thematic Analysis

Agile methodologies, as a comparatively new development in managing processes within the construction industry, have gained popularity for their ability to handle dynamic and unpredictable project environments (Sithambaram, Nasir, & Ahmad, 2021). This theme study aims to investigate the contributions that Agile makes to the success of projects, identify the obstacles that stand in its way, and propose the tactics that may be used to overcome these issues. The results, which came from a proper qualitative investigation of the opinions of experts in the field, give us important information about how Agile techniques and construction project management work together and change over time (Figure 7).

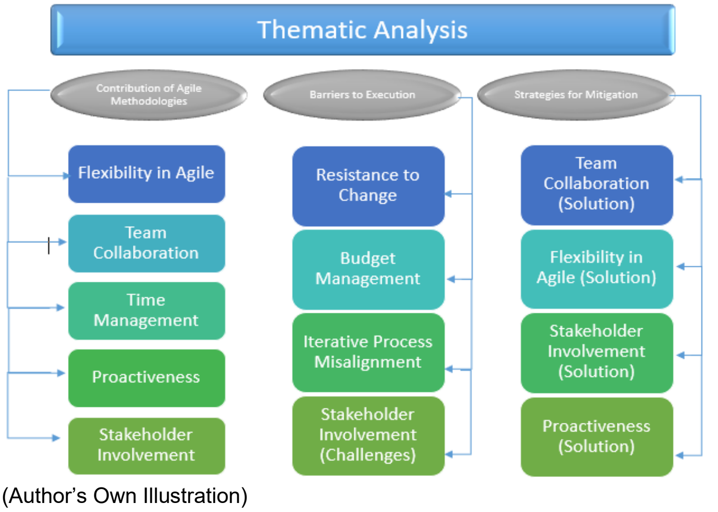

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Figure 7. The Figure Shows The Identified Themes, Codes and Their Relationships

DISCUSSION

Contributions of Agile Methodologies

The study identified five core contributions of Agile methodologies in construction: flexibility, team collaboration, time management, proactiveness, and stakeholder involvement. These themes emerged prominently in the data, confirming their relevance to enhancing construction project management efficiency. The adaptability of Agile techniques allows construction teams to navigate unpredictable circumstances, ultimately leading to higher efficiency and improved project outcomes (Albuquerque et al., 2020).

Flexibility in Agile

The most frequently mentioned benefit of Agile was flexibility, cited by nearly all participants. The ability to adapt to changing project needs was regarded as a crucial feature of Agile methodologies. Participants emphasised that flexibility allows teams to accommodate scope changes and client demands without disrupting project timelines or compromising quality (Said et al., 2020). One respondent noted, "If there is some new space requirement, we can go to the design team. We can make an extension in the building and adapt the plans accordingly."

This theme underscores the significance of adaptability in construction, where unforeseen challenges, supply chain disruptions, or regulatory modifications frequently necessitate rapid adjustments. Previous research has also emphasised Agile's role in fostering adaptability, particularly in construction projects that deal with frequent design changes, urban regulatory shifts, and evolving client expectations (Ghosh et al., 2021). The findings align with studies in Singapore and the Netherlands, where Agile-driven flexibility led to faster approvals and improved response times in urban construction projects (Vrijhoef & Koskela, 2005).

Team Collaboration

Another major theme was collaboration, which was highlighted by approximately 80% of participants. Agile encourages cross-functional teams to actively communicate, take responsibility, and ensure workflows remain smooth. Collaboration enhances workflow efficiency and accelerates decision-making, particularly in intricate projects that require constant adjustments. One participant observed, "We integrate proactiveness, different team leadership, unity, and decision-making into Agile project management."

These findings are consistent with research conducted in Turkey and Chile, where Agile construction methodologies improved multi-stakeholder collaboration, reducing interdepartmental delays and enhancing transparency in design approvals (Herrera, Mourgues, Alarcón & Pellicer, 2019). This result aligns with Agile literature, which emphasises cross-team engagement as a core pillar of Agile project management (Ciric Lalic et al., 2022).

Time Management

Seventy per cent of respondents cited time management as one of the primary benefits of Agile construction. Agile's iterative scheduling and resource optimisation techniques enable teams to maintain project momentum despite unexpected challenges. One interviewee explained, "We can economise on time and use devices properly to make sure that the project reaches completion on the due date."

This finding is particularly relevant in the context of Pakistan's construction sector, where delays in government approvals and material supply chain inefficiencies frequently impact project timelines (Hayat et al., 2022). Studies in Brazil and India have shown that Agile scheduling techniques reduce project overruns by up to 35%, reinforcing the importance of Agile time management practices in construction (Serrador & Turner, 2014).

Proactiveness

Sixty per cent of respondents identified proactiveness as an essential feature of Agile methodologies. Proactive project management involves anticipating risks and planning solutions before issues escalate. One respondent explained, "Being proactive enables the team to anticipate potential delays or risks and address them before they escalate, ensuring smoother project execution."

The results back up earlier research on Agile risk management in construction, which showed that proactive strategies make projects 40% more resilient in high-risk settings like building infrastructure and modular homes (Dikert et al., 2016).

Stakeholder Involvement

Fifty per cent of the respondents emphasised stakeholder involvement, particularly in ensuring that project deliverables align with client expectations. Agile's continuous feedback loops keep stakeholders engaged, leading to higher satisfaction and better project adaptability. One participant stated, "Continuous improvement and stakeholder collaboration make Agile well suited for addressing uncertainties and challenges in construction projects."

This theme resonates with research from South Africa and the UAE, where Agile stakeholder engagement models resulted in a 25% increase in project approval rates. Enhancing communication between developers, clients, and regulatory bodies is essential to overcoming resistance and ensuring smooth project execution.

Obstacles to Agile Implementation

The analysis also revealed four significant obstacles to Agile implementation: resistance to change, budget management challenges, iterative process misalignment, and stakeholder involvement challenges. These barriers highlight the complexities of integrating Agile methodologies into traditional construction workflows.

Resistance to Change

Nearly all respondents cited resistance to change as the most significant barrier. Agile's non-linear processes often clash with conventional, phase-based project management approaches, leading to reluctance among stakeholders and team members. One respondent remarked, "The resistance from people's behaviour... they don't accept the changes in our project or in our scope."

Cultural resistance is a common challenge in construction (Sohail & Cavill, 2008). Studies in Turkey and Malaysia suggest that aggressive change management strategies, including stakeholder education and pilot Agile projects, can reduce resistance by 50% (Babalola et al., 2019).

Budget Management Challenges

Seventy per cent of participants cited budget constraints as a key obstacle. Agile's iterative processes often introduce new expenses, particularly when clients fail to account for ongoing adjustments (Sin, Choy & Fung, 2020). One participant explained, "When clients realise that iterative processes require multiple refinements, they often become hesitant about additional costs."

Research from Brazil and India has shown that incremental cost transparency and early-stage budget flexibility agreements can reduce Agile-related budget overruns by 30%.

Iterative Process Misalignment

Sixty per cent of respondents pointed to misalignment between Agile's iterative approach and the traditional construction workflow. Construction relies heavily on fixed schedules and sequential deliverables, making it difficult to implement Agile's adaptive cycles. One participant noted, "We propose design #1, design #1A, and design #1B to plan for various possibilities, but the linear workflows resist iterative updates."

Stakeholder Involvement Challenges

Fifty per cent of the respondents spoke about the issues of engagement of the stakeholders, which reveals the problem of embedding the stakeholder standards into Agile measurements. There are clients who do not want to go through the entire circle of making decisions every now and then but would rather prefer that the result has already been set. One responder said, "Clients were resistant to the collaborative approach; they wanted fixed outcomes instead of the continuous improvement that Agile methods suggest."

To solve these problems, we need to communicate clearly and teach stakeholders about the benefits of Agile methods.

Strategies for Mitigation of Obstacles

The research identified four strategies to deal with those challenges: increasing team collaboration, using flexibility as an asset, improving stakeholder engagement, and practising proactivity. Such strategies suggest pragmatic ways of integrating Agile methodologies into the business of construction project management.

Improving Team Collaboration

There was a very high response from the participants (80%), who said that the most usual tactic was trying to get all the team members to work in unison. Change management methods within an organisation entail the formation of change leaders who can communicate changes effectively, taking responsibility for the team in its entirety in order to reduce the negative impacts of change that may occur at the time of deploying the Agile methodologies (Chambers et al., 2022). One participant stated, “Proactiveness, different team leadership, unity, and decision-making foster a culture of collaboration and help address resistance to Agile adoption.”

Highlighting Flexibility as a Strength

Educating stakeholders about the benefits of flexibility was cited by 70% of respondents as a critical strategy. By presenting flexibility as a strength, project managers can illustrate how iterative procedures efficiently accept changes, which eventually leads to improvements in the overall results of the project. One participant said, “Should there be new space requirements, we may speak with the design team to create an extension in the structure while ensuring it is seamlessly integrated into the overall plan.”

Enhancing Stakeholder Engagement

60% of respondents agreed that stakeholders need to be involved early and continuously so that resistance is reduced and cooperation is built. The feedback loop can be obtained at regular intervals, ensuring the issues of stakeholders are addressed to ensure greater trust and alignment. One said, "They are good at handling uncertainty and problems because they are always improving and involve stakeholders with their process, which makes sure they remain in control of the objectives of a project.

Encouraging Proactiveness

Half of the participants said that one way to help reduce obstacles is by encouraging proactivity. Active planning helps teams to foresee possible problems and act before they become more serious, therefore preserving project momentum and guaranteeing continuity (Yang, Yu, & Zhu, 2020). "Proactive involvement entails planning for possible problems ahead of time and acting quickly to stop disturbances in the project schedule," one respondent said.

RESULTS

The thematic map represents the key findings of this study by visually organising the relationships between the contributions of Agile methodologies, barriers to Agile adoption, and mitigation strategies within the Pakistani construction industry (Figure 8). The map highlights how Agile methodologies impact construction project management, the obstacles that hinder their adoption, and the possible solutions to overcome these challenges.

At the core of the thematic map are three primary themes:

Contributions of Agile (benefits) – Agile methodologies offer several advantages that enhance project efficiency and adaptability. These benefits include:

- Flexibility: Agile allows for real-time adjustments in project scope and design without disrupting overall workflows.
- Stakeholder engagement: Continuous collaboration and feedback loops help in aligning project outcomes with client expectations.
- Time efficiency: Agile-driven iterative cycles accelerate project delivery and reduce delays.
- Proactiveness: Agile teams anticipate risks early, leading to proactive decision-making and problem resolution.

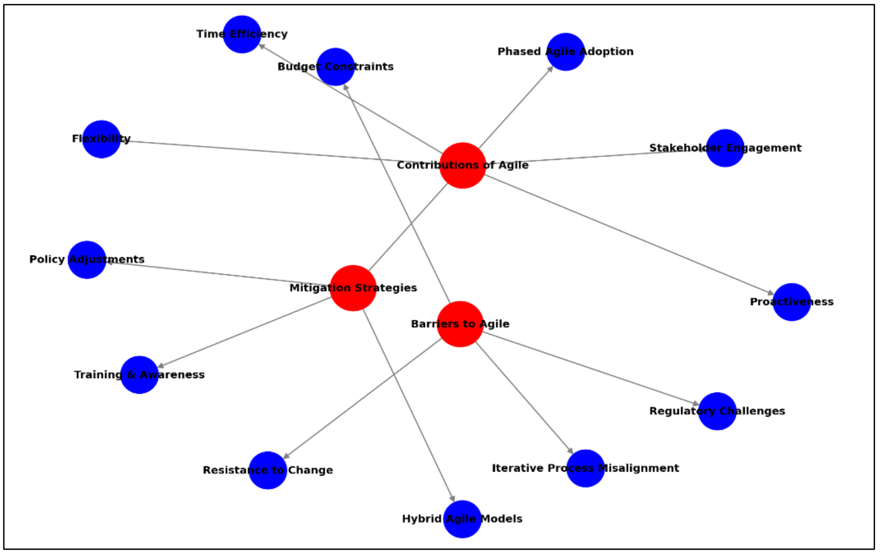
Barriers to Agile adoption (challenges) – Despite its benefits, Agile adoption in Pakistan's construction sector faces significant challenges, including:

- Resistance to change: Many construction professionals are accustomed to traditional project management techniques and are reluctant to adopt Agile.
- Budget constraints: Agile's iterative nature may lead to increased costs due to frequent modifications.
- Iterative process misalignment: The construction sector follows a linear workflow, which conflicts with Agile's cyclical approach.
- Regulatory challenges: Rigid contract structures and government regulations make Agile's flexible implementation difficult.

Mitigation strategies (solutions) – To address these barriers, various strategies can be implemented:

- Training & awareness: Educating professionals about Agile benefits can reduce resistance to change.
- Phased agile adoption: Gradual implementation of Agile principles in pilot projects can ease the transition.
- Policy adjustments: Reforming contractual regulations can make Agile more applicable in construction projects.
- Hybrid Agile models: Combining Agile with traditional project management can create a balanced approach tailored to the industry's needs.

The thematic map visually links these themes, illustrating how Agile methodologies influence project performance while also identifying the key barriers and solutions for its successful adoption in the Pakistani construction industry. It serves as a structured representation of the study's findings, offering a clear roadmap for industry stakeholders, policymakers, and researchers to enhance project efficiency through Agile methodologies.



(Author's Own Illustration)

Figure 8. The Figure Shows The Thematic Map of Agile Adoption in The Pakistani Construction Sector

CONCLUSION

This research shows how Agile strategies can totally transform the way construction projects are managed. Agile approaches enhance flexibility, collaboration, time management, proactiveness, and stakeholder involvement in handling the challenges of dynamic project settings. Change resistance, financial constraints, and potential misalignment of iterative processes among stakeholders negatively impact these approaches. Fostering collaboration, flexibility, stakeholder engagement, and proactiveness offers potential solutions to these challenges. The results are significant for professionals in the industry who want to adopt Agile in construction and enhance adaptive and resilient project management practices.

Limitations & Future Research

This study is limited by its small sample size (10 respondents) and reliance on qualitative interviews. Future research should explore larger surveys and conduct longitudinal studies on Agile adoption in Pakistan. Moreover, the study can be conducted through quantitative means to measure Agile's impact on cost and time savings. Also, a comparison of Agile adoption across multiple developing countries can be done to identify global best practices.

Future Recommendations

To facilitate Agile adoption in Pakistan's construction industry, several actionable recommendations are proposed:

1. Training programs: Industry stakeholders should invest in Agile training workshops for project managers, engineers, and contractors to enhance awareness and skill development.

2. Pilot projects: Organisations can introduce Agile through small-scale pilot projects before full-scale implementation, allowing for gradual adaptation.
3. Regulatory support: Policymakers should consider revising contract structures to allow more flexibility in project scope, enabling Agile's iterative approach.
4. Change management strategies: Resistance to change can be mitigated by implementing structured change management programs, including stakeholder engagement sessions and collaborative decision-making frameworks.
5. Technology integration: The use of Agile-supporting digital tools, such as Building Information Modelling (BIM) and cloud-based project management software, can streamline workflows and improve communication.

By implementing these recommendations, Pakistan's construction sector can overcome existing challenges and leverage Agile methodologies to enhance project efficiency and adaptability.

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APPLICATION OF PRINCIPAL COMPONENT ANALYSIS FOR EVALUATING THE BARRIERS OF IMPLEMENTING DIGITAL TWINS IN SUSTAINABLE CONSTRUCTION PROJECTS

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Abstract
Digital twin technology is a promising tool for enhancing sustainability in construction projects by providing a virtual representation of the physical assets and the processes. It can also improve the sustainability performance of construction projects by leveraging real-time data analytics and simulation capabilities, enabling proactive decision-making, predictive maintenance, and performance optimisation. Despite its potential, the adoption of digital twin technology remains low and slow. This research investigates the barriers to implementing digital twins in sustainable construction projects using Principal Component Analysis. Primary data were collected through a structured survey questionnaire. The analysis identified key barriers to integrating digital twin technology to support sustainability goals, including clients' reluctance to pay for such services, the high cost of technology investments for construction companies, a lack of expertise within organisations, cultural resistance in construction companies, data quality issues, limited collaboration among project team members, data compatibility challenges, and staff resistance to change. The analysis revealed four key barriers comprised of Policy, Structure, Cost, and Complexity, which collectively explained over 80% of the model's variance with satisfactory second-order reliability (0.882–0.945) and convergent validity (0.736–0.959). These findings highlight the multifaceted challenges organisations face, ranging from interoperability and leadership support to project size and data-related problems. These findings provide valuable insights into the challenges of adopting and integrating digital twin technology in sustainable construction management. They also offer a foundation for future research and the development of effective industry implementation strategies.

Keywords: *Construction Company; Profit Margin; Digitalisation; Resource Management; Clients*

INTRODUCTION

The construction sector has undergone a paradigm shift toward sustainable practices in recent years, driven by the urgency to mitigate climate change, address resource constraints, and respond to increasing environmental and community awareness. Emerging technologies have become essential tools to achieve construction sustainability targets by enhancing the efficiency, effectiveness, and environmental performance of construction projects. Among these technologies, digital twins have gained significant attention for their transformative potential in how construction projects are conceived, designed, developed, constructed, and managed. A digital twin is a real-time, virtual representation of a physical system, object, or process that mirrors or simulates its real-world counterpart (Grieves & Vickers, 2016; Zhang, Cheng, Chen & Chen, 2022). Essentially, a digital twin is a personalised, dynamic virtual model of an asset, process, city, product, place, or event. It enables stakeholders to visualise, interact with, and analyse assets within a virtual environment. As digital twin technology evolves, it empowers stakeholders to predict, simulate, and manage asset performance, offering actionable insights to enhance decision-making. Digital twin models integrate a variety of sensors, IoT (Internet of Things), and IoE (Internet of Everything) technologies embedded within assets such as smartwatches, motion sensors, temperature sensors, smart lights, and smart plugs, along with external data sources like meteorological data, water and gas usage metrics, and solar energy information. When represented in 3D, digital twins provide intuitive and effective visualisations, improving stakeholder engagement and understanding. Initially developed for the manufacturing and aerospace sectors, digital twins are increasingly being applied in the construction industry to enhance project outcomes, optimise resource use, and reduce environmental impacts. Despite their proven capabilities in achieving project efficiency and sustainability (Su, Zhong, Jiang, Song, Fu & Cao, 2023; Olanrewaju, Sanmargaraja, Oni, Anavhe & Mewomo, 2024), their implementation in construction remains limited and slow. This study aims to investigate the barriers to implementing digital twin technology to improve the sustainability performance of building projects using data collected through a survey questionnaire.

BACKGROUND AND THEORETICAL FRAMEWORK

The construction sector remains the least mechanised and digitised compared to other major economic sectors. However, the adoption of digital technologies in construction is growing steadily, driven by the need to enhance productivity, profit margins, collaboration, and competitiveness. Digital technologies encompass various tools, processes, and materials used across the lifecycle of buildings and infrastructure, from planning and design to construction and operation. Key technologies include Building Information Modelling (BIM), 3D printing, robotics and automation, augmented and virtual reality, drones, the Internet of Things (IoT), and digital twins. McKinsey (2020) introduced an industry map that highlights the interconnectedness of various digital technologies, a concept further explored by Olanrewaju et al. (2024), who developed a framework illustrating relationships among multiple construction technologies. Such connectivity is critical as it facilitates seamless data exchange, process integration, and workflow optimisation across projects and organisations. Construction technologies, specifically designed for the sector, are rapidly transforming its operations. Construction technologies aim to minimise inefficiencies and low productivity caused by poor collaboration, repetitive tasks, and lack of trust and communication (McKinsey, 2020). For example, demand for digital collaboration tools, wearables, BIM, 3D printing, artificial intelligence, and modular construction has surged significantly (Industry Dive, 2022). Digital construction is being utilised for purposes such as increasing productivity, improving safety/reducing risk, saving costs, addressing skill shortages, improving project delivery confidence, and shortening project durations. Among the prominent construction technologies, digital twins have emerged as a prominent tool with increasing adoption Olanrewaju, Sanmargaraja, Oni, Anavhe & Mewomo (2024). Construction digital twins are virtual counterparts of physical structures or infrastructure created using real-time data from sensors, IoT devices, and other sources. A digital construction twin typically relies on five key components to monitor and evaluate a construction project in the virtual environment: the physical asset, its digital counterpart, and the connection linking the two. Unlike a static 3D replica, a digital twin is dynamic, continuously updating and evolving with new information, even after the completion of construction. Several studies have explored the application of digital construction twins, highlighting their transformative potential (Jiang, 2021; Zhang, et al., 2022; Madubuike, Anumba, & Khallaf, 2022). Figure 1 illustrates the processes and data required to develop a digital construction twin, as described by Olanrewaju et al. (2024).

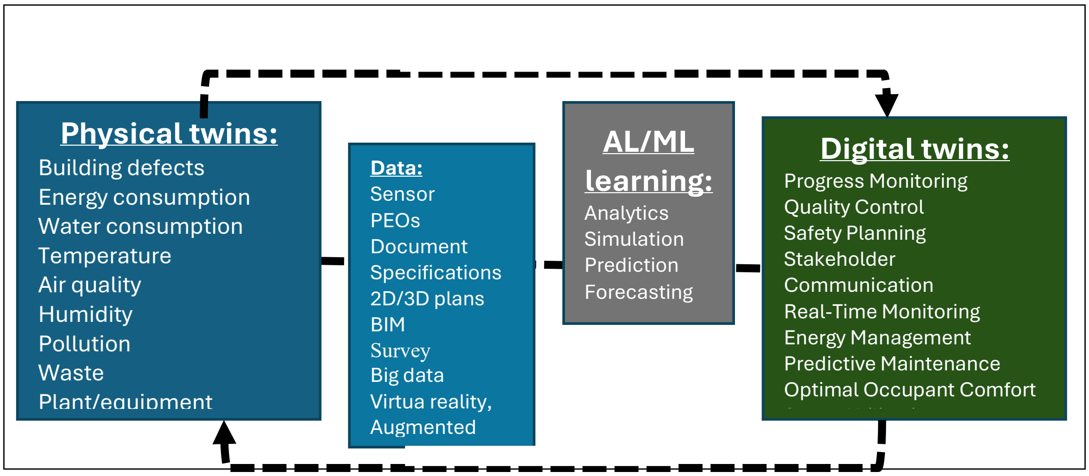

Figure 1. Mechanism for The Operation of Digital Twins for A Building

Digital twins are developed by collecting extensive data on real-world objects, processes, or locations and replicating them in a virtual environment. Utilising artificial intelligence (AI) and machine learning (ML), digital twins simulate and analyse the effects of changes in design, processes, time, or conditions without applying these changes to the physical counterpart. This approach provides predictive insights and supports informed decision-making while preserving the integrity of the physical entity. Digital twins empower design teams to test and evaluate various scenarios, enabling early detection of potential problems and optimisation of designs through a digital replica of the physical structure. This minimises errors, ensures compliance with project standards, and improves overall quality. Construction managers benefit by tracking progress, identifying potential inefficiencies, and addressing problems that inflate costs but do not add value before they escalate. Digital twins also enhance communication among project stakeholders, fostering collaboration. They can improve building maintenance and operational efficiency by 35%, reduce carbon emissions and carbon footprints by 50%, increase user productivity by 20%, and optimise space utilisation by 14% (Lukesh et al., 2023). These advantages help ensure budget adherence and efficient resource utilisation. Moreover, digital twins enable proactive identification of safety hazards and risks during construction, contributing to safer project environments (Azhar, 2017). Recent studies indicate that implementing digital twins in buildings can reduce energy consumption by 25%, lower maintenance costs by 15%, and significantly decrease on-site accidents. These findings underscore the transformative potential of digital twin technology in the construction sector.

Sustainable Construction and Digital Twins' Implementation

Sustainable construction has become a critical priority in response to escalating environmental concerns and the need for climate resilience approaches. Despite post-pandemic challenges, the sustainable building market has demonstrated remarkable resilience. According to Acumen Research and Consulting, the market for green construction is projected to reach $774 billion by 2030. Additionally, recent outcomes from COP29

(Conference of the Parties) reaffirm the urgent need to adopt sustainable construction practices to meet global climate goals. Looking toward 2050, several key trends will shape sustainable construction, including advanced materials, innovative technologies, and enhanced methods to reduce waste, accidents, pollution, emissions, and environmental degradation. However, the path to delivering sustainable construction is fraught with challenges arising from technical, financial, organisational, and regulatory complexities. For instance, sustainable construction often demands greater upfront investment due to specialised materials, advanced technologies, and meticulous design processes. These costs can deter adoption, especially when budget constraints dominate decision-making. Also, many construction professionals lack the requisite training or expertise to implement sustainable practices effectively, creating a significant skills gap (Olanrewaju, 2022). This highlights the need for industry-wide educational initiatives and professional development programs. Navigating the complex regulatory environment is challenging, as sustainable construction relies on environmentally compliant, durable, and efficient materials. Meeting these requirements can increase project timelines and complexity.

The construction sector is traditionally conservative and often reluctant to adopt new technologies or practices. Resistance stems from scepticism about long-term benefits and the additional resources required for implementation. Developers and contractors may prioritise cost savings and quick returns on investment over sustainability goals. When clients do not prioritise sustainability, contractors may find it difficult to justify the additional expenses and efforts. In addition, the fragmented nature of the construction sector, involving multiple stakeholders in a single project, complicates efforts to achieve cohesive sustainability targets. Digital twins offer a promising opportunity for many of these challenges. By providing a dynamic, real-time virtual representation of construction projects, digital twins enable cost and resource optimisation through simulation and predictive analysis; digital twins can minimise waste and reduce project costs over time. Improved communication and coordination among stakeholders are facilitated by shared, real-time insights. It also provides a platform for training and skill enhancement, bridging the expertise gap. By modelling and validating sustainable design options, digital twins help ensure compliance with environmental and building regulations. Potential hazards and inefficiencies can be identified and addressed proactively. A sustainable construction of digital twins takes the concept of digital twins and applies it to sustainable construction either to a new sustainable built or existing sustainable construction. However, the application of the technology to sustainable construction is relatively new, and there is currently no agreed-upon definition of sustainable building digital twins. However, some essential components have been identified:

Building Model and 3D Visualization

This component involves creating a detailed digital replica of the building in 3D, capturing structural, architectural, and spatial details. The model should encompass sustainable design features, such as natural lighting optimisation, water-efficient fixtures, and green materials, to support planning and monitoring.

Integration of Building Systems and Sensor Data

Digital twins should connect with IoT-enabled sensors throughout the building to monitor real-time data on energy use, water consumption, indoor air quality, temperature, and occupancy. This integration allows for precise tracking and adjustment of building performance, enabling proactive measures to reduce environmental impact.

Sustainability and Energy Efficiency Modelling

This involves simulating building performance for energy efficiency, renewable energy use, and emissions. Models should capture the behaviour of HVAC systems, lighting, and other energy-relevant processes to predict and optimise energy efficiency, carbon footprint, and overall sustainability performance in real-time.

Predictive Maintenance and Resource Optimization

Digital twins can support predictive maintenance by identifying potential problems in equipment and systems before they lead to failures. This includes optimisation of resources by managing equipment lifecycle, reducing material waste, and prolonging the use of sustainable assets, which in turn minimises the building's environmental footprint.

Performance Analytics and Optimization Algorithms

Analytics powered by AI and machine learning can assess performance trends, identify inefficiencies, and provide recommendations for sustainable optimisation. This component allows the digital twin to continually improve building operations, providing actionable insights that support long-term sustainability goals, such as achieving net-zero energy consumption.

Despite the significant benefits of digital twins in sustainable construction, their adoption remains limited due to various barriers. Without a clear understanding of these obstacles, the construction sector cannot fully capitalise on the potential benefits of digital twin technologies. This raises an important epistemological question: What are the barriers to implementing digital twins in sustainable buildings? Identifying these barriers is crucial for promoting sustainable practices and achieving a truly sustainable built environment. Understanding these barriers will also enable the sector to optimise digital twin integration and maximise its contribution to sustainability goals. As academic literature on digital twin technologies and sustainable construction continues to evolve, research in this area will significantly enrich the body of knowledge. It will provide the empirical evidence and theoretical insights necessary to guide future studies and inform the development of practical solutions for overcoming implementation challenges.

METHODOLOGY

The primary data were collected based on convenience sampling. Similar to other survey methods, it is inductive in nature. Convenience sampling is a data collection method where surveys are administered to available, accessible and willing respondents. It is an appropriate technique where sufficient information on population size and sample frame is not available. However, its findings may not be generalisable, but with a large number of respondents, the findings can be representative. Thus, its basic premise is that if sufficient data are collected and objectivity is maintained, the results will be representative of the population (Olanrewaju & Idrus, 2020). The questionnaires were administered to the respondents online. The survey was conducted from July 2023 to September 2023. Respondents were asked, based on evidence, to tick the degree to which they accept that each of the barriers will obstruct the implementation of digital twins in the delivery of sustainable buildings. The degrees of agreement were measured on a four-continuum scale, where 4 denoted the extreme barrier and 1 denoted the least barrier. Two and 3 were located in between. The questionnaire went through two pilot surveys that comprised relevant stakeholders. The extent of the barriers was determined by an Average Barrier Index. For interpretation purposes, an ABI score of 1.00 – 25.00 denotes less barrier; 26.00-50.00 denotes moderate barrier; 51.00 – 75 denotes strong barrier, and 76.00-100.00 denotes extreme barrier. The barrier with the highest ABI score is the most severe barrier. Other statistical tests computed were the one-way t-test, Cronbach alpha's reliability test, the convergent validity test, the factor analysis test, the mode test, and the standard deviation test. JASP was used to analyse the data.

Principal Component Analysis for The Barriers to Implementation of Digital Twins for Sustainable Buildings

Conducting principal component analysis (PCA) on barriers to the implementation of digital twins for sustainable buildings is required for many reasons. PCA reduces the complexity of the data by transforming it into a set of uncorrelated components. This simplification helps in understanding the most significant barriers without being overwhelmed by the numerous variables involved in the analytical examinations. By focusing on the principal components, the key barriers that need to be addressed for the successful implementation of the technologies can be identified holistically. This prioritisation is crucial for resource allocation and strategic planning, enabling stakeholders to focus their efforts on the most impactful problems. By clarifying which barriers are the most significant, PCA provides valuable insights that can inform better decision-making. Understanding the holistic barriers allows for the development of targeted strategies and interventions to overcome these obstacles, facilitating better implementation. PCA provides a data-driven approach to understanding the barriers, ensuring that strategies are based on empirical evidence rather than assumptions.

RESULTS OF THE SURVEY

The survey was administered to well over 500 respondents. However, 36 online responses were received by the deadline, following multiple reminders.

Analysing The Respondents' Profile

According to the findings, almost 90% of respondents have more than five years of work experience, while around 40% have more than ten years (Table 1). Table 2 contains the respondents' locations. Investment in construction technology is modest (see Table 3). The respondents held strategic positions (Figure 2).

Table 1. Respondent's Work Experience (In Years)

Year	Less Than 5	5 To 10	11 – 15	16 – 20	More Than 20
Frequency	4	10	8	22.2	8
Percentage	11.1	27.8	22.2	16.7	22.2

Table 2. Respondent's Location

Year	Malaysia	Singapore	Nigeria	Pakistan	Other
Frequency	9	6	12	3	6
Percentage	25.0	16.7	33.3	8.3	16.7

Table 3. How Much Did The Respondent's Company Invest in The Construction of Digital Twins?

Investment	Percentage	Cumulative Percentage
Less than 5%	13	40.625
5% to 10%	3	9.375
10% to 15%	5	15.625
15% to 20%	3	9.375
20% to 25%	2	6.25
25% to 30%	2	6.25
35% to 40%	1	3.125
40% to 45%	2	6.25
50 and above	1	3.125

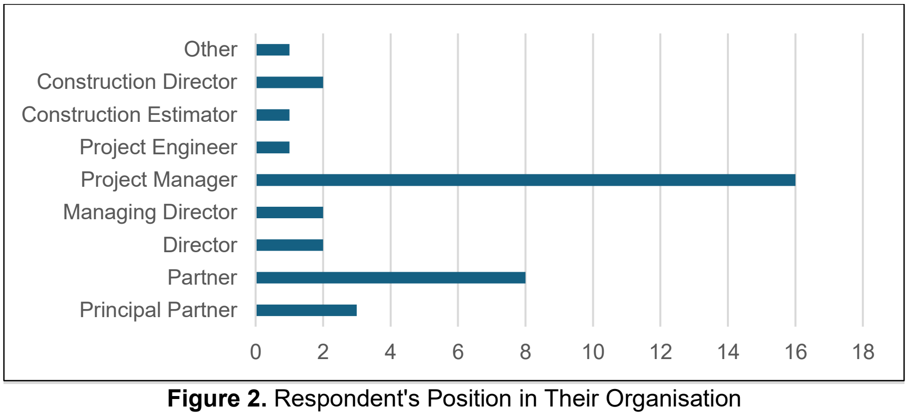

Figure 2. Respondent's Position in Their Organisation

Results of The Barriers to Sustainable Construction Digital Twin Implementations

Table 4 presents the results of a Bayesian analysis of various barriers to the implementation of digital twin technologies in sustainable building projects. Each variable represents a barrier that could hinder the implementation of digital twin technologies. The Bayes Factor (BF_{10}) measures the strength of the evidence supporting the presence of each barrier. A higher BF_{10} value indicates stronger evidence that the barrier significantly impacts the implementation of digital twin technologies. These results highlight the significant barriers that need to be addressed to improve the adoption of digital twin technologies in sustainable building projects. Addressing financial constraints, enhancing collaboration, improving expertise, and overcoming technological challenges are crucial steps for successful implementation.

The results show that most of the barriers are negatively skewed, suggesting that the higher-end responses are more frequent, indicating a greater perceived impact or importance of these barriers (Table 5). The negative kurtosis for most barriers suggests flatter distributions, indicating a wider range of responses. The exceptions with near-zero or slightly positive kurtosis suggest more typical or slightly peaked distributions.

Table 4. Bayesian One Sample T-Test

Variable	Full Description	BF_{10}	Error %
Realtime	Lack of availability of real-time data	4.544×10+13	8.883×10-19
Format	Lack of available data in the required format	9.151×10+14	2.765×10-17
Expertise	Lack of expertise in the organisation	1.162×10+15	2.477×10-17
Small	Size of project	1.128×10+14	2.528×10-17
Complex	Complexity of projects	3.187×10+13	2.098×10-17
Payment	Clients are not willing to pay	3.144×10+16	1.254×10-18
Collabor	Lack of collaboration among project team	1.076×10+16	4.641×10-18
Timing	Lack of time	1.401×10+14	3.005×10-17
Reluctant	Reluctance of staff to change	2.041×10+12	2.085×10-15
Leadership	Lack of leadership support	1.763×10+15	1.976×10-17
Providers	Lack of providers of such technologies	3.761×10+12	1.548×10-16
Compatibility	Data compatibility	9.525×10+14	4.390×10-17
Quality	Data quality	1.149×10+15	2.491×10-17
Accuracy	Data accuracy	5.967×10+12	6.577×10-16
Costinvestment	Cost of investment	8.119×10+14	2.905×10-17
Privacy	Data privacy and security	6.867×10+12	3.167×10-16
Culture	Organisational culture	7.777×10+13	2.597×10-16
Legal	Legal and regulatory challenges	2.863×10+13	2.646×10-16
Standard	Interoperability and standardisation	1.148×10+13	7.810×10-17

Notes: For all tests, the alternative hypothesis specifies that the population mean differs from 0.

Table 5. Descriptive Statistics

Factor	Skewness		Kurtosis	
	Statistic	Std. Error	Statistic	Std. Error
Lack of availability of real-time data	-0.258	0.393	-0.970	0.768
Lack of available data in the required format	-0.373	0.393	-0.708	0.768
Lack of expertise in the organisation	-0.652	0.393	-0.478	0.768
Size of project	0.033	0.393	-0.889	0.768
Complexity of the project	-0.276	0.393	-1.153	0.768
Clients are not willing to pay	-0.837	0.393	0.086	0.768
Lack of collaboration among project team	-0.522	0.393	-0.317	0.768
Lack of time	0.000	0.393	-0.678	0.768
Reluctance of staff to change	-0.351	0.393	-1.271	0.768
Lack of leadership support	-0.492	0.393	-0.586	0.768
Lack of providers of such technologies	-0.116	0.409	-0.931	0.798
Does not have relevance to the company	-0.025	0.403	-0.987	0.788
Data compatibility	-0.352	0.398	-0.553	0.778
Data quality	-0.552	0.393	-0.486	0.768
Data accuracy	-0.301	0.393	-1.183	0.768
Cost of investment	-0.604	0.393	-0.553	0.768
Data privacy and security	0.070	0.398	-0.792	0.778
Organisational culture	-0.400	0.403	-0.833	0.788
Legal and regulatory challenges	0.070	0.403	-0.509	0.788
Interoperability and standardisation	-0.201	0.398	-0.767	0.778

Table 6 presents Bayesian scale reliability statistics, which are used to assess the internal consistency of a scale or test. These results indicate that the scale or test in question demonstrates very high internal consistency across various reliability measures, suggesting it is a highly reliable tool for measuring the intended construct.

Table 6. Bayesian Scale Reliability Statistics

Estimate	McDonald's ω	Cronbach's α	Guttman's λ2
Posterior mean	0.952	0.956	0.958
95% CI lower bound	0.932	0.933	0.940
95% CI upper bound	0.969	0.974	0.977

Notes: Of the observations, pairwise complete cases were used.

Table 7 presents the results of Mardia's Test of Multivariate Normality, which is used to check if a multivariate dataset follows a normal distribution. While the skewness results do not suggest a departure from normality, the significant kurtosis result indicates that the dataset does not follow a multivariate normal distribution due to the presence of extreme values. All indicators have significant loadings ($p < .001$), indicating they are important factors (Table 8). High estimates, such as "Reluctance of staff to change" (1.223) and "Data accuracy" (0.982), suggest these are particularly influential barriers. The 95% confidence intervals further support these findings.

Table 7. Mardia's Test of Multivariate Normality

	Value	Statistic	df	p
Skewness	550.883	2938.04	3276	1
Small sample skewness	550.883	3235.27	3276	0.69
Kurtosis	662.212	-4.877		< .001

Notes: The statistic for skewness is assumed to be Chi^2 distributed, and the statistic for kurtosis standard normal.

Table 8. Factor Loadings

Factor	Estimate	Std. Error	z-value	p	95% Confidence Interval	
					Lower	Upper
Lack of availability of real-time data	0.852	0.183	4.65	< .001	0.493	1.211
Lack of available data in the required format	0.84	0.158	5.328	< .001	0.531	1.149
Lack of expertise in the organisation	0.929	0.177	5.239	< .001	0.581	1.277
Size of projects	0.545	0.177	3.083	0.002	0.199	0.892
Complexity of the projects	0.673	0.179	3.755	< .001	0.322	1.025
Clients are not willing to pay	0.944	0.16	5.881	< .001	0.629	1.258
Lack of collaboration among project team	0.847	0.156	5.431	< .001	0.542	1.153
Lack of time	0.944	0.159	5.937	< .001	0.633	1.256
Reluctance of staff to change	1.223	0.193	6.323	< .001	0.844	1.601
Lack of leadership support	0.792	0.16	4.943	< .001	0.478	1.106
Lack of providers of such technologies	0.953	0.158	6.018	< .001	0.643	1.263
Data compatibility	0.955	0.149	6.407	< .001	0.663	1.248
Data quality	0.966	0.168	5.758	< .001	0.637	1.294
Data accuracy	0.982	0.2	4.91	< .001	0.59	1.374
Cost of investment	0.905	0.188	4.82	< .001	0.537	1.274
Data privacy and security	0.769	0.181	4.248	< .001	0.414	1.124
Organisational culture	0.913	0.175	5.202	< .001	0.569	1.257
Legal and regulatory challenges	0.809	0.15	5.383	< .001	0.514	1.103
Interoperability and standardisation	0.868	0.173	5.028	< .001	0.529	1.206

The descriptive statistics provide a comprehensive overview of various barriers to implementing digital twins in sustainable buildings (Table 9). While all the barriers are critical, about 50% of the barriers are much more critical. 25% of the barriers have a moderate impact, while more than 45% of the barriers pose a strong or extreme threat to the implementation of digital twins in sustainable construction.

Table 9. Descriptive Statistics

Obstacle	Less Obstacle	Moderate Obstacle	Strong Obstacle	Extreme Obstacle	SD	Index
Clients are not willing to pay	6.0	7.0	15.0	8.0	24.33	90.28
Cost of investment	7.0	9.0	10.0	10.0	26.85	88.19
Lack of expertise in the organisation	8.0	7.0	14.0	7.0	25.37	86.11
Organisational culture	9.0	7.0	11.0	7.0	25.71	84.56
Data quality	8.0	9.0	13.0	6.0	25.71	84.03
Lack of collaboration among project team	8.0	10.0	14.0	4.0	22.72	82.64
Data compatibility	9.0	10.0	12.0	4.0	23.41	80.71
Reluctance of staff to change	12.0	5.0	11.0	8.0	29.62	80.56
Data accuracy	12.0	6.0	11.0	7.0	28.17	79.86
Lack of leadership support	10.0	10.0	14.0	2.0	22.42	77.78
Lack of availability of real-time data	12.0	8.0	12.0	4.0	25.14	77.08
Lack of available data in the required format	11.0	10.0	13.0	2.0	22.42	76.39
Lack of time	12.0	12.0	8.0	4.0	23.55	75.00
Lack of providers of such technologies	12.0	8.0	10.0	3.0	24.36	75.00
Interoperability and standardisation	11.0	12.0	9.0	3.0	24.09	73.57
Data privacy and security	13.0	11.0	7.0	4.0	24.62	72.86
Size of project	15.0	9.0	10.0	2.0	23.48	71.53
Complexity of the project sophisticated	14.0	8.0	13.0	1.0	24.42	71.53

PCA of The Barriers of Digital Twin Technologies in Sustainable Buildings Component Loadings

The PCA results on the barriers to implementing digital twins in sustainable buildings reveal four main components (RC1, RC2, RC3, and RC4) (Table 10). The uniqueness values indicate the proportion of variance for each variable that is not explained by the extracted components. Lower uniqueness values imply that the variable is well explained by the components. The overall MSA (measure of sampling adequacy) of 0.656 suggests that the sample is generally suitable for PCA. However, some variables, particularly "Lack of expertise in the organisation", "Complexity of the projects," "Cost of investment," "Legal and regulatory challenges," and "Interoperability and standardisation," have lower MSA values, indicating they may not be as well-suited for the analysis as others. Generally, most barriers are acceptable, with several showing strong suitability for factor analysis, supporting the robustness of the PCA.

The PCA results indicate that the four components collectively explain 80.3% of the total variance in the data (Table 11). The rotated solution redistributes the variance more evenly across the components, which aids in interpretation. Each component represents a distinct set of barriers to implementing digital twins in sustainable buildings, with the first component being the most influential. This balanced distribution highlights the multifaceted nature of the barriers, suggesting that multiple barriers must be addressed to overcome the poor efficient implementation of digital twin technologies in sustainable buildings.

Table 10. Component Loading

Barrier	Policy	Structure	Cost	Complexity	Uniqueness	MSA
Interoperability and standardisation	1.107				0.119	0.814
Legal and regulatory challenges	1.026				0.133	0.654
Lack of providers of such technologies	0.817				0.168	0.529
Organisational culture	0.776				0.248	0.641
Lack of time to implement the digital twins in project	0.713				0.253	0.553
Reluctance of staff to change	0.595				0.226	0.606
Lack of leadership support	0.553				0.378	0.614
Lack of availability of real-time data		1.064			0.133	0.866
Lack of expertise in the organisation		1.018			0.125	0.649
Lack of available data in the required format		0.805			0.227	0.848
Data compatibility		0.543			0.197	0.611
Clients are not willing to pay		0.507			0.269	0.862
Lack of collaboration among project team		0.477			0.248	0.809
Data privacy and security			0.917		0.198	0.606
Data accuracy			0.882		0.192	0.496
Cost of investment			0.712		0.207	0.825
Data quality			0.619		0.162	0.862
Complexity of the projects				0.986	0.083	0.541
Size of projects				0.931	0.187	0.511
2nd Order Reliability	0.945	0.935	0.882	0.905		
Convergent validity	0.798	0.736	0.783	0.959		

Notes: Applied Rotation Method is Promax

Table 11. Component Characteristics

Component	Unrotated Solution			Rotated Solution		
	Eigenvalue	Proportion var.	Cumulative	Sum sq. Loadings	Proportion var.	Cumulative
Policy	11.109	0.585	0.585	5.435	0.286	0.286
Structure	1.809	0.095	0.680	4.201	0.221	0.507
Cost	1.240	0.065	0.745	3.054	0.161	0.668
Complexity	1.091	0.057	0.803	2.559	0.135	0.803

DISCUSSION

The findings of the research are discussed in the following sections, highlighting key insights, trends, and implications related to the barriers and challenges of implementing digital twins in sustainable construction.

Analytical Discussion

The profile of sustainable buildings significantly differs from that of conventional buildings, as sustainable buildings are more complex and sophisticated. Leveraging this uniqueness requires the implementation of advanced construction technologies, such as digital twins. However, several barriers hinder their adoption, with reluctance from clients to invest in these technologies emerging as the most significant, according to respondents. This reluctance underscores the critical need to demonstrate the value and return on investment (ROI) of digital twin technologies to potential clients. Implementing digital twins is not inexpensive, often adding up to 15% of a project's capital cost. Clients face the dual financial burden of the additional cost for digital twins and the premium associated with sustainable building practices. Despite this, the value added by digital twin technologies far exceeds the initial investment. Professionals must proactively educate clients on the long-term benefits of these technologies, even though many clients mistakenly assume such services are included in the traditional scope of design teams. This misconception parallels the reluctance of clients to pay for value engineering and value management services provided by quantity surveyors or design teams, as noted by Olanrewaju (2016). The substantial cost associated with implementing digital twins represents another critical barrier. This highlights the need to explore cost-effective solutions, government subsidies, or phased implementation strategies to reduce the financial strain on clients and construction companies. The investment in construction technologies can be particularly challenging for small and medium-sized enterprises (SMEs), especially when clients are unwilling to pay due to a lack of appreciation for the benefits. Olanrewaju, et al. (2024) developed an association ruling framework for construction companies, revealing that a typical firm invests in up to five technologies to enhance productivity. The shortage of skilled personnel further compounds these challenges, emphasising the necessity of targeted training programs for existing staff and hiring experts proficient in digital twin technologies. Many construction companies lack qualified professionals with expertise in technologies such as BIM (Hai, and Tu, 2024; Pham, Dau, and Tran, 2024 and Kam, Lim, and Law, 2024), digital twins, IoT, sensors, blockchain, artificial intelligence, ERP software, and digital stamping. This skills gap is exacerbated by the inherent complexity of sustainable buildings, making the implementation of advanced technologies even more daunting. Addressing these barriers will require a multi-faceted approach, combining education, investment incentives, and strategic workforce development. Resistance within organisations is another significant barrier to adopting new technologies, and its high rating in the study is unsurprising. This resistance can arise when staff lack adequate knowledge of the technologies, even if they are aware of their potential benefits. To address this, fostering a culture of innovation and change within organisations is essential. Construction companies should document and share success stories to demonstrate the tangible benefits of digital twin technologies to clients and stakeholders, which can help build confidence and drive adoption. The complexity and diversity of construction data also present challenges. Poor-quality data can hinder the implementation of digital twins, particularly in sustainable building projects. Construction data can exist in various formats, including spreadsheets, text, audio, video, or images. The importance of high-quality data cannot be overstated, as data-driven decision-making is only as reliable as the quality of the underlying data. To ensure the effective functioning of digital twins, construction companies must prioritise robust data governance and management practices. However, quality data specific to sustainable buildings remains scarce, making this issue even more pressing.

Discussion of The Results of The PCA

The subsequent sections will delve into the results of the PCA, which provides further insights into these barriers and their interrelationships.

Policy

This component has 7 barriers that are highly interconnected. These barriers encompass a range of challenges that must be addressed together to ensure the whole integration and functionality of the digital twin technologies in the delivery of sustainable buildings. Ensuring that digital twin technologies are compatible with existing systems and adhere to industry standards is essential. Without standardisation, integration can become complex and inefficient, leading to delays and increased costs. Legal and regulatory challenges also play a significant role. Manoeuvring the complex web of legal requirements and regulations for sustainable construction can be daunting, especially where there is no specific standard, staff are not ready to change, and there is poor leadership support. Digital twin technologies must comply with stringent regulations, which differ between sectors and disciplines, making implementation time-consuming and difficult and presenting the face of uncooperative staff members in the projects. The limited availability of technology providers can hinder organisations from adopting these technologies effectively, as they may struggle to find solutions that meet their specific needs. Most construction companies invest in more than one of the technologies to increase efficiency and productivity, and thus, it is imperative that the technologies are compatible with one another. Organisational culture is a key determinant of success. A culture resistant to change, lacking in innovation, or unsupportive of new technologies can impede the implementation process of the digital twin in construction management. Fostering a supportive and innovative culture by reconciling the legal framework and harnessing the support of top and staff training will help greatly. Time constraints can also significantly impact the adoption of digital twin technologies. Project timelines often do not allow sufficient time for thorough implementation and integration, leading to incomplete deployments of the technologies in the construction. Sustainable construction can leverage the agile management principle because it is flexible and adaptable. The reluctance of staff to change is a common barrier in any technological adoption. Employees may resist new technologies and processes due to fear of the unknown or perceived threats to their job security. This can be complicated for sustainable construction, as most companies do not have the necessary profiles. Overcoming this reluctance requires effective change management strategies, including comprehensive training programmes, top management support and clear communication about the benefits and necessity of the digital twin technologies. The lack of leadership support can affect digital transformation efforts. Strong leadership is crucial for driving digital twin initiatives forward. Without the backing and support of senior management, these initiatives may struggle to gain the necessary resources and motivation.

Structure

There is a total of 5 barriers that formed the component. The component is a pivotal barrier to the successful implementation of digital twins in sustainable buildings. The ability to process and utilise real-time data is crucial for the functionality of digital twins, enabling dynamic and responsive decision-making in construction management. One of the major differences between digital twins and other construction technologies is the reliance on personalised real-time data. Effective real-time capabilities are essential for ensuring that digital twins can provide accurate and up-to-date information to the design and construction team. It would be unproductive, wasteful, and inefficient if real-time data were available but not in the required format, not even compatible, and worse off if the project team members were not cooperating with one another. Well-designed systems that facilitate the easy input and output of data in the required formats are crucial to achieving the objectives of the project. In addition, having skilled professionals who can manage and interpret this data is essential for the successful implementation of digital twins. Without the necessary expertise, construction companies may struggle to maximise the benefits of the implementation of the digital twin in sustainable construction management. It would be a barrier if the expertise was not available, the available data were not in the required format, they were incompatible, and there was a lack of collaboration among the team members. Ensuring that digital twins can seamlessly integrate with current systems and technologies is vital for their adoption. Incompatibility can lead to disruptions and inefficiencies, undermining the benefits that digital twins are supposed to provide. In all of these, the clients have to pay for the service; otherwise, it would be a barrier and would compound the already tense situation due to a lack of expertise, data incompatibility, poor collaboration, outdated data, and poor data format.

Cost

Digital twins' implementation is not cheap, especially for sustainable buildings that usually involve upfront expenditure, especially if x-rayed from the capital cost perspective. Sustainable construction often involves environmental-compliant materials and energy-efficient technologies, which can introduce cost variability and sourcing challenges. The cost of obtaining data with high accuracy and quality is foundational to the success of digital twins and is cost-intensive. Inaccurate or low-quality data can lead to erroneous decisions and outcomes, undermining the advantages of using digital twins. Ensuring high data accuracy and quality requires robust data management practices and systems to provide reliable and precise information for decision-making. Data privacy and security are paramount concerns. Protecting sensitive data from breaches and ensuring compliance with data protection regulations are also expensive. Threats due to cyber-attacks must be prevented. However, construction companies are not investing in cyber-attack threats yet. Most companies have not even considered the problem yet. With the magnitude of data involved in the creation of digital twins, it is important that construction companies protect themselves not only from cyberattacks but also from misuse, abuse, and errors. The interpretation of construction blockchain technologies in the profile would be essential (Tran, Do, Bui, Nguyen, and Tran, 2024). Therefore, the barriers or threats need to be addressed to avoid significant risks and liabilities for organisations, ensuring that the data used in digital twins remains secure and confidential. Data compatibility with existing systems and technologies is another important consideration.

Complexity

Project complexity factors are significant barriers to the successful implementation of digital twins in sustainable buildings. The formation of this component is not surprising. Sustainable constructions are complex and sophisticated. Adopting new technologies (e.g., renewable energy systems or sustainable materials) in construction can introduce uncertainties related to performance, cost, and integration. Highly complex projects can present numerous challenges, including intricate systems integration and multifaceted operational requirements. Managing this complexity requires advanced project management skills and robust frameworks to streamline processes and mitigate problems associated with implementing digital twins. The size of the projects also influences the implementation process, especially for projects with high complexity. Larger projects tend to have more extensive requirements and involve a greater number of stakeholders, making coordination and communication difficult. Sustainable construction projects aim to meet the needs of various stakeholders, including communities, investors, and regulatory bodies. Ensuring effective management of large-scale projects is essential to harnessing the benefits of digital twins, which can help manage complex building operations and ultimately enhance the sustainability scorecard of the projects. Coordination among project teams is vital in managing project complexity. Effective collaboration and communication among various teams involved in the project ensure that all aspects of the implementation process are aligned. This coordination helps in overcoming the challenges posed by project complexity and supports the successful adoption of digital twins. Technical expertise is essential to handle the complexity of implementing digital twins for a complex project.

Implications of The Research

The findings of the research hold several implications. This study extends the theoretical understanding of digital twin technology by identifying specific barriers to its implementation in sustainable construction projects. It contributes to the emerging body of literature on the integration of digital technologies and sustainability in the built environment. The PCA framework developed in this study provides a theoretical basis for categorising and analysing barriers comprising policy, structure, cost, and complexity. This framework can serve as a reference for future theoretical investigations into technology adoption in other sectors. The findings highlight actionable strategies for construction professionals, such as improving organisational expertise, fostering a culture of innovation, and investing in compatible technologies. Practical recommendations for addressing the lack of expertise include tailored training programs for engineers, architects, and project managers to improve their proficiency in digital twin tools. The study underscores the need for policies that incentivise the adoption of digital twin technologies. This includes financial subsidies, tax incentives, and grants for sustainable construction practices. The barriers identified present opportunities for tech companies to develop cost-effective, user-friendly digital twin solutions tailored to the construction industry.

CONCLUSIONS AND FUTURE RESEARCH

This research develops a PCA framework for the barriers to implementing digital twin technologies for sustainable buildings. Addressing the barriers to the adoption of digital twin technologies in sustainable buildings requires a comprehensive approach. Factors such as fostering a supportive culture, ensuring regulatory compliance, effective time management, and securing leadership support, are critical for successful implementation in sustainable construction. Similarly, an analysis of the investment considered in real-time data processing, ensuring system compatibility, prioritising data privacy and security, and developing necessary expertise would help reduce the barriers. Additionally, overcoming the problems related to data accuracy, quality, and financial investment, as well as project complexity, demands robust data management practices, effective financial planning, and strong leadership. This research is novel in its focus on the barriers to implementing digital twin technology in sustainable construction, an area largely unexplored in existing literature. While digital twins have gained attention in other industries, no prior research has specifically examined its integration within sustainable construction projects or analysed the multifaceted challenges impeding its adoption. By employing PCA, this study not only identifies and categorises these barriers into actionable components; Policy, Structure, Cost, and Complexity but also provides an empirical foundation for addressing them. The findings contribute a pioneering perspective, bridging the gap between advanced construction technologies and sustainability and offering actionable insights for stakeholders in policy-making, industry practice, and future research. However, despite the valuable insights the research provides for the construction sector and policymakers, there are some limitations to the findings. One notable limitation is the relatively small sample size, which may impact the generalizability of the results. Despite the small sample size and sampling technique, the rigorous statistical analysis confirmed the reliability and validity of the findings. To address this limitation, future research should prioritise the inclusion of a larger and more diverse sample to enhance the robustness, representativeness, and statistical power of the findings. Moreover, scope of the study could be expanded to include a wider range of barriers that may impact the adoption of digital twin technologies. Factors such as varying levels of technological readiness, regional policy differences, and industry-specific challenges were not fully explored, but they could offer a more nuanced understanding of the obstacles faced by stakeholders. A comprehensive examination of these additional barriers would provide deeper insights into the interplay of technical, organisational, and cultural factors that influence digital twin adoption. By addressing these limitations and broadening the research focus, future studies can contribute to more actionable and widely applicable recommendations, thereby facilitating the integration of digital twin technologies into sustainable construction projects on a larger scale.

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ASSESSING ARTIFICIAL INTELLIGENCE (AI) ADOPTION LEVELS IN THE CONSTRUCTION INDUSTRIES OF ZAMBIA AND KENYA

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Abstract
The construction industry plays a crucial role in economic growth, significantly contributing to revenue generation, capital formation, and job creation. These elements are vital for enhancing a nation's Gross Domestic Product (GDP) and overall development. The integration of Artificial Intelligence (AI) tools in construction presents a promising opportunity to optimise project management and address existing challenges. However, in Zambia and Kenya, the adoption of AI in the construction sector remains largely underdeveloped compared to other industries such as transportation, healthcare, banking, and logistics. A questionnaire survey was conducted with 162 respondents who were among the key players in the construction industry. The data was analysed using both descriptive and inferential statistical methods. The standard deviation values for the responses ranged between 0.52 and 1.44, and the mean values fell within the range of 2.67 to 4.76, indicating varying degrees of response consistency. AI tools have been widely adopted through BIM applications, with average mean ranks between 3.51 and 3.44. In contrast, tools such as neural networks have been the least popular AI tools, achieving a mean rank of 1.85. These findings revealed that, despite rapid urbanisation and increasing demand for infrastructure, AI adoption in construction remains limited, with most applications restricted to the design and planning stages. Additionally, no significant differences were found in AI adoption levels between Zambia and Kenya.

Keywords: *Artificial Intelligence (AI); AI Adoption; Gross Domestic Product (GDP); Construction Industry; Design and Planning*

INTRODUCTION

The construction sector is essential, especially in developing regions, and plays a crucial role in promoting and enhancing sustainability (Lima, Trindade, Alencar, Alencar, & Silva, 2021). The construction sector is characterised by complex operations, resource-intensive processes, and a substantial impact on both the built environment and the broader economy (Abioye et al., 2021). The construction industry in Africa has been steadily expanding, propelled by growing urbanisation, increased infrastructure demands, and economic development (Ramachandran, 2021). In Zambia and Kenya, construction activities have become central to their respective national agendas, driving substantial investments (Mitlin, 2021). The construction industry in most nation-states globally has not fully harnessed the potential of Artificial Intelligence (AI), trailing behind other sectors such as business services, manufacturing, finance, transport, and utilities (Adedeji Olawale et al., 2023). The delayed adoption and integration of AI technologies in construction highlight numerous potential challenges, including the economic costs of implementation, acceptance of new technologies, heightened requirements for construction equipment and processes, a knowledge deficit, and individual reluctance (Gurgun, Koc, & Kunkcu, 2024). Basaif et al. (2020) conducted a study on AI awareness in the Malaysian construction industry and found that awareness was generally low. Most practitioners lacked AI knowledge, had no formal training, and did not use AI for risk analysis. Additionally, companies provided limited AI training, hindering its adoption in project management.

AI tools are advanced information technology geared towards enhancing the effectiveness of construction management by supporting sustainable practices (Wamba-Taguimdje, Fosso Wamba, Kala Kamdjoug, & Tchatchouang Wanko, 2020), resource efficiency, and minimising waste in construction and infrastructure development (Ihsanullah, Alam, Jamal, & Shaik, 2022; Huang & Koroteev, 2021). The increasing adoption of various technologies has facilitated the digitisation, automation, and seamless integration of construction processes across all stages of the construction value chain. Both countries are emphasising the importance of regulatory frameworks and quality standards to ensure the durability and sustainability of infrastructure. The integration of these technologies not only supports the economic growth of Zambia and Kenya but also aligns with global trends toward smarter, more resilient urban development (Tanui & Tembo, 2023).

The incorporation of Artificial Intelligence (AI) into the construction industry has garnered substantial attention in recent years due to its potential to transform various aspects of construction project management (Zhu, Hwang, Ngo, & Tan, 2022). AI technologies such as machine learning, predictive analytics, and robotics offer significant advantages in automating routine tasks, optimising resource allocation, and enhancing decision-making processes (Zhang, Shi, & Yang, 2020). Big data analytics is another area that has employed AI tools, which have been used in the construction industry to enhance project efficiency by analysing vast data from design, finance, materials, and workforce management (Sin, Choy, & Fung, 2020). This growing interest stems from the need to address common challenges in the construction sector, including project delays, cost overruns, and quality deficiencies, which are prevalent in many developing countries, including Zambia and Kenya (Kumar & Kumari, 2025).

Post-COVID-19 pandemic, the construction industry has strived to adopt technologies to enhance productivity, improve site safety, and streamline project management (Kamarazaly, Chin, Ling, Au, & Hoong, 2024). However, these efforts have faced significant challenges, including inflated costs, limited skilled labour, and resistance to change, slowing the pace of digital transformation. Kong and Jie (2024) highlighted that while digital transformation increases productivity, cost savings, and safety at construction sites in Malaysia, progress is hindered by high technology costs, concerns about low return on investment, and a shortage of skilled labour and digital awareness. Similarly, Raslim, Ern, Liyana and Ariffin (2024) found that although smart wearables have the potential to enhance safety on construction sites, their adoption in Malaysia remains low, primarily due to inflated costs, a lack of skilled workers, and limited awareness. The success of such technologies depends on leadership support, adequate financial resources, and a culture of innovation. Additionally, Basaif et al. (2020) identified a research gap in examining the impact of organisational culture on the adoption of artificial intelligence for risk analysis within the Malaysian construction industry, specifically focusing on certain categories of practitioners.

According to the Government AI Readiness Index, Kenya ranks 101st and Zambia 143rd globally, indicating a moderate level of readiness for AI adoption (Oxford Insights, 2023). Despite this, AI integration is notably absent in the construction industries of these countries. Despite the growing recognition of AI's potential, the actual integration of these technologies within the construction sectors of Zambia and Kenya remains limited. Therefore, this study aims to assess the level of AI adoption in the construction industry of Zambia and Kenya, exploring the underlying factors influencing this adoption. By employing a qualitative, multiple case study approach, the research sought to uncover insights into the current state of AI integration, the challenges faced, and the opportunities available for enhancing technological adoption in the sector.

MATERIALS AND METHODS

The research design adopted for this study was a mixed-methods approach, incorporating both quantitative and qualitative data collection methodologies.

Study Area

The study was conducted in the Zambian and Kenyan construction industries, the investigation delved into construction projects across various regions, urban and rural settings, and different types of developments, including residential, commercial, and infrastructure projects.

Study Population

The study population is defined as a set of cases, determined, limited, and accessible, that will constitute the subjects for the selection of the sample and must fulfil several characteristics and distinct criteria (Hossan, Dato' Mansor, & Jaharuddin, 2023). The study population encompassed a broad spectrum of professionals and stakeholders involved in the construction sector of Zambia and Kenya.

Study Sample

As highlighted by Hossan et al. (2023), a representative sample ensures that the results of a study can be extrapolated to the entire population. Additionally, Mulisa (2022) emphasises the importance of sampling in providing accurate estimations and predictions about population characteristics. The choice of sampling method significantly impacts the quality and reliability of the research outcomes, making it a fundamental aspect of research design and methodology (Zickar & Keith, 2023). The study sample for the study entailed all the construction players in Kenya and Zambia, who are in diverse construction landscapes, to ensure a comprehensive representation of these countries. Yamane Sample Size Formula (Aliu, Oke, & Oni, 2024) for sample size determination was employed to ensure that the sample accurately represents the population.

$$n = \frac{N}{1 + [N(e^2)]}$$

where $e = \pm 8\%\ sampling\ error = 0.08$

$$N = 143{,}860$$

$$n = \frac{143860}{1+[143860(0.08^2)]} = 156.08 = 157 \text{ construction players}$$

Sampling Techniques

Sampling entails choosing a subset from the study population to estimate or predict information about the entire population (Mulisa, 2022).The sampling method applied was convenience sampling, a non-probabilistic technique that collects data from accessible members of the population who are willing to participate. This method was appropriate for studies with time limitations and where other resources may not be available. Additionally, the snowball sampling method was also utilised to target accessible construction projects. This approach involved identifying initial participants who then referred other relevant stakeholders, thereby expanding the sample size (Ojo, Ajayi, Owolabi, Oyedele, & Akanbi, 2022).

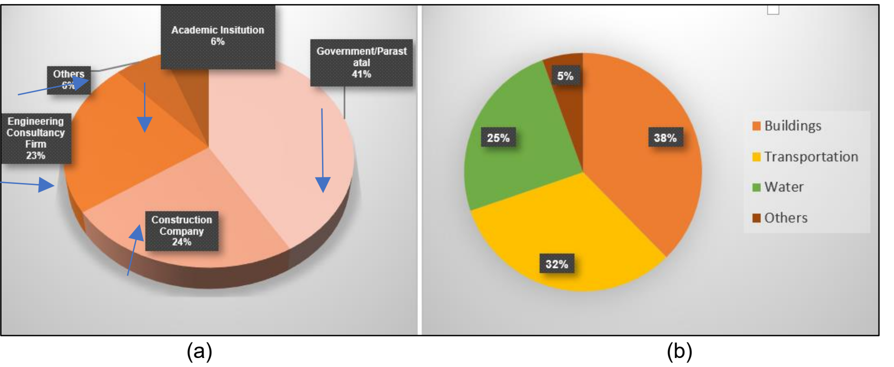
Data Collection, Analysis Instruments and Procedure

A questionnaire survey technique was used to collect preliminary data from a targeted group of respondents, focusing on managers at higher and middle levels possessing substantial organisational knowledge and experience. This method was chosen for its appropriateness in allowing respondents sufficient time to consider and respond to questions, thereby facilitating convenient data analysis through statistical methods. The collected data was analysed using several statistical techniques to understand the relationships between variables and achieve the study's objectives.

RESULTS AND DISCUSSION

Questionnaire Survey

A total of 162 responses were gathered through a questionnaire administered using Google Forms. The data was downloaded in Excel format to a password-protected personal computer for analysis. The study focused on construction sector professionals in Zambia and Kenya. Table 1 and Figure 1a show the distribution of the participants per country under study. Table 2 and Figure 1b show the sectors where the respondents work.



(a) (b)

Figure 1. (a) Type of Establishment of Respondents (b) The Industry Sub-Sectors of Respondents

Table 1. Demographics of Respondents

Background Information		Frequency	Percentage of Frequency
Nationality	Zambian	44	27.2
	Kenyan	118	72.8
Gender	Male	132	81.5
	Female	30	18.5
Age	18 to 30	80	49.4
	31 to 40	72	44.4
	41 to 50	7	4.3
	51 to 60	2	1.3
	Above 60	1	0.6
Education Level	Diploma	9	5.6
	Bachelor's	110	67.9
	Master's	41	25.3
	Doctorate's	2	1.2
Title	Architect	5	3.1
	Engineer	118	72.8
	Contractor	9	5.6
	Quantity surveyor	5	3.1
	Project/construction manager	18	11.1
	Operations officer	6	3.7
	Other	1	0.6
Experience	Less than 2 years	21	13
	2 to 5 years	66	40.7
	5 to 10 years	51	31.5
	10 to 20 years	19	11.7
	Above 20 years	5	3.1

Table 2. Construction Sub-Sectors and Establishments

Background Information		Frequency	Percentage of Frequency
Type of Establishment	Government agency/ parastatal	67	41.4
	Engineering consultancy firm	37	22.8
	Construction company	39	24.1
	Academic institution	9	5.5
	Other	10	6.2
Construction Sub-Sector	Water sector	40	24.7
	Transportation sector	52	32.1
	Buildings	61	37.6
	Other	9	5.6

Level of Adoption of AI in The Construction Sector

Participants were asked to respond using a 5-point Likert scale, with mean score values interpreted as follows: 4.3 < mean score ≤ 5 indicated strongly agree, 3.5 < mean score ≤ 4.3 indicated agree, 2.6 < mean score ≤ 3.5 indicated undecided, 1.8 < mean score ≤ 2.6 indicated disagree, and 0 < mean score ≤ 1.8 indicating strongly disagree. The findings from the study, as detailed in Table 3 and Figure 2, revealed a mixed response among participants regarding the awareness and adoption of Artificial Intelligence (AI) in the construction industry. The standard deviation values were between 0.52 and 1.44. The mean of the variables varied between 2.67 and 4.76, indicating that the average response was between undecided and strongly agree on a five-point Likert scale.

AI awareness within the construction industry is notably high, evidenced by a coefficient of variation (COV) of just 11%, as shown in Table 3, signalling a strong consensus among industry professionals about the potential of AI technologies. However, the actual adoption of AI across various operations and project stages reflects a troubling inconsistency, with COV values ranging from 47% to 52%. This stark contrast highlights a critical gap: while the industry recognises AI's transformative potential, the execution of these technologies varies significantly from one organisation to another. Moreover, the overall readiness for AI integration–reflected in a COV of 35%–indicates only moderate agreement regarding the industry's capacity to embrace these innovations. This inconsistency emphasises a pressing challenge: Despite widespread awareness, the implementation of AI is alarmingly uneven. The construction sector stands at a pivotal moment where leveraging AI effectively could revolutionise operations and enhance project outcomes. Addressing these discrepancies is essential for fully harnessing the benefits of AI and driving the industry towards a more efficient and resilient future.

Table 3. Level of Adoption of AI

Variable Code	Variable	Min	Max	Mean	Std. Dev	COV
LA1	I have heard about Artificial Intelligence (AI)	2	5	4.76	0.520	11%
LA2	Establishment I work in uses Artificial Intelligence applications in its day-to-day operations	1	5	2.99	1.412	47%
LA3	We apply Artificial Intelligence during the design and planning stage of the project	1	5	2.89	1.440	50%
LA4	We apply Artificial Intelligence during the construction stage of the project	1	5	2.67	1.396	52%
LA5	We apply Artificial Intelligence during the post-construction /monitoring stage of the project	1	5	2.83	1.407	50%
LA6	The construction industry is ready to fully and aggressively implement Artificial Intelligence in its operations.	1	5	3.40	1.203	35%

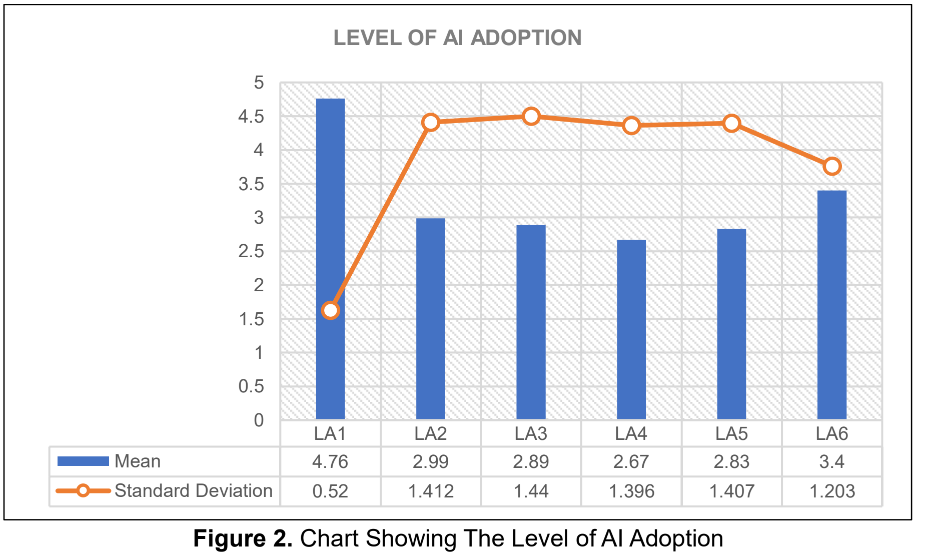


Figure 2. Chart Showing The Level of AI Adoption

These findings revealed that while there is widespread awareness of AI among construction professionals in Zambia and Kenya, its actual adoption and integration into daily operations and across different project stages remain limited. The general indecision about AI usage reflected a cautious approach within the industry, possibly due to uncertainties around cost, implementation challenges, and perceived benefits (Abioye et al., 2021).

Regional Variation in The Adoption of AI

The results in Table 4 show that in all the statements provided, the p-values were above the significance level of 0.05, indicating there is a 5% risk of incorrectly rejecting the null hypothesis. Since the p-values exceeded this threshold, it suggested that there were no statistically significant differences in AI adoption across Zambia and Kenya. Therefore, the null hypothesis was retained for each of the statements, indicating that the distribution of the responses was similar across the two countries for each of the aspects of AI adoption evaluated.

Table 4. Regional Variation in Adoption of AI

Level of Adoption/Regional	Sig.	Decision
The distribution of 'I have heard about Artificial Intelligence (AI) is the same across the categories of Country.'	.863	Retain the null hypothesis
The distribution of 'Establishment I work in uses Artificial Intelligence applications on its day-to-day operations is the same across categories of Country.'	.968	Retain the null hypothesis
The distribution of 'We apply Artificial Intelligence during the design and planning stage of the project is the same across categories of Country.'	.353	Retain the null hypothesis
The distribution of 'We apply Artificial Intelligence during the construction stage of the project is the same across categories of Country.'	.571	Retain the null hypothesis
The distribution of 'We apply Artificial Intelligence during post-construction /monitoring stage of the project is the same across categories of Country.'	.471	Retain the null hypothesis
The distribution of 'The construction industry is ready to fully and aggressively implement Artificial Intelligence in its operations is the same across categories of Country.'	.239	Retain the null hypothesis

The absence of statistically significant differences in AI adoption between Zambia and Kenya suggested that the construction industries in both countries exhibited similar patterns in integrating AI technologies. This uniformity reflected shared challenges and opportunities within the construction sectors of these two nations (Bang & Olsson, 2022). Both Zambia and Kenya appeared to experience comparable levels of technological advancement, workforce readiness, and industry awareness regarding AI, leading to similar responses observed in the study. Therefore, initiatives to enhance AI adoption in the construction sectors of Zambia and Kenya could be implemented uniformly across both countries. Since no significant differences were found, strategies for promoting AI could be developed with a broad regional focus, reducing the need for country-specific adjustments (Inusah, Kazaz, & Ulubeyli, 2025).

Level of Usage of Artificial Intelligence

Table 5 and Figure 3 present a detailed analysis of AI tool usage within the construction industry of Zambia and Kenya, focusing on various AI and software tools and their frequency of use. ArchiCAD Graphisoft was very frequently used, with a mean score of 3.51. Notably, 38.9 per cent of participants reported using it always, while 16.0 per cent used it very frequently. The popularity of ArchiCAD Graphisoft reflected its robust capabilities in architectural design and project management. This tool's frequent use highlighted its importance in ensuring design accuracy and project coordination, which are critical for monitoring construction quality (Ali, Mehdipoor, Samsina Johari, Hasanuzzaman, & Rahim, 2022). Autodesk Revit also demonstrated significant adoption, with a mean score of 3.44. Notably, 37.0 per cent of participants reported using it always, and 19.1 per cent used it very frequently. These high usage rates underscored Autodesk Revit's pivotal role in Building Information Modelling (BIM), facilitating detailed architectural designs, documentation, and construction management (Rane, 2023).

Table 5. Level of Usage of AI Tools

	Always		Very Frequently		Frequently		Rarely		Never		Mean
	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	
Robotics	13	8.0	14	8.6	13	8.0	30	18.5	92	56.8	1.93
Machine learning	16	9.9	21	13.0	22	13.6	42	25.9	61	37.7	2.31
Deep learning	10	6.2	15	9.3	23	14.2	35	21.6	79	48.8	2.02
Neuro-networks	3	1.9	19	11.7	15	9.3	38	23.5	87	53.7	1.85
Computer vision	30	18.5	27	16.7	20	12.3	33	20.4	52	32.1	2.69
Automated planning and scheduling	29	17.9	37	22.8	29	17.9	24	14.8	43	26.5	2.91
Optimisation	23	14.2	35	21.6	40	24.7	27	16.7	37	22.8	2.88
Knowledge-based systems	32	19.8	29	17.9	33	20.4	23	14.2	45	27.8	2.88
Natural language processing	14	8.6	24	14.8	33	20.4	19	11.7	72	44.4	2.31
Autodesk Revit	60	37.0	31	19.1	26	16.0	10	6.2	35	21.6	3.44
Autodesk Fusion 360	38	23.5	19	11.7	32	19.8	17	10.5	56	34.6	2.79
Autodesk Naviswork	31	19.1	24	14.8	26	16.0	25	15.4	56	34.6	2.69
Autodesk Robot	29	17.9	23	14.2	24	14.8	31	19.1	55	34.0	2.63
ArchiCAD Graphisoft	63	38.9	26	16.0	27	16.7	22	13.6	24	14.8	3.51
Trimble Tekla Structures	40	24.7	19	11.7	21	13.0	27	16.7	55	34.0	2.77
ProtaStructures	39	24.1	30	18.5	23	14.2	26	16.0	44	27.2	2.96
Prokon	48	29.6	31	19.1	29	17.9	18	11.1	36	22.2	3.23
Procore	15	9.3	19	11.7	28	17.3	26	16.0	74	45.7	2.23
Fieldwire	10	6.2	15	9.3	26	16.0	25	15.4	86	53.1	2.00
Autodesk PlanGrid	20	12.3	19	11.7	25	15.4	25	15.4	73	45.1	2.31
Autodesk BIM 360	25	15.4	33	20.4	32	19.8	26	16.0	46	28.4	2.78
Trimble e-Builder	17	10.5	19	11.7	16	9.9	30	18.5	80	49.4	2.15
Buildertrend	6	3.7	17	10.5	17	10.5	30	18.5	92	56.8	1.86
ESTEEM	12	7.4	13	8.0	16	9.9	33	20.4	88	54.3	1.94

Prokon and ProtaStructures were also frequently used, with mean scores of 3.23 and 2.96, respectively. Prokon was always utilised by 29.6 per cent of participants, while ProtaStructures was reported as always used by 24.1 per cent of participants. Both tools contribute to efficiency and quality control by providing detailed structural insights and optimisation. Conversely, tools such as Buildertrend and ESTEEM were rarely used, with means of 1.86 and 1.94, respectively. Buildertrend was always used by only 3.7 per cent of the participants, and ESTEEM by 7.4 per cent. These low usage rates suggested that these tools may not have been as integral to most construction workflows compared to other AI tools.

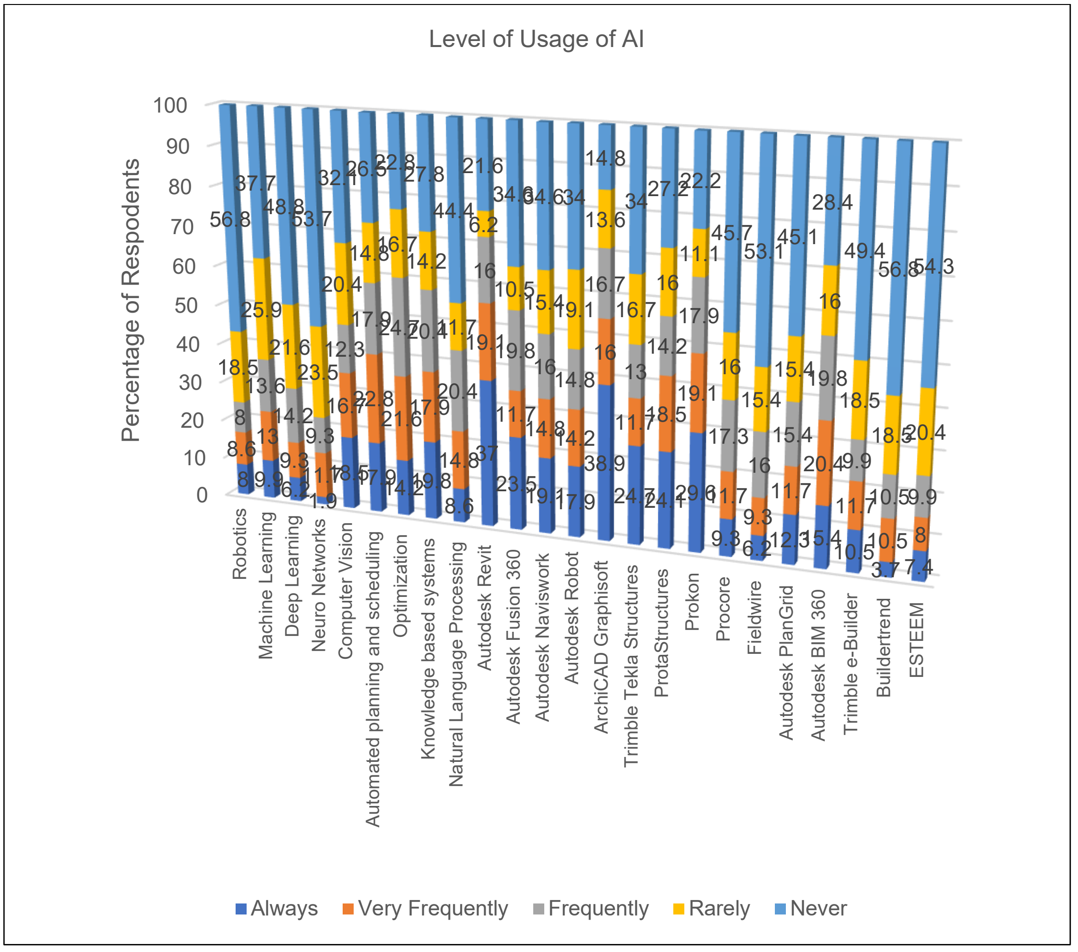


Figure 3. Chart Showing The Level of AI Usage of Respondents

Computer Vision, with a mean of 2.69, and Automated Planning and Scheduling, with a mean of 2.91, were frequently used. Computer Vision was always employed by 18.5 per cent of participants, indicating its role in tasks such as site surveillance, progress tracking, and quality inspection. Automated Planning and Scheduling were always used by 17.9 per cent of participants, reflecting their importance in managing project timelines and resource allocation, which are crucial for maintaining project efficiency and quality. Optimisation, with a mean of 2.88, and Knowledge-Based Systems, with a mean of 2.88, also show frequent usage. Both tools are valuable for improving decision-making processes through data analysis and system management. Optimisation was always used by 14.2 per cent of participants and Knowledge-Based Systems by 19.8 per cent, highlighting their roles in enhancing operational efficiency and problem-solving.

Machine Learning, with a mean of 2.31, and Deep Learning, with a mean of 2.02, had lower mean scores compared to other tools, reflecting their less frequent application in the construction industry. Machine Learning was always used by 9.9 per cent of participants, while Deep Learning was always used by 6.2 per cent. These lower adoption rates suggested that these advanced AI methodologies might have been emerging technologies in construction, with applications that were still evolving. Neuro-networks, with a mean of 1.85, and Robotics, with a mean of 1.93, were among the least used tools, with Neuro-networks being always used by only 1.9 per cent and Robotics by 8.0 per cent. This limited usage could have been attributed to the specialised nature of these tools or the developing stage of their application in construction practices.

The findings revealed a diverse and evolving landscape of AI tool usage within the construction industry of Zambia and Kenya, reflecting the industry's varied needs and different stages of technology adoption. The moderate adoption rates of these AI tools suggested that these technologies were gaining traction. The rising use of these tools reflected an industry trend toward embracing more advanced technologies to optimise operations and ensure successful project outcomes.

CONCLUSIONS

The construction sectors in Zambia and Kenya are poised for rapid growth, fuelled by increasing urbanisation and escalating infrastructure demands. Yet, despite the evident potential of Artificial Intelligence (AI) to enhance efficiency and productivity, adoption rates remain notably low. This study illuminated the complex landscape of opportunity and challenges surrounding AI integration in these industries. While construction professionals demonstrated a strong awareness of AI technologies, their actual implementation was hindered by concerns over costs, implementation complexities, and uncertainty regarding the tangible benefits of AI. The findings revealed that both Zambia and Kenya shared similar challenges and opportunities in AI adoption, with no significant differences between the two countries. Despite a reliance on established tools like ArchiCAD Graphisoft and Autodesk Revit for design and project management, the limited utilisation of advanced AI applications–such as machine learning and robotics–indicated a need for a more comprehensive approach to technology integration within the sector.

To bridge this gap, it is essential to emphasise educational initiatives, pilot programs, and collaborative efforts that promote a culture of innovation. A focused strategy to educate stakeholders and encourage collaboration could pave the way for more effective AI adoption, ultimately improving project efficiency, decision-making, and overall productivity. As the construction industry evolves, embracing AI will be crucial to overcoming persistent challenges like cost overruns and schedule delays. By fostering an environment that champions innovation and technological advancement, Zambia and Kenya could leverage AI to drive sustainable growth and elevate the quality of construction practices, establishing a robust foundation for future success.

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UNLOCKING SUSTAINABLE FUTURES: A SYSTEMATIC REVIEW ON THE BENEFITS OF INDUSTRIALIZED BUILDING SYSTEM (IBS)

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Abstract
In the dynamic realm of construction, the Industrialized Building System (IBS) stands out as a transformative approach, promising a multitude of benefits. This study embarks on a journey to unravel the benefits through a systematic literature review. By synthesizing an extensive array of scholarly works, this research aims to shed light on the range of benefits that IBS implementation brings to the construction industry. The systematic review methodology ensures a rigorous and unbiased exploration, encompassing factors such as cost and finance, sustainability, environmental, safety, social benefit, labour reduction, and construction site. Furthermore, this study delves into the challenges and facilitators associated with IBS adoption, offering a holistic understanding of the intricacies involved. The findings not only underline the significant advantages that IBS presents but also provide invaluable insights for industry practitioners, policymakers, and researchers striving to navigate the terrain of modern construction practices. As the construction industry seeks innovative solutions for sustainable and efficient building, this study's revelations contribute to the ongoing dialogue, fostering awareness and informed decision-making around the potential perks of integrating Industrialized Building Systems.

Keywords: *Industrialised building system; systematic literature review; benefits.*

INTRODUCTION

The construction industry is identified as one of the most important pillars for a country's economic growth and it is widely acknowledged for its vital economic role for a country (Kamaruddin et al., 2018; Zainordin N. et al., 2023). Hence, it is undeniable that the construction industry had boost the economic for the country and had contributed significantly to the Gross Domestic Product (GDP) of a country. According to a study by Myers (2016) as supported by Lui (2020), Gross Domestic Product (GDP) refers to the formal measure used by government worldwide for measuring the development of economic annually within the country in figures. Thus, it shows that the construction industry is a significant pillar in enabling a country to achieve competitiveness internationally.

According to the Construction Industry Development Board (CIDB), the Industrialized Building System (IBS) is a construction method whereby the components are manufactured in a controlled and monitored environment such as factory, and the components are then transported to construction site and installed with minimum workforce (CIDB Malaysia - IBS

Portal, 2022). With the implementation of Industrialized Building System (IBS), this provides a rapid solution for construction works as it involves pre-fabrication of components off-site. This method of construction was widely adopted in the construction industry in other countries. As mentioned by Zabihi et al. (2013) and Ashrafi (2017), the Industrialized Building System (IBS) had been adopted by countries such as Germany, the United Kingdom and Japan, after the Second (2nd) World War that boost the demands on buildings.

However, the adoption rate of the system in Malaysian construction industry is still considered unsatisfactory. Based on a statistic from the Construction Industry Development Board (CIDB), the adoption rate of Industrialized Building System for private sector only contribute to 35% at the year of 2020 which does not fulfil the target of 50% adoption rate. This is due to the fact that the construction professionals are still lacking on the awareness of benefits brought by the Industrialized Building System (IBS). Jabar et al. (2018) and Gan et al. (2017) mentioned in their study that the construction stakeholders tend to have negative perceptions on Industrialized Building System (IBS) and are unaware of the advantages. This issue would then escalate into the barrier for the implementation of Industrialized Building System IBS) in Malaysian construction industry. Therefore, one of the main objectives for this research is to determine the benefits of implementing Industrialized Building System (IBS) in construction industry Malaysia.

LITERATURE REVIEW

According to Leong & Zainal (2021), Industrialized Building System can be defined as mass production in a factory or at the site factory depend on standardize shapes and dimensions. Further emphasis by Kwang et al. (2021), Industrialised Building System (IBS) is the term coined by the industry and government to describe the adoption of industrial construction and the use of prefabrication of components in building construction.

The perks or benefits of implementing Industrialized Building System (IBS) in construction industry are tabulated and shown in Table 1. In this study, there are total of 21 scholars being referred. In general, the benefits of Industrialized Building System (IBS) can be categorized into seven (7) groups after referring to the journals, including cost and finance, sustainability, environmental, safety, social benefit, labour reduction, and construction site as shown in Table 1, by accumulating ticks via referring journals.

METHODOLOGY

In this study employ a rigorous systematic literature review process to comprehensively and objectively analyse the existing body of knowledge related to benefits of implementing Industrialised building system (IBS). By following a well-defined methodology, the aim to identify the benefits of implementing Industrialised building system (IBS) by relevant studies from diverse sources. This systematic approach enables to minimize bias, ensure transparency, and establish a robust foundation for the research findings. Through the systematic review, it is intended to provide a comprehensive overview of the current state of research, identify gaps in knowledge, highlight trends, and draw meaningful insights that contribute to a deeper understanding of benefits of implementing Industrialised building system (IBS).

Table 1. Perks of Implementing Industrialized Building System (IBS)

No.	Authors (Year) / Perks of Implementing IBS	Cost and Finance	Sustainability	Environmental	Safety	Social Benefit	Labour Reduction	Construction Site
1.	Tarang et al., 2022	*		*			*	*
2.	Al-Aidrous et al., 2021				*		*	
3.	Alawag et al., 2021	*		*	*		*	*
4.	Lee et al., 2021	*	*	*	*		*	*
5.	Leong & Zainal, 2021	*		*			*	*
6.	Kwang et al., 2021	*	*	*	*		*	
7.	Samad et al., 2020	*		*	*	*	*	*
8.	Shafie, 2020	*		*	*		*	*
9.	Kasim et al., 2019	*	*	*	*		*	*
10.	Ismail et al., 2019	*		*	*		*	*
11.	Adnan et al., 2019	*		*	*		*	*
12.	Lim & Sam, 2018	*		*	*		*	*
13.	Jabar & Ismail, 2018	*	*	*	*		*	*
14.	Nawi et al., 2018	*		*	*		*	*
15.	Rahim & Qureshi, 2018	*		*	*		*	*
16.	Gan et al., 2017	*		*	*		*	*
17.	Ashrafi, 2017	*		*		*	*	*
18.	Santoso et al., 2017	*	*	*	*	*	*	*
19.	Nawi et al., 2013	*	*	*	*		*	*
20.	Abedi et al., 2011	*	*	*	*		*	
21.	Nawi et al., 2011		*	*	*		*	
	Total Times Referred	**19**	**8**	**20**	**18**	**3**	**21**	**17**

The research methodology adopted for the present of research work is presented in Figure 1. In the initial phase, an exhaustive literature review is carried out to extract the Industrialised building system (IBS) attributes. Further with the systematic literature review process where there (3) filters have been set. There are:

a) Filter 1 – Database selection for collection the journal. Where in this research, the Scopus journal has been chosen.
b) Filter 2 – Selection of keyword. The keywords used are: 'benefits' and 'industrialised building system'
c) Filter 3 – Time period inclusion between year 2011 to 2022.

A systematic review was conducted using a combination of the keyword highlighted above. The perks or benefits of Industrialised building system (IBS) has been tabulated according to scholars and number of times referred to the attributes has been tabulated accordingly. Last stage, presenting the findings on attributes of Industrialised building system (IBS) in the form of infographic presentation- sunburst. By referring to Figure 2, shown the numbers of journal has been used for this research. There are 21 journals in the construction industry that focus on the implementation of Industrialized Building System (IBS).

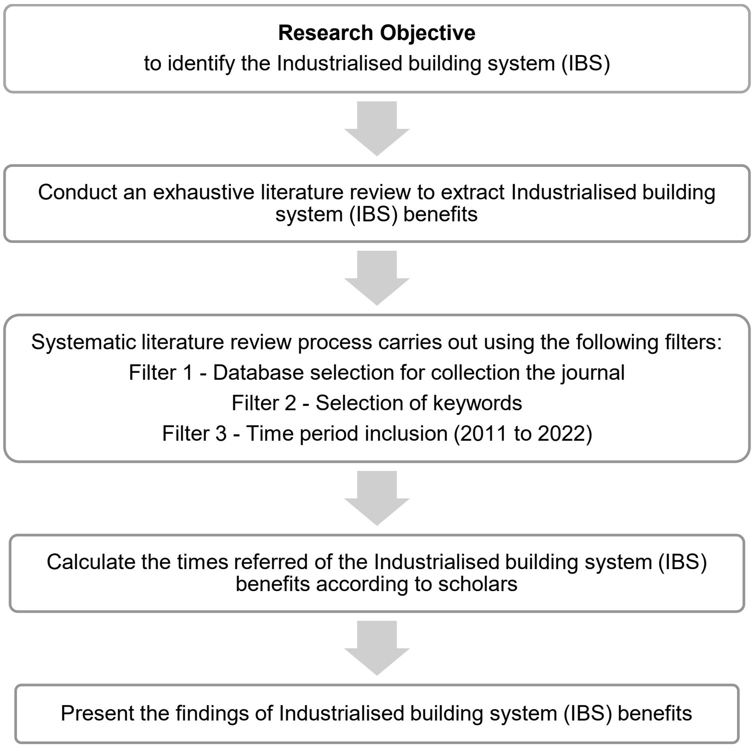

Figure 1. Research Methodology

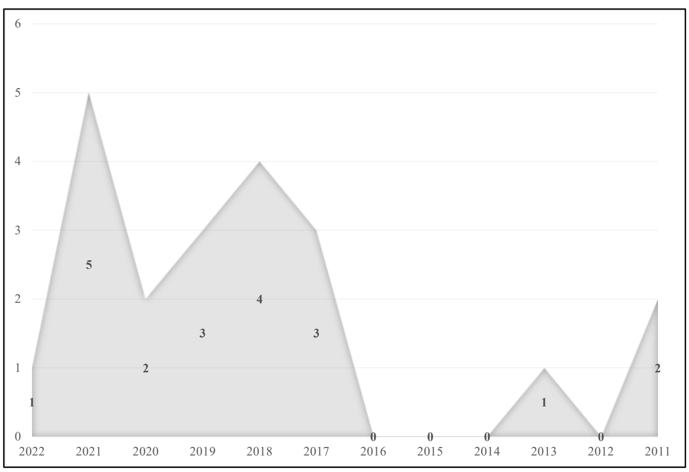

Figure 2. Number of Journals Referred According to Year

RESULTS AND DISCUSSION

Results

Based on Table 1, the ranking on times referred for benefits of Industrialized Building System (IBS) rank based on the Table 2 below and further reflected on Figure 3 Spider-web tabulation numbers of times referred benefits of Industrialized Building System (IBS).

Table 2. The Ranking Based on Total Times Referred for Perks of Implementing Industrialized Building System (IBS)

No.	Perks of Implementing IBS	Total Times Referred	Ranking
1.	Cost and finance	19	3
2.	Sustainability	8	6
3.	Environmental	20	2
4.	Safety	18	4
5.	Social benefit	3	7
6.	Labor reduction	21	1
7.	Construction site	17	5

The ranking on seven (7) perks of implementing IBS has been rank based on numbers of times referred and highlighted by the twenty (21) scholars. The first rank is labor reduction and follow by environmental, cost and finance, safety, construction site, sustainability and social benefits are the lowest rank among all seven (7) perks.

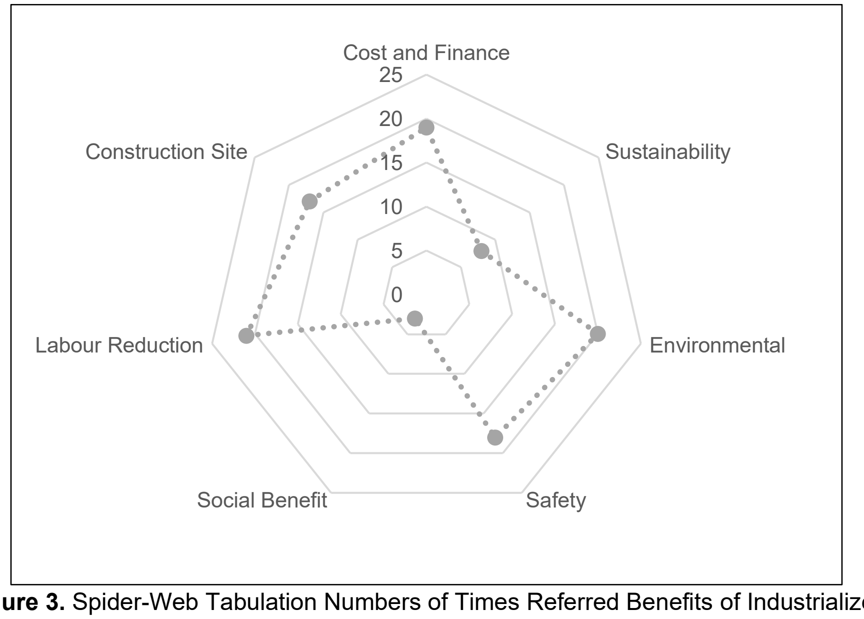

Figure 3. Spider-Web Tabulation Numbers of Times Referred Benefits of Industrialized Building System (IBS)

Discussion

Labor Reduction

In fact, one of the major sub-benefit included under the labor reduction benefit group is the reduction of labor demand on site. According to Table 2, there are a total of 21 scholars mentioned that this is identified as sub-benefit for Industrialized Building System (IBS) in their studies. Based on a study conducted by Rahim and Qureshi (2018), Industrialized Building System (IBS) provides the benefit of reducing labor demand on site due to the higher mechanization as the process for the system are repeatable. In fact, Ismail et al. (2019) pointed out in the study that the labor demand on site is greatly reduced with the introduction of Industrialized Building System, including the tradesmen such as the carpenters and the bar-benders. Moreover, Nawi et al. (2011) and Kasim et al. (2019) mentioned that due to the higher degree of mechanization involved in Industrialized Building System (IBS) projects, it allows prefabrication at centralized factories, thus provides a significant decrease to the labor requirements on site. According to Lee et al. (2021), Industrialized Building System (IBS) only require minimal installation works on the construction site as compared to conventional construction such as setting up formwork on construction site.

Environmental

As according to Table 2, wastage reduction during construction process was also classified as a sub-benefit for the benefit group of environmental. Based on a questionnaire survey conducted by Kasim et al. (2019) to Grade 7 contractors that registered with the Construction Industry Development Board (CIDB), majority of the respondents strongly agree that there is minimal wastage generation with the implementation of Industrialized Building System (IBS). Aside from that, Rahim and Qureshi (2018) also claimed that due to the off-site prefabrication of materials at factories, hence lesser wastage was generated on site and thus contribute to cleaner site environment. As according to Lee et al. (2021), minimization of site wastage had brought about the benefit for providing more environmental-friendly impact as compared to conventional method. Furthermore, under the group of environmental benefit, Industrialized Building System (IBS) is identified to generate lesser negative impacts on the environment. This sub-benefit was being mentioned by 7 scholars ranging from year 2011 to 2021 as tabulated in Table 1. The adoption of Industrialized Building System (IBS) is considerably environmental-friendly and thus reducing the negative impacts on environmental aspect (Ashrafi, 2017 & Gan et al., 2017 & Leong & Zainal, 2021). According to Nawi et al. (2011), with better usage of available building materials, the implementation of Industrialized Building System (IBS) had significantly contributed to the decrease of negative impacts on the environment. Besides, Leong & Zainal (2021) mentioned in their study that the harmful impacts on environment was greatly reduced with the utilization of Industrialized Building System (IBS) as compared to conventional construction that generates various pollutions. In addition, Ashrafi (2017) also mentioned that due to the decrease of environmental impacts by Industrialized Building System (IBS), conflicts with authorities and surrounding facilities can also be avoided.

Cost and Finance

For the group of cost and finance, the lower overall construction costs due to time-saving construction process is one of the major benefits for Industrialized Building System (IBS). According to Jabar and Ismail (2018), earlier completion time of construction project had resulted to a benefit of cost savings and hence lower overall construction costs incurred. Likewise, Adnan et al. (2019) also mentioned that the savings in the construction time can compensate the construction costs, hence allowing overall construction costs to be reduced. Based on another study by Ismail et al. (2019), the implementation of Industrialized Building System (IBS) increases the speed of construction completion and contribute to cost savings in over construction costs. Besides, savings in labor costs is also identified as a sub-benefit under the benefit group of cost and finance. This sub-benefit had been mentioned by 4 scholars including Nawi et al. (2013), Nawi et al. (2018), Kwang et al. (2021) and Lee et al. (2021). According to Kwang et al. (2021), with the implementation of Industrialized Building System, it provides a cost saving in labor costs as compared to conventional construction method. This is due to the fact that Industrialized Building System (IBS) is prefabricated off-site, hence it reduces the demand of labors on-site and it significantly reduce the costs for labors (Nawi et al., 2013 & Nawi et al., 2018 & Lee et al., 2021).

Safety

Moreover, minimization of hazards and risks to workers is also included as one of the sub-benefits for implementation of Industrialized Building System (IBS). The adoption of Industrialized Building System (IBS) is said to be efficient in providing the sub-benefit of minimizing the risks related to site safety and meanwhile improving health and safety of workers on site (Nawi et al., 2011 & Jabar & Ismail, 2018 & Lim & Sam, 2018 & Shafie, 2020 & Al-Aidrous et al., 2021). Besides that, Santoso et al. (2017) identified that off-site construction is one of the reasons that Industrialized Building System (IBS) can minimized the hazards and risks to workers on site. Likewise, Samad et al. (2020) also mentioned that conventional construction method often results in unhealthy work environment, while on the other hand the usage of Industrialized Building System (IBS) allows reduced construction works on site and hence minimize the safety risks for workers. Apart from that, another sub-benefit that is categorized under the benefit group of safety is the reduction on construction accidents. This statement had been cited from 3 scholars including Santoso et al. (2017), Samad et al. (2020) as well as Al-Aidrous et al. (2021). According to Samad et al. (2020), safety aspects play an important role in determining the successfulness for delivering construction projects. Hence, it was identified that with the usage of Industrialized Building System (IBS), better and safer working environment can be obtained and meanwhile accidents on site can be reduced Al-Aidrous et al. (2021). Based on a study by Santoso et al. (2017), construction accidents on site including falling of materials from high level are significantly reduced with the implementation of Industrialized Building System (IBS) as the construction works are more controllable and done off-site.

Construction Site

The scholars mentioned this fact in their study including Abedi et al. (2011), Gan et al. (2017) as well as Shafie (2020). In fact, Abedi et al. (2011) and Shafie (2020) mentioned in their study that the implementation of Industrialized Building System (IBS) allows for proper coordination and construction site management as the activities carry out on site is relatively lesser and easier to be managed with. Construction site management includes the management of resources, quality and time, as well as the coordination of works, with better construction site management it improves productivity of works. Not only that, the implementation of Industrialized Building System (IBS) is also identified to have the advantages of promoting cleanliness and tidiness of construction site. This is considered as one of the sub-benefits under the group of construction site and it had been mentioned by 14 scholars as identified in Table 2.3. According to Samad et al. (2020), hygiene is identified as an essential aspect that helps determining the successfulness of construction projects. Hence, Santoso et al. (2017), Ashrafi (2017), Jabar & Ismail (2018), Adnan et al. (2019) and Lee et al. (2021) mentioned in their study that with the utilization of Industrialized Building System (IBS) for projects, a cleaner and neater construction site can be obtained. Moreover, this statement is also supported by Ismail et al. (2019), as the cast-in-situ wet and dirty conventional construction methods can be substituted with the implementation of Industrialized Building System (IBS). According to Rahim & Qureshi (2018), due to the benefits of providing cleaner and tidier construction site, the construction industry for countries including Malaysia and Singapore had slowly shifted from conventional construction to Industrialized Building System (IBS).

Sustainability

As for the benefit group of sustainability, the sub-benefit identified under this group is the optimum usage of materials. The scholars including Nawi et al. (2011), Abedi et al. (2011), Santoso et al. (2017) and Lee et al. (2021). Nawi et al. (2011) and Lee et al. (2021) mentioned that optimum usage of materials is also identified as a benefit for the implementation of Industrialized Building System (IBS). According to Abedi et al. (2011), the optimum usage of materials such as control and careful selection of materials such as steel and sand, will significantly contribute to sustainability aspect. Besides that, the implementation of Industrialized Building System (IBS) allows optimization on usage of materials and material conservation as compared to conventional construction method (Santoso et al., 2017). Moreover, allow repetitive usage of mould and system formwork is also identified the benefit group of sustainability as mentioned by 5 scholars including Nawi et al. (2011), Jabar & Ismail (2018), Ismail et al. (2019), Kasim et al. (2019) and Kwang et al. (2021). Based on a study by Jabar & Ismail (2018), the system formwork for Industrialized Building System (IBS) that is made of steel, aluminium as well as scaffolding, can be used repetitively can it improves sustainability. Likewise, Kasim et al. (2019) and Kwang et al. (2021) stated in their study that the repetitive usage of system formwork made of steel and the scaffolding are able to provide substantial cost saving and improve sustainability.

Social Benefits

As for the benefit group of social benefit, reduction on dust and noise pollution had been determined as a sub-benefit according to the journals referred. In overall, there are 3 scholars mentioning this fact as benefit of Industrialized Building System (IBS) in their study. Among the scholars, includes Santoso et al. (2017), Ashrafi (2017) and Samad et al. (2020). Ashrafi (2017) identified that with the implementation of Industrialized Building System (IBS), pollutions on dust and noise are greatly reduced on site and hence preventing conflicts with authorities or neighbors. Due to the fact that Industrialized Building System (IBS) involves prefabrication in factory, hence the pollution of dust and noise on site that are caused by construction works can be reduced even if the projects' site is in urban areas (Santoso et al., 2017). Moreover, Samad et al. (2020) also pointed out that unlike conventional construction that will result in dust and noise pollution, the usage of Industrialized Building System (IBS) provides social benefits of reducing pollutions not only to employees on site, but also to local community.

CONCLUSION

Once the benefits have been identified, the next step involves formulating strategies to prepare and educate construction stakeholders about the potential advantages offered by the Industrialized Building System (IBS). Raising awareness about the benefits of Industrialized Building Systems (IBS) within the construction industry involves targeted communication and educational strategies. There can be achieve by the following strategies:

1. Educational Workshops and Seminars: Organize workshops, seminars, and webinars that focus on explaining the concept of IBS and its advantages. Invite industry experts, practitioners, and academics to share insights and case studies showcasing successful IBS implementations.

2. Case Studies and Success Stories: Compile and share real-world case studies that highlight the positive outcomes of IBS projects. Emphasize factors such as reduced construction time, cost savings, improved quality, and enhanced safety.
3. Demonstration Projects: Collaborate with industry stakeholders to initiate demonstration projects that use IBS. Invite professionals to visit these projects, observe the efficiency and quality first-hand, and discuss the benefits with project teams.
4. Collaboration with Professional Associations: Partner with construction-related professional associations and industry groups. Present the benefits of IBS at their conferences, events, and meetings, reaching a broader audience of industry professionals.
5. Industry Publications and Newsletters: Write articles or publish content in industry magazines, newsletters, and online platforms. These platforms allow you to communicate the advantages of IBS to a wide range of construction practitioners.
6. Online Resources and Web Presence: Create a dedicated website or web page that provides comprehensive information about IBS, including its benefits, case studies, research findings, and resources. Use social media platforms to share updates and engage with industry professionals.
7. Networking Events: Host networking events that bring together professionals from different sectors of the construction industry. Use these events as platforms for discussing and promoting the benefits of IBS in a more informal setting.
8. Collaboration with Educational Institutions: Partner with universities, colleges, and vocational schools offering construction-related programs. Integrate information about IBS benefits into relevant courses, encouraging future professionals to adopt and promote IBS.
9. Engage Influential Industry Leaders: Identify influential figures within the construction industry and engage them in advocating for IBS benefits. Their endorsement can carry significant weight and encourage others to explore IBS.
10. Government Support and Regulations: Collaborate with government agencies involved in construction regulations and policies. Advocate for policies that promote and incentivize IBS adoption, while highlighting its benefits for sustainable and efficient construction.
11. Interactive Platforms: Develop interactive tools, such as online calculators or cost comparison tools, that allow construction professionals to estimate the benefits of IBS in their specific projects.
12. Feedback and Testimonials: Gather feedback from those who have implemented IBS and share their positive experiences as testimonials. Authentic feedback can resonate with others considering adopting IBS.

The key-take-away that consistent and targeted communication is key to creating lasting awareness about the benefits of IBS within the construction industry. People in the construction industry who advocate for the benefits of IBS. The support is very important and can encourage others to find out about irritable bowel syndrome.

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EXPLORING THE SYNERGY BETWEEN DIGITALISATION AND SUSTAINABILITY: INSIGHTS FROM MALAYSIAN QUANTITY SURVEYORS

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Abstract
The integration of digitalisation in the construction industry has become a key driver of sustainability, enabling more efficient resource management, and reducing environmental impact. Quantity Surveyors (QS) play a crucial role in ensuring that digital advancements align with sustainable construction practices, particularly in cost management and project efficiency. This study explores the synergy between digitalisation and sustainability from the perspective of Malaysian QS professionals, highlighting the impact, challenges, and opportunities of adopting digital tools in sustainable construction. The research aims to examine how digital technologies such as Building Information Modelling (BIM), Artificial Intelligence (AI), and blockchain contribute to sustainability, identify the barriers faced by QS professionals in implementing digital solutions, and provide insights into their role in promoting cost efficiency and waste reduction. Findings indicate that while digitalisation enhances sustainability by improving cost forecasting, resource optimisation, and environmental performance, challenges such as high implementation costs, skill gaps, and resistance to change hinder widespread adoption. The study concludes that industry-wide training programs, policy incentives, and collaborative initiatives are essential to support QS professionals in leveraging digitalisation for sustainability. These insights provide valuable implications for policymakers, industry stakeholders, and QS practitioners in driving Malaysia's construction industry towards a more sustainable and digitally integrated future.

Keyword: *Digitalisation; Sustainability; Quantity Surveyors; Building Information Modelling (BIM); Artificial Intelligence (AI); Blockchain; Cost Management; Sustainable Construction; Malaysian Construction Industry*

INTRODUCTION

Digitalisation has emerged as a transformative force in the construction industry, revolutionising project execution, cost management, and sustainability practices (Zainordin, N. et al., 2024a; Guo et al., 2022). Technologies such as Building Information Modelling (BIM), Artificial Intelligence (AI), blockchain, digital twins, and the Internet of Things (IoT) have significantly enhanced resource optimisation and real-time decision-making (Shen et al., 2021). As a result, the role of Quantity Surveyors (QS) has evolved beyond traditional cost estimation to incorporate sustainability-driven decision-making, particularly in life cycle costing, carbon footprint assessment, and resource efficiency analysis (Olawumi & Chan, 2018).

The integration of digital tools, including BIM and AI-powered cost estimation, empowers QS professionals to improve cost accuracy and minimise environmental impact (Ding et al., 2020). However, widespread adoption of digital technologies in the QS profession is hindered by several challenges, such as limited technical expertise, high implementation costs, and resistance to change (Perera et al., 2020). While existing studies highlight the potential benefits of digitalisation in enhancing sustainability, there remains a lack of empirical research on how QS professionals in Malaysia are leveraging these technologies (Mohd-Rahim et al., 2021). Addressing this knowledge gap is crucial to informing industry policies and developing professional training programs. This study aligns with previous research that underscores the urgent need for a digital transformation strategy in the QS profession to support sustainable construction practices (Zainordin, N. et al., 2024a; Ismail et al., 2022).

Literature Review

Definition and Key Concepts

Digitalisation in construction refers to the integration of advanced digital technologies to optimise processes, improve efficiency, and enhance decision-making across a project's life cycle (Guo et al., 2022). Unlike traditional construction methods, digitalisation facilitates real-time collaboration, predictive analytics, and automated project management, leading to more informed decision-making and reduced project risks (Zainordin, N. et al., 2024a; Shen et al., 2021). This transformation is driven by data-driven tools, automation, and digital workflows, which collectively enhance productivity, reduce costs, and support sustainability objectives. The shift towards digital construction is crucial in addressing contemporary challenges in the built environment, including inefficiencies, material wastage, and environmental concerns.

Technologies in Digital Construction

The rapid advancement of technology has revolutionised the construction industry, introducing innovative tools and systems that drive digital transformation. These technologies not only enhance project delivery but also contribute to sustainable development by optimising resource management, minimising waste, and improving overall efficiency. Among the most significant digital innovations are Building Information Modelling (BIM), Artificial Intelligence (AI), the Internet of Things (IoT), Blockchain Technology, and Digital Twin Technology, each of which plays a vital role in modernising construction processes. Building Information Modelling (BIM) has emerged as a fundamental tool in digital construction, offering a comprehensive digital representation of a building's physical and functional characteristics. By enabling virtual modelling and simulation, BIM enhances design coordination, clash detection, and resource optimisation (Ding et al., 2020). This technology allows construction professionals to assess energy efficiency and environmental impact before actual project execution, reducing costly rework and ensuring better sustainability outcomes.

Similarly, Artificial Intelligence (AI) is transforming the construction industry by improving predictive cost estimation, risk analysis, and automated decision-making (Zainordin, N. et al., 2024a). Through machine learning algorithms, AI-driven applications can analyse vast datasets to minimise material waste, enhance project sustainability, and optimise construction schedules (Perera et al., 2020). The ability of AI to predict potential risks and inefficiencies enables proactive decision-making, reducing delays and cost overruns. Another transformative technology is the Internet of Things (IoT), which facilitates real-time monitoring of construction sites through interconnected sensors and smart devices (Zainordin, N. et al., 2024a). These sensors track material usage, energy consumption, and environmental conditions, ensuring compliance with sustainability standards and promoting resource efficiency (Olawumi & Chan, 2018). By providing real-time insights, IoT enhances safety measures, improves productivity, and supports the industry's transition toward smart construction.

In addition to IoT, Blockchain Technology is redefining transparency and accountability within the construction sector. As a decentralised digital ledger, blockchain strengthens security and trust in construction contracts, procurement, and payments. It ensures secure transactions, ethical sourcing of sustainable materials, and reduces fraud risks, thereby fostering greater integrity in the supply chain (Ismail et al., 2022). The immutable nature of blockchain records also enhances legal compliance and minimises disputes related to contractual obligations. Another ground-breaking innovation is Digital Twin Technology, which creates a virtual replica of a physical structure, allowing for real-time simulations, predictive maintenance, and performance monitoring (Zainordin, N. et al., 2024b). This technology enhances energy efficiency and resource management, enabling construction professionals to simulate various scenarios and optimise building performance before physical implementation (Mohd-Rahim et al., 2021). By providing a data-driven approach to construction and facility management, digital twins contribute to the industry's long-term sustainability goals (Zainordin, N. et al., 2024b). Collectively, these digital tools play an instrumental role in modern construction, fostering greater accuracy, efficiency, and sustainability throughout a project's lifecycle. As the construction industry continues to embrace digital transformation, the integration of these technologies will be crucial in shaping a more sustainable and resilient built environment.

Benefits and Challenges of Digitalization

The adoption of digital technologies in the construction industry has the potential to transform project delivery by enhancing efficiency, reducing costs, and promoting sustainability. However, despite its numerous advantages, digitalisation also presents challenges that must be addressed for successful implementation. While the long-term benefits outweigh the difficulties, overcoming barriers such as high implementation costs, skill gaps, and resistance to change remains crucial for widespread digital adoption in the sector. One of the most significant advantages of digitalisation in construction is enhanced efficiency. The integration of automation and digital workflows reduces human errors, improves project coordination, and accelerates construction timelines (Guo et al., 2022). By leveraging real-time collaboration tools and predictive analytics, construction teams can optimise project planning, minimise delays, and ensure smoother execution of tasks.

Another key benefit is cost savings, as digital technologies improve financial planning and budget management. Advanced cost estimation tools and real-time budget tracking provide more accurate financial forecasts, minimising budget overruns and ensuring better resource allocation (Zainordin, N. et al., 2024b; Shen et al., 2021). Through data-driven insights, project managers can make more informed decisions, reducing unnecessary expenditures and optimising material usage. Furthermore, digitalisation plays a crucial role in promoting sustainability within the built environment. By minimising material waste, optimising energy consumption, and facilitating the use of eco-friendly materials, digital tools help reduce the overall carbon footprint of construction projects (Ding et al., 2020). Technologies such as Building Information Modelling (BIM), the Internet of Things (IoT), and Digital Twin Technology support sustainable design and construction by enabling energy-efficient building performance assessments before actual construction begins.

Despite its advantages, digitalisation also presents several challenges that hinder its widespread adoption. One of the most significant barriers is high implementation costs. The initial investment in software, hardware, and workforce training can be substantial, particularly for small and medium-sized enterprises (SMEs) that may struggle with financial constraints (Perera et al., 2020). Many companies are hesitant to adopt digital tools due to concerns about return on investment and the long learning curve associated with new technologies. Another major challenge is the skill gap and lack of technical expertise among construction professionals. Many industry practitioners lack the necessary digital skills to fully utilise technologies such as BIM, AI, and blockchain, creating a knowledge gap in the sector (Mohd-Rahim et al., 2021). Without adequate training and education, the potential benefits of digitalisation cannot be fully realised, limiting its impact on the construction industry.

Additionally, resistance to change remains a persistent issue in the industry. The construction sector has traditionally relied on conventional methods, and many stakeholders are reluctant to embrace new technologies due to perceived risks and uncertainties (Ismail et al., 2022). Overcoming this resistance requires a shift in mindset, strong leadership, and strategic policies that promote digital adoption as a standard practice. While digitalisation presents several challenges, its long-term benefits in efficiency, cost management, and sustainability make it a critical component of future construction practices (Zainordin, N. et al., 2024b). Addressing barriers such as high implementation costs, skill gaps, and resistance to change through investment in training, government support, and industry-wide digitalisation policies will ensure that the construction sector can fully leverage technological advancements. As the industry continues to evolve, embracing digital transformation will be essential in shaping a more efficient, cost-effective, and sustainable built environment.

Sustainability in the Built Environment

Sustainability in the built environment has become an essential aspect of modern construction, emphasising the need to balance economic growth with environmental preservation and social well-being. As global concerns over climate change, resource depletion, and urbanisation intensify, sustainable construction practices are increasingly recognised as fundamental to ensuring long-term resilience and liveability in cities. By adopting sustainable principles, the construction industry can minimise negative impacts while maximising benefits for communities and future generations.

Definition and Principles of Sustainability

Sustainability in the built environment refers to the minimisation of environmental, social, and economic impacts associated with construction activities, while simultaneously enhancing long-term benefits for communities and stakeholders (Olawumi & Chan, 2018). This concept is often framed within three key dimensions:

1. Environmental Sustainability – This dimension focuses on reducing carbon emissions, energy consumption, and waste generation while promoting renewable energy sources and sustainable building materials. Environmentally sustainable construction integrates energy-efficient designs, green technologies, and eco-friendly materials to mitigate environmental degradation.
2. Social Sustainability – This aspect emphasises creating safe, inclusive, and healthy built environments that cater to the well-being of communities. It considers factors such as labor rights, public health, accessibility, and social equity, ensuring that construction projects contribute positively to society by fostering liveable and resilient spaces.
3. Economic Sustainability – This dimension ensures cost-effective solutions, resource efficiency, and long-term affordability in construction projects. The goal is to achieve financial viability without compromising environmental or social integrity (Shen et al., 2021). Economic sustainability also encourages the use of life cycle costing (LCC) and value-driven design approaches to ensure sustainable investment returns.

By integrating these three dimensions, sustainable construction aims to create a built environment that is resilient, energy-efficient, and beneficial to both present and future generations.

Sustainability Initiatives in Malaysia

Recognising the need for sustainable development, Malaysia has implemented several national frameworks and certification programs to promote green construction. These initiatives serve as regulatory benchmarks to encourage sustainable practices, improve environmental performance, and drive green innovation in the construction industry. Some of the key sustainability initiatives in Malaysia include:

1. Construction Industry Development Board (CIDB) Sustainable Infrastructure Rating – This national framework evaluates infrastructure sustainability based on environmental, social, and economic criteria. It provides guidance for developers and policymakers in ensuring that infrastructure projects align with sustainability goals and climate action strategies (CIDB Malaysia, 2020).
2. Green Building Index (GBI) – As Malaysia's leading green certification system, GBI assesses buildings based on energy efficiency, indoor environmental quality, sustainable site planning, and material use. GBI-certified buildings are designed to reduce energy consumption, water usage, and carbon emissions, contributing to a greener and more sustainable built environment (GBI Malaysia, 2019).
3. Low Carbon Cities Framework (LCCF) – This initiative aims to reduce carbon emissions through smart urban planning, energy-efficient building designs, and green infrastructure. It aligns with Malaysia's commitment to climate change mitigation by promoting low-carbon urban development strategies (Malaysian Green Technology and Climate Change Centre, 2021).

These sustainability initiatives reflect Malaysia's commitment to fostering a greener and more resilient built environment. By adopting sustainable construction practices, enhancing policy frameworks, and encouraging industry-wide participation, Malaysia is paving the way for a more environmentally responsible and future-ready construction sector.

The Role of Quantity Surveyors in Digitalization and Sustainability

As the construction industry embraces digitalisation and sustainability, the role of Quantity Surveyors (QS) has evolved beyond traditional cost management. QS professionals are now instrumental in integrating digital tools and sustainable practices to enhance project efficiency, financial transparency, and environmental responsibility. By leveraging advanced technologies such as Building Information Modelling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), and blockchain, QS professionals contribute to a more data-driven, efficient, and sustainable built environment.

How QS Professionals Contribute to Digital Transformation

The adoption of digital technologies has transformed the way QS professionals manage construction projects, particularly in the areas of cost estimation, procurement, contract administration, and risk management. Traditionally, cost estimation and financial planning relied on manual calculations and historical data; however, digitalisation now allows for real-time, automated, and highly accurate cost forecasting.

1. Building Information Modelling (BIM) – QS professionals utilise BIM-integrated cost estimation tools to extract accurate material quantities, analyse cost variations, and optimise budget allocation. BIM enhances design coordination and clash detection, reducing costly errors and rework, which ultimately supports sustainable resource management (Ding et al., 2020).
2. Artificial Intelligence (AI) – AI-driven algorithms assist in predictive cost estimation and risk analysis, allowing QS professionals to anticipate financial risks, optimise project cash flow, and improve cost control measures. By automating repetitive tasks, AI enhances efficiency and enables QS professionals to focus on strategic decision-making (Perera et al., 2020).
3. Blockchain Technology – Blockchain facilitates secure and transparent transactions in procurement, contract administration, and payment verification. This decentralised ledger system reduces fraud, ensures ethical sourcing of materials, and enhances accountability throughout the construction supply chain (Ismail et al., 2022).

By integrating these digital tools, QS professionals enhance the financial and contractual management of projects, ensuring improved decision-making, cost efficiency, and sustainability compliance.

Cost Management and Life Cycle Assessment for Sustainable Projects

A critical responsibility of QS professionals in sustainable construction is Life Cycle Costing (LCC), which assesses the total cost of ownership over a building's lifespan. LCC considers factors such as initial construction costs, operation and maintenance expenses, energy consumption, and end-of-life disposal, ensuring that financial decisions align with long-term sustainability goals (Mohd-Rahim et al., 2021).

The integration of digitalisation in LCC significantly improves the accuracy and effectiveness of sustainability assessments:

1. IoT-Enabled Data Collection – IoT sensors provide real-time monitoring of material usage, energy consumption, and environmental performance, enabling QS professionals to make data-driven cost evaluations and sustainability recommendations.
2. AI-Powered Predictive Analytics – AI algorithms analyse historical data and forecast long-term cost implications, allowing QS professionals to optimise resource allocation and select cost-effective, eco-friendly materials (Guo et al., 2022).

By incorporating digitalisation into cost management and sustainability assessments, QS professionals play a crucial role in driving environmentally responsible and financially viable construction practices. Their expertise ensures that projects are not only cost-effective but also aligned with global sustainability objectives, reinforcing the importance of QS in the digital era.

Synergy between Digitalization and Sustainability

The convergence of digitalisation and sustainability is revolutionising the construction industry by promoting resource efficiency, environmental responsibility, and data-driven decision-making. Digital tools enable real-time monitoring, predictive analytics, and process automation, which contribute to sustainable construction practices and the reduction of environmental impact. The adoption of digitalisation ensures that construction projects are not only cost-efficient and productive but also aligned with global sustainability goals.

How Digital Tools Enhance Sustainable Practices

The integration of digital technologies has significantly improved the industry's ability to implement and measure sustainable construction practices. Key digital tools that support sustainability include:

1. Building Information Modelling (BIM) – BIM enhances green building design by enabling simulations of energy performance, material selection, and carbon footprint assessment. Through clash detection and optimised design coordination, BIM reduces material waste and supports energy-efficient building solutions (Shen et al., 2021).
2. Artificial Intelligence (AI) – AI-powered predictive analytics play a crucial role in forecasting material needs, minimising resource wastage, and optimising procurement strategies. AI-driven decision-making allows for better material selection, cost control, and reduced environmental impact (Ding et al., 2020).
3. Internet of Things (IoT) Monitoring – IoT sensors enable real-time tracking of energy and resource consumption, ensuring that buildings and construction sites operate efficiently and comply with sustainability standards. By monitoring water usage, electricity consumption, and environmental conditions, IoT contributes to energy conservation and carbon footprint reduction (Olawumi & Chan, 2018).
4. Blockchain Technology – Blockchain enhances transparency and accountability in construction supply chains, ensuring ethical sourcing of materials and secure financial transactions. By reducing fraud and inefficiencies, blockchain promotes responsible procurement and minimises the environmental impact of construction activities (Ismail et al., 2022).

5. Digital Twin Technology – Digital twins serve as virtual replicas of physical structures, allowing real-time simulations and environmental impact assessments before construction begins. This technology supports predictive maintenance, energy optimisation, and life cycle assessment, making it a powerful tool for achieving sustainable urban development (Mohd-Rahim et al., 2021).

By integrating these digital innovations, the construction industry can achieve a balance between efficiency, cost-effectiveness, and environmental stewardship. Digitalisation empowers industry professionals to make data-driven sustainability decisions, ensuring that future construction projects are resilient, environmentally responsible, and aligned with global climate action goals.

METHODOLOGY

The research methodology outlines the approach, data collection techniques, and analytical methods employed to investigate the synergy between digitalisation and sustainability in the Malaysian construction industry, with a specific focus on Quantity Surveyors (QS) professionals. A well-structured methodology ensures the reliability and validity of the study's findings (Creswell & Creswell, 2018).

Research Design

This study adopts a mixed-methods approach, integrating both quantitative and qualitative research methods to provide a comprehensive understanding of digitalisation's role in promoting sustainable construction practices (Bryman, 2016). The quantitative component involves collecting numerical data to measure the extent of digital adoption, its impact on cost management, and sustainability outcomes. Meanwhile, the qualitative component captures in-depth insights from QS professionals regarding challenges, opportunities, and best practices in digital construction (Creswell, 2014).

Data Collection

To ensure a robust and diverse dataset, multiple data collection methods are employed:

Surveys

A structured questionnaire is distributed to Malaysian Quantity Surveyors to gather quantitative data on digital tool adoption, perceived benefits, and challenges in integrating sustainability (Denscombe, 2017). The survey includes:

- Likert-scale questions to assess attitudes toward digitalisation.
- Multiple-choice questions to capture demographic and professional information.
- Open-ended responses for broader insights into real-world experiences with digital tools.

Interviews

Semi-structured interviews are conducted with experienced QS professionals, construction stakeholders, and sustainability experts to provide qualitative insights into industry experiences, digital transformation trends, and sustainability best practices (King et al., 2019). These interviews help to:

- Contextualize survey findings with practical industry perspectives.
- Explore emerging themes in digital construction.
- Identify barriers and enablers of digital adoption.

Case Studies

Real-world case studies of Malaysian construction projects that have successfully integrated digitalisation and sustainability are analysed (Yin, 2018). These case studies highlight:

- Best practices in adopting digital tools for cost management and sustainability.
- Lessons learned from project implementation.
- Measurable impacts on cost efficiency, waste reduction, and project sustainability.

Data Analysis Methods

The collected data undergoes systematic analysis using both statistical and thematic techniques to derive meaningful conclusions (Silverman, 2020).

Quantitative Analysis

Survey data is analysed using descriptive and inferential statistics, such as:

- Frequency distributions to understand digital adoption rates.
- Mean comparisons to assess the impact of digital tools.
- Correlation analysis to examine relationships between digitalisation and sustainability outcomes (Field, 2018).
- Statistical software such as SPSS or NVivo may be used for data processing and interpretation.

Qualitative Analysis

Interview transcripts and open-ended survey responses are analysed using thematic analysis, where emerging themes related to digitalisation, sustainability, cost management, and QS roles are identified (Braun & Clarke, 2006). This ensures a rich, contextual understanding of industry perspectives.

Case Study Evaluation

A comparative analysis of best-practice projects is conducted to assess the effectiveness of digital tools in enhancing sustainable construction. This helps in:

- Identifying key success factors in digital integration.
- Providing practical recommendations for future industry adoption.

By employing this mixed-methods approach, the study ensures a comprehensive and well-rounded investigation, bridging quantitative metrics with qualitative industry insights to enhance understanding of digitalisation's role in sustainable construction practices.

FINDINGS AND DISCUSSION

This section presents the key findings from the study, derived from survey responses, interviews, and case studies. The results provide insights into the impact of digitalisation on sustainability in Quantity Surveying (QS) practices, as well as the challenges and potential solutions for industry-wide adoption (Table 1).

Table 1. Challenges and Potential Solutions

Challenges	Potential Solutions
High Implementation Costs	Government incentives and funding for SMEs (CIDB Malaysia, 2020).
Skill Gaps and Training Needs	Incorporating digital skills training into QS education (GBI Malaysia, 2019).
Resistance to Change	Industry-wide awareness campaigns and pilot programs (Ismail et al., 2022).

Analysis of Survey and Interview Results

The survey responses and interview data highlight widespread recognition of digitalisation as a key enabler of sustainability in the construction industry. However, the extent of adoption varies, with larger firms demonstrating greater integration of Building Information Modelling (BIM), Artificial Intelligence (AI), and Internet of Things (IoT) compared to small and medium-sized enterprises (SMEs). The findings indicate the following trends:

1. Adoption of Digital Tools

    - 80% of respondents reported using at least one digital tool in their QS practices, with BIM (65%) and AI-powered cost estimation (52%) being the most used.
    - Blockchain and Digital Twin Technologies showed lower adoption rates (20% and 18%, respectively) due to high implementation costs and limited technical expertise.

2. Perceived Benefits of Digitalization

    - Cost savings: 70% of respondents agreed that digital tools improve cost management by reducing errors in cost estimation and procurement.
    - Efficiency: 68% reported that automation and AI-driven analytics enhanced project planning and resource allocation.

- Sustainability: 57% indicated that digital tools help minimise waste and improve material efficiency, aligning with green building objectives.

3. Challenges to Digitalization

   - High Initial Costs: 55% of QS professionals identified financial constraints as a major barrier to adopting advanced digital technologies.
   - Skill Gaps: 48% of respondents cited a lack of digital expertise as a key challenge, particularly in SMEs.
   - Resistance to Change: 40% of participants mentioned organisational reluctance and preference for traditional QS methods as obstacles to digital transformation.

Key Themes Emerging from Data

Digitalisation as a Driver of Sustainable QS Practices

Findings from the interviews indicate that digital tools significantly contribute to sustainability by:

- Enhancing energy-efficient designs through BIM simulations (Shen et al., 2021).
- Reducing material waste via AI-driven predictive analytics (Ding et al., 2020).
- Monitoring energy and resource consumption in real-time using IoT sensors (Olawumi & Chan, 2018).

These findings align with case study evaluations, where projects implementing digital solutions demonstrated a 20–30% reduction in material waste and energy consumption.

The Role of Quantity Surveyors in Digital Transformation

Interviews with senior QS professionals revealed that digitalisation enhances the role of QS in sustainable construction by:

- Improving cost forecasting and risk assessment through AI-powered analytics (Perera et al., 2020).
- Enhancing transparency and accountability using blockchain for contract and payment verification (Ismail et al., 2022).
- Supporting life cycle cost analysis (LCC) with real-time data integration, allowing for informed decision-making on material selection and long-term sustainability (Mohd-Rahim et al., 2021).

Experts emphasised that collaborations between academia, industry, and policymakers are essential to overcoming these barriers and ensuring wider adoption of digital tools in QS practices.

How Digitalization Impacts Sustainability in QS Practices

The findings confirm that digitalisation and sustainability are interlinked, with digital tools playing a crucial role in:

- Optimising cost management while reducing environmental impact.
- Enhancing data-driven decision-making for sustainable material selection.
- Minimising risks and inefficiencies in QS workflows.

Despite the challenges, the study suggests that the long-term benefits of digitalisation outweigh its initial costs, making it a critical component of future QS practices.

CONCLUSION AND RECOMMENDATIONS

This study explored the synergy between digitalisation and sustainability in the Malaysian construction industry, with a specific focus on Quantity Surveyors (QS) professionals. The findings confirm that digital transformation is a key enabler of sustainable construction, as technologies such as Building Information Modelling (BIM), Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and digital twins significantly enhance cost management, resource efficiency, and environmental sustainability.

Survey and interview results indicate that a majority of QS professionals recognise the benefits of digitalisation, particularly in reducing material waste, improving project cost estimation, and enhancing decision-making for sustainable construction. However, the study also highlights key barriers to digital adoption, including high implementation costs, skill gaps, and resistance to change. These challenges suggest that while digitalisation holds immense potential, strategic interventions are required to facilitate wider adoption across the industry.

Overall, the study emphasises that digitalisation and sustainability are interdependent, and integrating digital tools into QS practices is essential for driving innovation, improving efficiency, and supporting Malaysia's long-term green building agenda. Despite the challenges, proactive efforts by policymakers, industry leaders, and academia can accelerate digital transformation, ensuring a more sustainable and data-driven construction sector.

To ensure the effective integration of digitalisation and sustainability in the Malaysian construction industry, particularly within Quantity Surveying (QS) practices, several strategic recommendations are proposed. These recommendations focus on industry and government support, education and skills development, enhanced collaboration, and future research directions to address current challenges and promote widespread adoption of digital tools.

The successful adoption of digital technologies in construction requires strong industry and government support. Government agencies, such as the Construction Industry Development Board (CIDB) Malaysia, should introduce financial incentives and funding programs to assist small and medium-sized enterprises (SMEs) in adopting digital tools (CIDB Malaysia, 2020). Many SMEs face significant financial constraints in implementing Building Information Modelling (BIM), Artificial Intelligence (AI), blockchain, and the Internet of Things (IoT), making government support essential for fostering digital transformation.

In addition to financial assistance, mandatory digital adoption policies should be introduced, particularly in public construction projects. Government-led projects serve as a model for private sector initiatives and can help accelerate the integration of digitalisation and sustainability. Establishing digitalisation requirements in procurement processes, contract administration, and project management can ensure that the entire industry moves towards a more technologically advanced and sustainable future.

A major barrier to digital transformation in the QS profession is the lack of digital literacy and technical expertise among practitioners. To address this, higher education institutions should integrate digital skills training into QS programs, equipping future professionals with the ability to use BIM, AI, blockchain, and other emerging technologies effectively (GBI Malaysia, 2019). Digital literacy should become an essential component of Quantity Surveying curricula, ensuring that graduates enter the workforce with strong competencies in digital tools for cost management and sustainability analysis.

Additionally, Continuous Professional Development (CPD) programs offered by professional bodies such as the Royal Institution of Surveyors Malaysia (RISM) and the Board of Quantity Surveyors Malaysia (BQSM) should be expanded to include specialised training in digital methodologies. These programs can help practising QS professionals stay updated on industry advancements and develop the necessary skills to leverage digital tools for enhanced efficiency and sustainability.

The successful integration of digitalisation and sustainability requires strong collaboration between academia, industry, and government bodies. Strengthening industry-academia partnerships can facilitate research on digital sustainability in QS practices, leading to the development of customised digital solutions for the construction sector. Collaborative efforts can also promote knowledge sharing, best practices, and innovation, enabling the industry to transition towards a more data-driven and eco-friendly approach.

Furthermore, awareness campaigns should be conducted to highlight the benefits of digitalisation in sustainable construction. Many construction professionals, particularly those from traditional backgrounds, remain hesitant to adopt digital solutions due to misconceptions about cost and complexity. By organising seminars, workshops, and public engagement initiatives, stakeholders can be educated on how digital tools improve cost efficiency, reduce waste, and enhance sustainability (Ismail et al., 2022). Increasing awareness can reduce resistance to change and encourage wider industry adoption of digital technologies.

To further advance digitalisation in sustainable QS practices, additional research is necessary. One crucial area of exploration is the long-term cost-benefit analysis of digital tools in sustainable construction. While digital adoption requires significant initial investment, its long-term impact on cost savings, efficiency, and environmental sustainability remains a key area for further investigation.

Additionally, case studies of successful digital integration in Malaysian construction projects can provide practical models for industry-wide adoption. Examining real-world applications of BIM, AI, and blockchain in cost management, procurement, and sustainability assessment can offer valuable insights into best practices and potential challenges.

Finally, research should also focus on the role of emerging technologies, such as 5G-enabled IoT and advanced AI models, in enhancing QS efficiency and sustainability. The rapid evolution of smart construction technologies presents new opportunities for real-time data analytics, predictive maintenance, and automated decision-making, which could further revolutionise the construction industry's approach to sustainability.

By implementing these recommendations, the Malaysian construction industry can overcome existing challenges and fully leverage digitalisation for sustainable development. Through strategic investments, enhanced education, and collaborative initiatives, the QS profession can play a pivotal role in driving digital transformation and ensuring a greener, more efficient built environment. Ultimately, the integration of digitalisation and sustainability will contribute to the nation's long-term goals of reducing carbon emissions, optimising resource efficiency, and fostering innovation in construction practices.

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INTEGRATED OF SAFETY PERFORMANCE VIA PROJECT MANAGERS' COMPETENCIES IN GREEN CONSTRUCTION: A REVIEW OF ASSESSMENT COMPONENTS AND CONCEPTUAL FRAMEWORK

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Abstract
The wide-ranging activities within the green construction sector encompass a variety of activities, from sourcing materials to their treatment, and utilizing them for construction, building execution and operation, and eventual demolition at the end of its lifespan. Throughout these processes, accidents, injuries, and even fatalities are common due to the intricate nature of certain tasks involved. These processes introduce new challenges in achieving optimal safety performance, which differs from conventional construction practices. The efforts to enhance safety standards in green construction often receive inadequate attention, possibly due to the new challenges faced by project managers in effectively implementing and enforcing safety protocols. This deficiency can lead to a neglect of safety standards. Thus, this paper attempts to develop project managers' competencies attributes in relation to safety performance in the green construction perspective. Accordingly, this study aims to propose a conceptual framework of project managers' competencies toward safety performance in green construction. Specifically, the objective is to identify the key components of safety performance and the relevant attributes of project managers' competencies. To support this, a systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, ensuring a transparent, replicable, and comprehensive approach to identifying, screening, and selecting relevant safety performance components for this study. Next, a review of the existing model and theory of competencies also conducted to identify the competency attributes. Through a comprehensive literature review conducted in this study, it was found that safety performance in green construction consists of five (5) interrelated components: 1) safety leading: participation; 2) safety leading: compliance; 3) safety leading: employer's commitment; 4) safety leading: effectiveness of control measures at the workplace; 5) safety lagging: number of accidents. Meanwhile, the project managers' competencies were comprised into three interrelationship attributes namely skills, knowledge, and attitudes.

Keywords: *Safety Performance; Green Construction; Project Manager; Competent*

INTRODUCTION

The construction industry is a major driver of economic growth that provides jobs and generates income for individuals and businesses. It represents approximately $10 trillion of the global Gross Domestic Product (GDP) (Nnaji & Karakhan, 2020). Essentially, the construction industry covers a broad spectrum of activities that involve the extraction and acquisition of raw materials, the manufacturing and processing of building materials, the design, planning, and implementation of construction projects for buildings and various structures, along with their ongoing maintenance and eventual demolition (Darko et al., 2019; Li et al., 2022). However, over the past decade, the construction sector has faced consistent criticism due to its substantial environmental impact, particularly regarding the consumption of resources and the emission of greenhouse gases. Therefore, there is an urgent need to address the environmental impacts of the construction industry. As the world population continues to grow and urbanize, the demand for new buildings and infrastructure is also increasing, leading to an even greater impact on the environment (Xie et al., 2022).

Construction firms are being encouraged to shift towards ecological modernization by adopting environmental management practices and technologies that can reduce their impact on the environment while also maintaining a level of economic development. This can include implementing recycling programs, using sustainable building materials, incorporating energy-efficient design, and pursuing green building certifications (Xie et al., 2022). Additionally, many countries have implemented regulations and standards that aim to reduce the environmental impact of the construction industry, such as LEED (Leadership in Energy and Environmental Design) certifications (Kalyana Chakravarthy et al., 2022). According to previous research conducted by Onubi et al. (2020a), it was suggested that prioritizing green construction site practices is crucial when aiming to mitigate the adverse effects of building activities on the natural environment. The green construction concept aims to develop buildings that utilize as few natural resources as possible during construction and operation. According to Hwang and Ng (2013), green construction projects in the construction industry may face greater challenges in terms of safety performance compared to conventional construction projects. These challenges are not clearly defined and pose significant concerns that require immediate attention. In addition, new hazards may arise that are not present in conventional construction projects. Additionally, Zhang & Mohandas (2020) emphasize the importance of addressing these safety concerns to ensure the successful implementation of green construction. It is crucial to prioritize safety performance in green construction due to the emergence of new hazards and considerations related to materials, technologies, site practices, and hazardous materials. By prioritizing safety, not only can environmental sustainability be promoted, but the well-being of workers and future occupants can also be protected.

SAFETY PERFORMANCE VIA PROJECT MANAGER'S COMPETENCIES IN GREEN CONSTRUCTION

Globally, the construction industry has earned a reputation as one of the most hazardous sectors, with safety in green construction often treated as a mere academic discussion due to the distinctive challenges it presents compared to conventional construction (Abdelkhalik & Azmy, 2022; Hwang et al., 2018; Zaini et al., 2022). Developed countries like Singapore have particularly focused on mitigating safety risks specific to green projects, noting a higher accident rate compared to traditional builds (Hwang et al., 2018; Li et al., 2022; Supriyatna et al., 2020). Considering the serious state of construction safety in Singapore and the ongoing construction of numerous green building projects in the country, it can be deduced that the safety conditions in the green building construction industry of Singapore are likely to be challenging or worrisome. This underscores the need to examine factors influencing safety performance in green construction. It supported by Dewlaney et al. (2012) who has discovered that contractors pursuing LEED certifications face increased safety risks, with workers exposed to hazards like working at heights, electrical currents, unstable soils, and heavy equipment (Li et al., 2022; Supriyatna et al., 2020). Additionally, Zhang and Mohandes (2020) and Mohandes and Zhang (2021) highlighted that common practices associated with green construction, such as the installation of solar panels, thermoplastic polyolefin, and noise isolation panels, introduce new safety risks in construction projects (Onubi et al., 2021). Attributes inherent to green construction, like the use of sustainable materials, may also contribute to schedule delays, safety incidents, and reduced productivity (Li et al., 2019). It is perceived that evaluating the construction workforce engaged in green construction is essential to ensure that construction activities adhere to occupational health and safety (OHS) regulations (Durdyev et al., 2022).

According to Wang et al. (2022), key personnel in construction projects, such as project managers, chief supervision engineers, and safety officers, have the responsibility for upholding safety standards on construction sites. A project manager is tasked with delivering the project to meet the client's specified performance criteria. Therefore, the lack of familiarity with green technology among project managers may negatively impact safety outcomes (Hwang & Ng, 2013). Recent accidents, injuries, and fatalities on construction sites have highlighted the poor safety performance associated with green construction practices (Durdyev et al., 2022; Hwang, 2018; Onubi et al., 2020; Zhang & Mohandes, 2020). Despite technological advancements improving efficiency and productivity, they have also introduced new hazards on an unprecedented scale compared to traditional methods. Safe implementation of green construction practices requires a highly competent workforce proficient in hazard and risk management.

Previous studies have indicated that, although research on safety performance in green construction is not as extensive as that in traditional construction safety, it is a field that is continually developing. As sustainable construction practices become more prevalent, it will be essential to conduct further research to ensure that safety considerations evolve alongside advancements in green building technologies and methods. Therefore, it is critical to ensure that the construction workforce possesses the necessary skills and qualifications for green construction projects. Conducting a thorough evaluation of the competency of the construction workforce in green construction could be a valuable area for future research. The findings from such evaluations would offer insights into the strengths and areas for improvement in the current workforce's competency, assisting in the identification of strategies to promote safe and effective construction practices within the framework of sustainability.

Safety Performance

Safety performance serves as a critical measure of an organisation's effectiveness in safeguarding the well-being of individuals engaged in various aspects of construction, operation, and maintenance activities related to structures. It encompasses a broad spectrum of measures aimed at ensuring the safety and welfare of workers and other stakeholders involved in these processes. This includes the adoption of secure work practices, the use of safe equipment and materials, and the implementation of structural designs that prioritise the safety of both workers and the public. Moreover, safety performance entails compliance with relevant safety regulations and industry standards, alongside the provision of comprehensive training and education to workers on safe practices. By addressing these aspects, organizations can uphold high standards of safety across their operations, thereby minimizing risks and promoting a culture of safety within the construction industry (Syed-Yahya et al., 2022). Safety performance components play a crucial role for organizations in evaluating the effectiveness of their initiatives and risk management measures aimed at preventing workplace fatalities and injuries. By tracking these components, organizations gain valuable insights into the efficacy of their safety measures, enabling them to identify strengths and areas for improvement. This information empowers organizations to take proactive steps, such as implementing corrective actions and enhancing safety protocols, to foster a safer working environment. Ultimately, safety performance components serve as a tool for organizations to prioritize safety, mitigate risks, and continuously improve their safety practices to protect the well-being of their workforce (Shaikh et al., 2020). A high level of safety performance indicates the efficiency and organization of the worksite, underscoring the importance of safety management activities. Conversely, safety performance can also refer to the actions or behaviours exhibited by individuals in various job roles, with the aim of safeguarding the well-being of workers, clients, the general public, and the environment. It encompasses proactive measures taken to ensure the well-being of all stakeholders involved. Both definitions highlight the critical role of safety in fostering a secure and healthy working environment (Mohamed, 2002; Nadhim et al., 2018).

Attributes of Project Managers' Competencies in Green Construction

Table 1. The Competency Attributes Used in Different Research Field

					Core Personality Characteristics									
No	**Title**	**Author (Year)**	**Knowledge**	**Skills**	Attitudes	Awareness	Self-concepts	Traits	Motivations	Ability	Image	Behaviour	**Research Field**
1.	Sustainable Safety Management: A Safety Competencies Systematic Literature Review	(Rahman et al., 2022)	√	√								√	Construction Industry
2.	The role of Competency in Safety Performance	(Salleh, 2017)	√	√	√								Petrochemical Industry
3.	The effect of safety risk management and airport personnel competency on aviation safety performance	(Majid et al., 2022)	√	√	√								Aviation Industry
4.	Certified Construction Project Manager (CCPM)	(CIDB, 2019)	√	√	√								Construction Industry
5.	Project Management Competence: Definitions, Models, Standards and Practical Implications	(Horváth, 2019)	√	√	√								Project Management
6.	Acquiring competences for the didactic profession	(Kelemen, 2012)	√		√					√			Education
7.	Profiling the competent project manager	(Crawford, 2000)	√	√	√	√	√	√	√	√	√	√	Project Management
8.	Competence at work: models for superior performance	(Spencer & Spencer, 1993)	√	√				√	√	√	√	√	Human Research Management

Competencies, as defined by Jabar et al. (2013) and Kelemen (2012), encompass three interrelated attributes: Knowledge, Skills, and Attitudes. However, it's important to acknowledge that the specific elements comprising competencies can vary depending on the theoretical framework or model utilized. Some studies, such as those by Rahman et al. (2022); Ahmad Latiffi & Zulkiffli (2020) and Moradi et al. (2020) have highlighted only two elements of competencies, namely Skills and Knowledge. Moreover, previous research consistently underscores the importance of both Skills and Knowledge as crucial attributes for ensuring effective performance. However, CIDB (2019) has defined competency as the combination of Knowledge, Skills, and Attitude (KSA). In the current study, the attributes of competency were developed based on Crawford's integrated model of competence. Refer to Table 1, these attributes have been empirically supported as fundamental components of competence by researchers such as Majid et al. (2022); Salleh (2017); Crawford (2005); Horváth (2019); Jabar et al. (2013); Kelemen (2012) and Spencer & Spencer (1993). These attributes are recognised to have a direct impact on assigned tasks and performance. Thus, this study adopted three interrelated competencies, namely knowledge, skills and attitudes, as key competencies for project managers in achieving safety performance in green construction.

METHODOLOGY

The purpose of this current review is to overcome the limitations of previous studies by investigating trends in research concerning safety performance in green construction. To accomplish this goal, the researchers adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. This approach entails formulating a specific research question, implementing systematic search strategies to gather relevant literature, evaluating the quality of the studies, and analysing the collected data (Khudzari et al., 2024). By adhering to PRISMA guidelines, the review aims to provide a comprehensive and structured analysis of the existing body of literature on safety performance in green construction (Ali et al., 2022; Moher et al., 2019; Page et al., 2021). The study was conducted between January 2023 and July 2023. The review focuses on three key aspects: the green construction (population), indicators (interest), and safety performance (context) (Stern et al., 2014) and aims to answer the following question: what are the components used in safety performance among practitioners in green construction?

Systematic Searching Strategies

The systematic searching methods procedure involves four primary stages: retrieval, screening, eligibility, and inclusion, as depicted in Figure 1. These stages adhere to the PRISMA guidelines and are essential for ensuring a rigorous and structured approach to gathering and selecting relevant literature for the review (Moher et al., 2019).

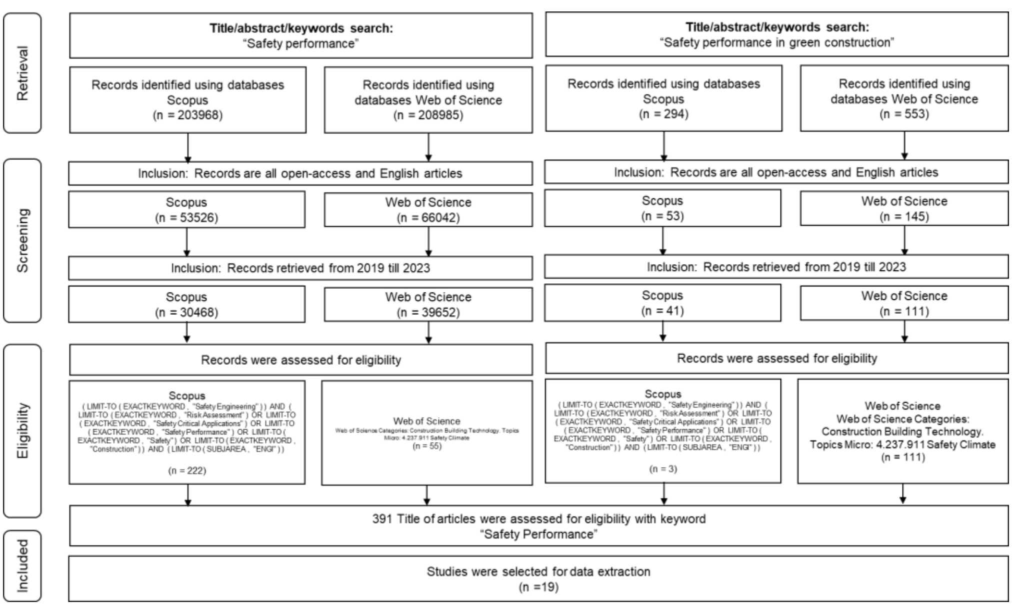

Figure 1. The Four (4) Primary Stages in The Systematic Searching Methods Procedure

Retrieval

The study utilized Scopus and Web of Science as primary databases for accessing scholarly articles due to their recognized reputation as reputable repositories of scientific publications. These platforms provide advanced search functionalities and access to a diverse array of scholarly resources. To retrieve relevant articles, the search focused on two primary domains: (1) "safety performance" and (2) "safety performance in green construction." The search string was carefully formulated to incorporate these terms within the fields of title, abstract, and keywords, ensuring a comprehensive retrieval of relevant literature.

Screening

During the screening process, all 70,272 selected articles underwent evaluation based on predetermined criteria for article selection. This assessment was facilitated by utilizing the database's sorting function, which enabled an automated screening process. Additionally, duplicate articles were identified and removed from the selected pool to ensure the integrity of the dataset. In total, 391 articles met the criteria for inclusion, while 69,881 articles were excluded based on the criteria outlined in Table 2. This rigorous screening process ensured that only relevant and high-quality articles were included in the study, aligning with its objectives.

Table 2. Inclusion Criteria's

Items	Criteria
Type of publication	All Open-access articles
Language	English
Retrieval Articles	2019 until 2023

Eligibility

During the eligibility process, the retrieved articles that remained after the screening stage were individually reviewed to verify their alignment with the research criteria (Ali et al., 2022). This review involved scanning through the papers and assessing their titles and abstracts. Articles that did not meet the specified criteria were eliminated from consideration. The elimination process focused on identifying articles that did not address safety performance components relevant to the construction industry. Additionally, components that were not directly pertinent to the field of safety were excluded. As a result of this thorough review, 391 articles were accessed, 372 articles were deemed ineligible and removed from further consideration, leaving 19 articles that met the criteria for inclusion in the study. This meticulous process ensured that only articles directly relevant to the research objectives were retained for analysis.

Data Abstraction and Analysis

In this research study, a qualitative strategy was adopted to synthesize and analyse integrative data. The researcher thoroughly reviewed the complete texts of all 19 articles, with particular attention given to the abstracts, findings, and discussion sections. Data abstraction involved selecting relevant information from the evaluated study that could address the research questions and subsequently organizing and inputting this data into a table. In the initial phase of thematic analysis, the aim is to identify components by examining the abstract data across all the reviewed articles, searching for patterns and similarities. By comparing the components for similarity, the comparable and abstracted data were consolidated into three main components. The three main components consist of safety participation as a leading component, safety compliance as leading component, and safety outcomes acting as a lagging component.

Conceptual Framework Development

The conceptual framework development process was structured around two main categories: independent variables and dependent variables. The independent variable, project managers' competencies, was drawn from Crawford's integrated model of competence, which emphasized three essential attributes: 1) Skills, 2) Knowledge, and 3) Attitudes. In contrast, the components of the dependent variable, safety performance components, were established based on relevant literature. This involved a thorough review of existing research to identify and define key components of safety performance in the context of green construction.

ANALYSIS OF FINDINGS

Safety Performance Components in Green Construction

Safety performance components serve as measurements used to evaluate safety in current situations or to anticipate future trends. Previous studies have noted that green construction practices may bring about distinct safety challenges and risks that require attention. These challenges arise from the diverse and complex risks associated with green activities. Several research scholars have highlighted that safety performance components are often described using varying terminologies. This discrepancy can result in confusion and inconsistency in how safety performance is assessed and evaluated. As a result, it's crucial for researchers and practitioners in the construction industry to strive for clarity and uniformity in defining and utilizing safety performance components to effectively address safety concerns in green construction projects. Usukhbayar and Choi (2020) and Makki and Alidrisi (2022) reviewed safety components in the construction industry, emphasizing safety leading as one of the components of safety performance. However, when it comes to measuring safety performance in green construction projects, the specific components and measurement methods may differ due to the unique challenges and considerations associated with green construction practices. Therefore, while safety leading may still be relevant as a safety performance component in green construction, additional or modified components tailored to the specific characteristics of green construction projects may also be necessary to comprehensively assess safety performance in this context. Onubi et al. (2022) highlighted safety lagging and safety leading as safety performance components. Lagging components in safety performance are metrics that measure the time lost and costs incurred due to injuries. They depend on the outcomes of safety performance and the number of failures recorded in implemented safety plans. Lagging components are reactive, assessing past incidents and injuries. Examples of lagging components include injury rates, lost workdays, and workers' compensation claims. These components reflect safety performance outcomes and provide insights into the effectiveness of safety programs after incidents have occurred.

Al-kasasbeh et al. (2021) highlighted several safety performance criteria that contribute to both the leading and lagging categories, based on the Occupational Safety and Health Administration (OSHA) definition. OSHA emphasizes the importance of using leading components to assess safety performance and prevent workplace accidents. Leading components are proactive metrics that help identify potential hazards and evaluate the effectiveness of safety programs before incidents occur. These components are future-oriented and include factors such as rates of training completion, reporting of near-miss incidents, level of employee engagement, and assessments of safety culture. By focusing on leading components, organizations can take proactive measures to mitigate risks and promote a safer work environment. Additionally, Yiu et al. (2019) provided a clear categorization of the key characteristics associated with projects demonstrating outstanding safety performance. One of these characteristics closely related to safety performance is high participation in safety activities and supportive safety compliance. Safety participation entails voluntary actions taken by individuals that may not directly impact their own safety but contribute to the overall safety of the organization. On the other hand, safety compliance refers to fundamental behaviours exhibited by employees to safeguard workplace safety, such as task performance and attentiveness to the production process. These characteristics highlight the importance of both proactive engagement and adherence to safety protocols in achieving superior safety performance outcomes (Abas et al., 2020). As a result, leading components can be summarized into two dimensions: safety compliance and safety participation. Through a comprehensive literature review, the components of safety performance for construction have been developed. The three interrelated components of safety performance components consist of two leading components - safety participation and safety compliance - and one lagging component - the number of accidents. This table reflects the proactive measures taken to enhance safety culture and compliance, alongside the retrospective assessment of safety outcomes through accident data.

Table 3. The Three Interrelated Components of Safety Performance Components

Item	Safety Performance Components	Description	Authors
1.	Slead: Participation	Refers to the level of employee engagement and involvement in the safety process	(Abas et al., 2020; Al-kasasbeh et al., 2021; DOSH, 2024; Makki & Alidrisi, 2022; Onubi et al., 2022; Usukhbayar & Choi, 2020; Yiu et al., 2019)
2.	Slead: Compliance	Measures the degree to which safety regulations and procedures are being followed.	(Abas et al., 2020; Al-kasasbeh et al., 2021; DOSH, 2024; Onubi et al., 2022; Yiu et al., 2019)
3.	Slead: Employer's commitment	Refers to the employer's dedication to ensuring a safe work environment.	(Bush et al., 2019; DOSH, 2024; Zin & Ismail, 2012)
4.	Slead: Effectiveness of control measures at the workplace	Focuses on the efficiency of the safety measures implemented in the workplace.	(DOSH, 2024; He, 2022; Zhang & Mohandes, 2020)
5.	Slag: No. of Accidents	The *outcomes after the incident*: The time lost, injury rates, lost workdays, workers' compensation claims.	(Abas et al., 2020; Al-kasasbeh et al., 2021; Onubi et al., 2022; Yiu et al., 2019)

However, according to the Malaysian Department of Safety and Health (DOSH), safety performance components should be aligned with two additional components: employer's commitment and the effectiveness of control measures at the workplace. Employer's commitment emphasizes the importance of the employer's dedication to ensuring a safe work environment. This commitment may be demonstrated through various actions, including providing resources for safety programs, fostering a safety culture, actively supporting safety initiatives, and adhering to safe behaviour practices as stipulated in OSHA 1994 Section 17 (Duties of employers and self-employed to their employees). This component underscores the critical role that employer commitment plays in promoting and maintaining a safe workplace for employees (Bush et al., 2019; Zin & Ismail, 2012). The effectiveness of control measures at the workplace centers on the efficiency of safety measures implemented in the workplace. It emphasizes the importance of implementing scientific and reasonable measures for construction quality and safety control. By doing so, risks can be mitigated, project performance can be enhanced, and the well-being of all individuals involved can be ensured (He, 2022; Zhang & Mohandes, 2020). Thus, Table 3 presents five (5) safety performance components, formulated based on a comprehensive review of existing literature and the Department of Occupational Safety and Health (DOSH) safety guidelines.

DISCUSSIONS OF FINDINGS/ CONCEPTUAL FRAMEWORK

In this paper, a conceptual framework as shown in figure 2 is constructed to establish a causal relationship between the independent variable (Project Managers' Competencies) and the dependent variable (Safety Performance). The literature review affirms that competencies, comprising skills, knowledge, and attitudes, significantly influence performance. Furthermore, this study underscores safety performance and, as a result, formulates specific components to evaluate and assess it. The first component, participation in safety activities, relates to the steps and actions undertaken before task commencement aimed at reducing or eliminating hazards and risks. The second component, the compliance component entails adhering to safety requirements throughout task execution to guarantee a safe working environment. This encompasses adherence to relevant health and safety laws and regulations, which is crucial for managing and mitigating hazards and risks to safeguard workers from injury or harm. It involves following correct procedures for equipment usage, utilizing personal protective equipment, and adhering to safety protocols for handling and disposing of hazardous materials. The third component, employer's commitment, emphasizes employers' dedication to ensuring a safe work environment. This dedication may be demonstrated by providing sufficient resources for safety programs, cultivating a safety culture, actively backing safety initiatives, and ensuring adherence to relevant regulations and standards. Employers' commitment to safety is pivotal in establishing a workplace where the welfare of workers is paramount and safety measures are efficiently executed. The fourth component, the effectiveness of control measures at the workplace, concentrates on evaluating the efficacy of safety measures implemented within the work environment. This entails assessing how well these measures mitigate risks and hazards, improve project performance, and ensure the well-being of all individuals involved. The fifth component, the lagging component, entails analysing and evaluating safety performance following incidents. It also includes employing problem-solving skills to identify and implement corrective actions aimed at preventing similar incidents from recurring in the future. Therefore, the conceptual framework depicted in Figure 3 illustrates the interconnectedness and interdependence of various competency attributes that play a role in safety performance within the green construction industry.

CONCLUSION

In summary, safety performance in green construction presents a crucial area necessitating attention and research given its evolving nature. As the industry increasingly adopts sustainable practices and technologies, it becomes imperative to thoroughly understand and address the potential safety implications arising from these advancements. Further research endeavors can aid in enhancing our comprehension of the specific hazards and risks inherent in green construction, facilitating the formulation of effective strategies to manage and mitigate these risks. Additionally, with the growing demand for green construction, prioritizing the safety of workers and the public is paramount, ensuring that sustainability objectives are pursued without jeopardizing their well-being.

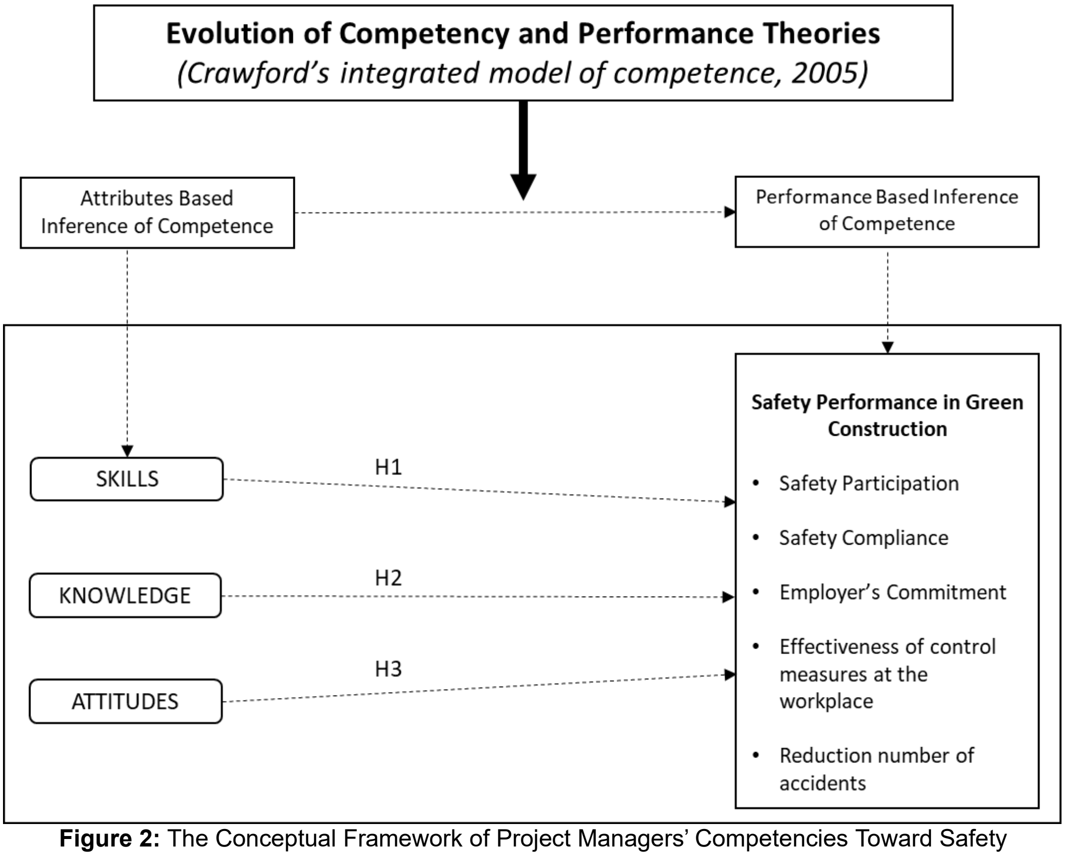

Figure 2: The Conceptual Framework of Project Managers' Competencies Toward Safety Performance based on The Crawford Integrated Model of Competence

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ANALYSING SUCCESS FACTORS OF FACILITIES MANAGEMENT IMPLEMENTATION INTERDEPENDENCIES IN HEALTHCARE USING INTERPRETIVE STRUCTURAL MODELLING

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Abstract
The implementation of Facilities Management (FM) in the healthcare sector plays a pivotal role in ensuring operational efficiency, safety, and service quality. However, limited studies have systematically examined the underlying factors that determine successful FM implementation. This research aims to identify and analyse the critical success factors (CSFs) that influence FM implementation in healthcare organisations. Using the Interpretive Structural Modelling (ISM) and MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) techniques, fifteen CSFs were evaluated through expert input from thirteen experienced healthcare FM practitioners. Their driving–dependence relationships were analysed to establish a structured ISM-based hierarchy that clarifies how leadership, capability, and organisational collaboration drive effective FM implementation. The analysis revealed that Knowledge and Competencies, Top Management Commitment and Support, Teamwork Effectiveness, and Contract Management are the strongest driver factors forming the foundation for healthcare FM success. Strategic Planning and Work Environment serve as linkage factors connecting these drivers to dependent outcomes such as Risk Management, Performance Measurement, and Accreditation. The study contributes to both theory and practice by providing a validated ISM-based model that explains interdependencies among the CSFs and guides decision-makers in prioritising strategic enablers for FM improvement. It recommends strengthening leadership, competency development, and policy alignment as essential strategies for sustainable FM transformation in healthcare organisations.

Keywords: *Healthcare; Hospital; Facilities Management; Critical Success Factors; Interpretive Structural Modelling*

INTRODUCTION

The role of Facilities Management (FM) in the healthcare sector has evolved from a support function to a strategic discipline that ensures operational efficiency, safety, and service quality. Hospitals and healthcare facilities are among the most complex and high-risk environments to manage, requiring the integration of infrastructure, technology, and human resources within a framework of strict regulatory and safety standards (Olanrewaju et al., 2018; Salah et al., 2018). Effective FM is therefore essential not only for maintaining physical assets but also for enabling continuous, high-quality healthcare delivery (Amos, 2022; Chanter & Swallow, 2008).

Healthcare FM involves two interconnected domains: hard FM**,** which focuses on the maintenance and technical performance of buildings and systems, and soft FM, which encompasses services such as cleaning, catering, and security (Liyanage, 2008; Pitt et al., 2016). The integration of these domains is critical to ensure safe, compliant, and patient-centred environments. However, FM implementation in healthcare remains challenging due to rising operational costs, complex asset lifecycles, and diverse stakeholder expectations

(Talib, 2013; Pheng et al., 2016). These challenges are further amplified by rapid digital transformation, post-pandemic operational pressures, and sustainability demands (Abd Rahman et al., 2023; Salem & Elwakil, 2023).

Previous studies have explored FM performance indicators and maintenance efficiency (Shohet et al., 2004; Omar et al., 2016; Lai et al., 2022), yet few have examined how critical success factors (CSFs) interact to determine FM implementation success in healthcare. The absence of a structured, empirical framework limits the ability of healthcare organisations to prioritise and manage these factors systematically. Hence, there is a pressing need to develop a model that captures the interdependencies among CSFs to support decision-making and improve implementation effectiveness.

This study addresses that gap by identifying and analysing the CSFs that influence FM implementation in the healthcare sector through Interpretive Structural Modelling (ISM) and MICMAC analysis. These methods enable the visualisation of hierarchical and causal relationships among the factors, providing a deeper understanding of how they interact within a healthcare FM system.

Accordingly, the objective of this research is to identify and structure the CSFs that determine FM implementation success in healthcare organisations using the ISM–MICMAC approach. The study is guided by the following aims:

1. To identify the key success factors influencing FM implementation in healthcare organisations;
2. To examine the interdependencies among these factors through ISM and MICMAC techniques; and
3. To develop a validated, hierarchical model that prioritises these factors based on their relative influence and dependence.

The findings reveal that leadership commitment, professional competencies, and teamwork are the strongest driver factors forming the foundation for successful healthcare FM implementation. The model provides both theoretical insight and practical guidance for policymakers and practitioners to strengthen FM strategies and achieve sustainable performance outcomes.

LITERATURE REVIEW

The successful implementation of Facilities Management (FM) in healthcare requires an integrated understanding of organisational, technical, and strategic factors that collectively influence performance. A critical examination of prior literature highlights that while FM is recognised as a key enabler of operational excellence, the underlying interrelationships among its success factors remain poorly understood. Recent Malaysian evidence supports this perspective, with Hashim, Kamarazaly and Lim (2024) demonstrating that early FM integration during the design stage enhances building operability and significantly reduces downstream maintenance costs.

Facilities Management in The Healthcare Context

Healthcare facilities are among the most complex and demanding environments to operate due to their continuous service delivery requirements, diverse infrastructure, and high regulatory standards (Olanrewaju et al., 2018; Salah et al., 2018). The FM function within healthcare encompasses a wide range of services, including maintenance, safety management, and patient support, each directly affecting service quality and organisational efficiency (Amos, 2022).

FM in healthcare can be categorised into two dimensions: hard FM**,** which deals with building systems, infrastructure, and maintenance, and soft FM, which focuses on service delivery, cleanliness, and user comfort (Liyanage, 2008; Pitt et al., 2016). Effective FM requires both domains to operate synergistically under constrained budgets, demanding compliance, and technological transformation (Talib, 2013; Abd Rahman et al., 2023). Recent studies emphasise the growing importance of digitalisation, sustainability, and data-driven decision- making in healthcare FM (Salem & Elwakil, 2023; Adegoriola et al., 2023).

The Role of Critical Success Factors (CSFs) in Facilities Management

The concept of Critical Success Factors (CSFs), introduced by Daniel (1961) and expanded by Rockart (1979) has become a cornerstone for identifying essential organisational priorities that drive project and system success. In FM, CSFs refer to the limited number of managerial and operational conditions that must be achieved to ensure effective facility operation and long-term sustainability (Finney & Corbett, 2007; Abdullah, 2015; Hopland & Kvamsdal, 2018).

Previous research in FM has primarily focused on discrete elements such as maintenance management (Omar et al., 2016), performance indicators (Shohet et al., 2004; Lai et al., 2022), and service quality (Amos et al., 2020). However, such studies tend to treat success factors independently, without investigating their interdependencies or the hierarchical influence they exert on one another. Recent scholarship (Ali et al., 2023; Myeda et al., 2023) has called for integrated models that capture these relationships to inform evidence-based FM decision-making.

Review of Prior Research in Healthcare FM

Shohet et al. (2004) introduced a performance evaluation model for healthcare facilities using eleven key indicators, while Omar et al. (2016) examined maintenance-related CSFs in Malaysian hospitals. Lai et al. (2022) expanded on this by developing a six-aspect performance framework encompassing quality, financial management, learning and growth, internal business processes, asset maintenance, and energy efficiency. Olanrewaju et al. (2019) identified thirteen factors influencing healthcare FM performance, including managerial competency, resource allocation, and user satisfaction.

More recent studies (Adegoriola et al., 2023; Salem & Elwakil, 2023) have employed systems-based or modelling approaches to understand FM interdependencies. Yet, the healthcare context remains underexplored, especially regarding how leadership, knowledge, and organisational enablers interact to drive FM implementation outcomes. These findings indicate a persistent fragmentation in FM literature where models address operational indicators but not the causal relationships among CSFs.

Success Factors Identified from Literature

Drawing upon extensive literature and prior empirical work (Pakrudin et al., 2017), fifteen success factors were identified as being potentially significant for healthcare FM implementation. These factors span leadership, human capital, process management, technology, and quality domains. Table 1 summarises these success factors, their conceptual definitions, and supporting literature.

Table 1. Success Factors, Concepts, and Importance in Healthcare

Item	Success Factors	Concept and Importance	Citation in Literature
1	Top management commitment and support	Top management support is crucial in FM healthcare. Up to 80% of organizations may fail without committed leadership at the top level. Clear, consistent, and realistic communication of goals and targets linked to the hospital strategy is also essential.	Alexander, 1994; Jaehn, 2000; Goyal et al., 2007; Jensen, 2011; Agarwal et al., 2016; Atkin, 2021; Singh, 2021
2	Strategic planning	Strategic planning aligns FM with core business CSFs, supports sustainable development, and meets healthcare organizations' short and long-term needs. Typical initiatives address future environmental changes and are integrated into an organization-wide plan.	Letza, 1996; Thomas, 2011; Barrett, 2009; Vest et al., 2009; Chotipanich et al., 2011; Virtue et al., 2013; Atkin, 2021; Wiggins, 2022
3	Performance measurement	Measuring FM healthcare performance involves quantifying efficiency and effectiveness, assessing organizational performance, and ensuring transparency and accountability through data collection. It is vital for success and can be improved by adopting performance-based maintenance and benchmarking practices.	Neely et al., 1995; Kollberg et al., 2011; Yuen et al., 2012; Noe et al., 2006; Amaratunga et al., 2002; McDougall et al., 2000; Yousefli, et al., 2017; Shohet, et al., 2010; Lai, 2022
4	Customer focus	Customer focus is key in healthcare FM, with a focus on quality service and satisfaction. Hospitals should prioritize staff empowerment, housekeeping, customer-friendly design, and feedback to improve patient outcomes.	Amaratunga, 2000; Kincaid, 1994; Wan et al., 1999; Loosemore, 2001; Gonzalez, 2019; Daksith, 2020
5	Knowledge and competencies	In healthcare FM, knowledge and competencies are essential for successful healthcare management. This includes FM knowledge to provide proactive contributions, managerial skills, and knowledge of both management and facilities for integrated support.	Varcoe, 1993; Alexander; 1994, Nutt; 2000, Puddy,2001; Sapri et al., 2005; Pathirage, 2008; Wahid et al, 2009; Yasin, 2010, Jankelová et al., 2016; Adeyemi, 2019.
6	Information and communication technology (ICT)	ICT plays a crucial role in FM healthcare, helping observe energy usage and system breakdowns, manage helpdesk systems, and integrate services to support business objectives. ICT applications can improve quality, prevent errors, and prioritize patient care.	Owen et al., 1988; Scupola, 2012; Waring et al., 2002; Shohet, 2004; Nat Natarajan, 2006; Potes et al., 2013; Windlinger et al.,2014; Sulaiman, 2021; Atkin, 2021
7	Teamwork effectiveness	The effective collaboration of healthcare FM teams, prioritizing patient needs through clearly defined roles, ongoing improvement, and cooperation, aims to enhance patient care and safety while reducing workload.	Jaca, C., Viles, E., Tanco, M., Mateo, R. and Santos, J., 2013; Suwaibatul et al., 2012; Fraser et al., 2013; Chesluk, 2015, Manjula et. al., 2012; Waggie et al., 2021; Myeda et al., 2023

Item	Success Factors	Concept and Importance	Citation in Literature
8	Contract management	Healthcare FM contract management coordinate in-house and outsource services, use SLA's, and documentations for agreed standards and procedure, including service outcomes, cost reduction, and measurement.	Payne and Rees, 1999; Wan Yeung Kam-Shim, 1999; Roberts, 2001; Kadefors, 2008; Nazali Mohd Noor, M. and Pitt, M., 2009; Brochner et. al, 2019; Atkin, 2021
9	Strategic decision making	Strategic decision making in FM involves processing complex information for timely and quality service delivery, with clear role definition and sound professional judgement. It includes major decisions like capital investment, service line expansion and facility upgrades.	Shohet et al., 2004; Barret, 2000; Kamaruzzaman, 2010; Irizarry, 2014; Jaca, 2013; Okoroh, 2006; Fraser, 2014; Wiggins, 2020; Lai et. al, 2022
10	Resource and training	FM professionals need expertise in project management and technology. Training is required to keep up with changes in the field, improve operations, and prioritize public health, quality of care, and cost saving.	Mahadkar et al., 2012; Kell, 1991; Ramadevi et al., 2016; Fraser et al., 2013; Kell, 1991; Atkin 2021
11	Continuous improvement	Continuous enhancement involves continually improving processes and results through assessment and approaches like total quality management and strategic management. It is crucial for FM's success and contributes to the healthcare business.	Amaratunga et al., 2002; Gowen III et al., 2012; Buttigieg et al., 2016; Lai et. al, 2022; Amos, 2022
12	Equipment and facility upgrading	Effective equipment and facility management is vital in healthcare for optimized operations. Strategic planning, maintenance, and monitoring are important for managing facilities and equipment. Life cycle cost is crucial for maintenance and upgrading. Upgrading facilities and equipment improves competitiveness, satisfaction, and market share.	Loosemore et al., 2001; Shohet et. al, 2004; Kihiu et. al, 2012; Sulaiman et.al, 2020; Atkin 2021; Zamzam, 2021; Abd Rahman et. al, 2023, Salem et. al, 2023
13	Risk management	Risk management is vital in healthcare FM to identify, analyse, control, and finance risks. Physical and technology hazards must be mitigated for high performing building systems and patient safety. It is a critical success factors for best – value service delivery.	Okoroh et. al, 2002; Okoroh et. al 2006; Brinia et al., 2013; Delcea et al., 2016; Lai et.al 2022
14	Work environment	Work environment in FM healthcare encompass physical, social, and psychological factors. It affects safety, productivity, and well – being FM must ensure comfort, safety, and free of harassment and health hazards.	Gallagher, 1998; Duffy, 2000: Douglas, 1996; Amaratunga et al., 2002; Atkin 2021; Schultz, 2022
15	Accreditation	Accreditation improves healthcare quality and safety by recognizing organization meet predetermined standards. Its preferred method to promote better performance, recognize areas for improvement and monitor larger health organization.	Braithwaite et al., 2010; Greenfield et al., 2008, Shaw et al., 2010; Duckett, 1983, Saleh et al., 2013, Cleveland et al., 2011; Pitt et al., 2016; Pasinringi, 2021 Nazareth et al., 2023

Research Gap and Conceptual Linkage

The review of prior studies indicates that FM success in healthcare depends on multiple interrelated factors. However, existing research has generally examined these CSFs in isolation, offering limited understanding of how they influence each other hierarchically. The lack of a structured, empirically validated model prevents practitioners and policymakers from identifying which factors should be prioritised during FM implementation.

This study therefore addresses the following key gap:

"*There is insufficient empirical evidence explaining the structural interdependencies and causal relationships among CSFs in healthcare FM implementation.*"

To bridge this gap, this research employs the Interpretive Structural Modelling (ISM) and MICMAC techniques to establish a hierarchical model that systematically maps these interrelationships. This approach aligns directly with the study's objective to develop a structured understanding of how CSFs collectively determine FM implementation success in healthcare environments.

RESEARCH METHODOLOGY

This study adopts an Interpretive Structural Modelling (ISM) approach to examine the interrelationships among fifteen Critical Success Factors (CSFs) influencing Facilities Management (FM) implementation in the healthcare sector. The ISM technique was complemented with a MICMAC analysis to classify the CSFs according to their relative driving and dependence power. This methodological combination provides both structural depth (through ISM) and categorical insight (through MICMAC), allowing for a comprehensive understanding of how various CSFs interact to support successful FM implementation This emphasis on professional expertise and competency is consistent with the findings of Au-Yong, Ali and Ahmad (2017), who emphasised that the competence and commitment of facilities managers are pivotal to achieving maintenance performance and successful FM implementation in Malaysia.

Overview of The ISM Approach

The ISM technique is a well-established methodological framework for identifying and structuring complex relationships among elements within a system (Mandal & Deshmukh, 1994; Singh et al., 2007). In this study, the ISM method was selected for its ability to convert expert-based qualitative judgments into a hierarchical model that represents the contextual interdependencies among CSFs. The method allows FM experts to systematically determine which factors drive others and which are more dependent within the healthcare FM context.

Following the recommendations of Sage (1977) and prior FM-related ISM applications (Talib et al., 2011; Adegoriola et al., 2023), this research applied six sequential steps to develop the structural model:

1. Identify the element set (list of CSFs).
2. Define contextual relationships among the factors.
3. Develop the Structural Self-Interaction Matrix (SSIM).
4. Construct the Reachability Matrix.
5. Conduct Level Partitioning.
6. Build the ISM-based model and validate through MICMAC analysis.

The ISM technique was complemented with the MICMAC analysis to categorise the CSFs according to their relative driving and dependence power. This dual approach is particularly suitable for FM studies involving interdependent managerial and technical variables, as it converts expert knowledge into a structured model that reveals causal linkages.

Step 1: Development of The Structural Self-Interaction Matrix (SSIM)

Table 2. The Blank SSIM for The FM Implementation in The Healthcare Industry

	Success Factors		(i)														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
(i)	1	Teamwork Effectiveness															
	2	Contract Management															
	3	Knowledge and Competencies															
	4	Strategic Decision Making															
	5	Resource and Training															
	6	Top Management Commitment and Support															
	7	Equipment And Facility Upgrading															
	8	Strategic Planning															
	9	Information and Communication ICT															
	10	Risk Management															
	11	Customer Focus															
	12	Work Environment															
	13	Performance Measurement															
	14	Continuous Improvement															
	15	Accreditation															

Table 3. Experts' Profile

No.	Expert	Position	Certification	Years Working in Healthcare Industry
1	A	Facility Engineer	Degree in Electrical	10
2	B	Healthcare Engineer	Degree in Mechanical	6
3	C	Healthcare Engineer	Degree in Mechanical	13
4	D	Healthcare Engineer	Degree in Electrical and Electronic	10
5	E	Healthcare Engineer	Degree in Electrical	12
6	F	Facility Manager	Degree in Electrical	9
7	G	Facility Manager	Degree in Electrical	6
8	H	Healthcare Engineer	Degree in Electrical and Electronic	7
9	I	Senior General Manager	Degree in Civil	22
10	J	Facility Manager	Degree in Electrical and Electronic	15
11	K	Facility Manager	Certified Healthcare Facility Manager	10
12	L	Facility Manager	Degree in Mechanical	15
13	M	Facility Manager	Certified Healthcare Facility Manager	13

The first stage involved constructing a Structural Self-Interaction Matrix (SSIM) that captures the pairwise relationships among the fifteen identified critical success factors (CSFs). Thirteen subject-matter experts in healthcare FM participated in this evaluation process. The experts were selected based on a minimum of ten years of professional experience in healthcare FM, representing both public and private healthcare institutions, to ensure diverse and credible insights. Each expert was asked to determine the directional relationship between pairs of factors using four symbols (V, A, X, O) as described by Mandal et al. (1994):

- **V** – factor *i* leads to factor *j*
- **A** – factor *j* leads to factor *i*
- **X** – factors *i* and *j* influence each other
- **O** – factors *i* and *j* are unrelated

The general structure of the SSIM is illustrated in Table 2**,** and the expert profiles contributing to the analysis are summarised in Table 3.

The final, aggregated SSIM derived from expert consensus is presented in Table 4. Transitivity rules were applied to ensure logical consistency, where if *A* > *B* and *B* > *C*, then *A* > *C* (Miles et al., 1994).

Table 4. Final SSIM of CSFs for Successful Implementation of FM in Healthcare Industry

		Success Factors	**(i)**														
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
(i)	1	Teamwork Effectiveness	V	V	X	V	V	A	V	V	V	V	V	X	V	X	V
	2	Contract Management	A	V	A	A	A	V	V	X	V	V	V	V	V	V	X
	3	Knowledge and Competencies	X	V	V	V	X	V	V	V	V	V	V	V	V	V	V
	4	Strategic Decision Making	A	V	A	V	V	A	V	X	V	V	A	V	V	V	X
	5	Resource and Training	A	V	X	A	V	A	V	A	V	V	A	V	V	V	V
	6	Top Management Commitment and Support	V	A	A	V	V	V	V	V	V	V	V	V	V	V	V
	7	Equipment And Facility Upgrading	A	A	A	A	A	A	V	A	V	V	A	V	V	V	V
	8	Strategic Planning	A	X	A	X	V	A	V	V	V	V	A	A	V	V	X
	9	Information and Communication ICT	A	A	A	A	A	A	A	A	V	V	A	A	A	V	V
	10	Risk Management	A	A	A	A	A	A	A	A	A	V	A	A	V	V	V
	11	Customer Focus	A	A	A	V	V	A	V	V	V	V	V	V	V	V	A
	12	Work Environment	X	A	A	A	A	A	A	V	V	V	A	V	V	V	V
	13	Performance Measurement	A	A	A	A	A	A	A	A	V	A	A	A	V	A	V
	14	Continuous Improvement	X	A	A	A	A	A	A	A	A	A	A	A	V	V	V
	15	Accreditation	A	A	A	X	A	A	A	X	A	A	V	A	A	A	V

Step 2: Develop The Reachability Matrix

Table 5. Final Reachability Matrix of CSFs for Successful Implementation of FM in Healthcare Industry

		Success Factors	**(i)**															**Driving Power**
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
(i)	1	Teamwork Effectiveness	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	13
	2	Contract Management	0	1	0	0	0	1	0	1	1	1	1	1	1	1	1	10
	3	Knowledge and Competencies	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15
	4	Strategic Decision Making	0	1	0	1	0	0	1	1	1	1	0	1	1	0	1	9
	5	Resource and Training	0	1	1	0	1	0	1	0	1	1	0	1	1	1	1	10
	6	Top Management Commitment and Support	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	13
	7	Equipment And Facility Upgrading	0	0	0	0	0	0	1	0	1	0	0	1	1	1	1	6
	8	Strategic Planning	0	1	0	1	0	0	1	1	1	1	0	0	1	1	1	9
	9	Information and Communication ICT	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	4
	10	Risk Management	0	0	0	0	0	0	1	0	0	1	0	0	1	1	1	5
	11	Customer Focus	0	0	0	1	1	0	1	1	1	1	1	1	1	1	0	10
	12	Work Environment	1	0	0	0	0	0	0	1	1	1	0	1	1	1	1	8
	13	Performance Measurement	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	3
	14	Continuous Improvement	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	4
	15	Accreditation	0	1	0	1	0	0	0	1	0	0	1	0	0	0	1	5
		Dependence	5	7	3	7	4	3	9	9	12	11	6	9	13	12	14	

The SSIM was converted into a binary reachability matrix by replacing the symbols (V, A, X, O) with binary values (1 and 0) based on the following rules:

- If the SSIM entry is **V**, the (i, j) position is assigned 1, and (j, i) is assigned 0.
- If **A**, the (i, j) position is 0, and (j, i) is 1.
- If **X**, both (i, j) and (j, i) are 1.
- If **O**, both (i, j) and (j, i) are 0.

The resulting matrix captures the reachability (driving power) and dependence (influence received) for each Assuming each row yields the total driving power, while summing each column provides the total dependence value. The final reachability matrix for the fifteen CSFs is shown in Table 5.

Step 3: Level Partitioning

Once the reachability matrix was established, Level Partitioning was carried out to identify the hierarchical structure of the CSFs. For each factor, a reachability set (factors it can influence) and an antecedent set **(**factors that influence it) were defined. The intersection of these sets determined the position of the factor in the hierarchy.

Factors with identical reachability and intersection sets were assigned to the highest level in each iteration, signifying their dependence on other factors. These top-level elements were then removed, and the process was repeated iteratively until all factors were classified.

The six iterations and resulting hierarchical levels are presented in Tables 6 to 11. Each iteration refined the relationships and clarified which factors acted as drivers, linkages, or dependents within the system.

Table 6. Iteration 1

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,3,4,7,8,9,10,11,12,13,14,15	1,3,6,12,14	1,3,12,14	
2	2,6,7,8,9,10,11,12,13,14,15	1,2,3,4,5,8	2,8	
3	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	1,3,5	1,3,5	
4	2,4,7,8,9,10,12,13,15	1,3,4,6,8,11,15	4,8,15	
5	2,3,7,9,10,12,13,14,15	3	3	
6	1,4,6,7,8,9,10,11,12,13,14,15	2,3,6	6	
7	7,9,10,12,13,14,15	1,2,3,4,5,6,7,8,11	7	
8	2,4,7,8,9,10,13,14,15	1,2,3,4,6,8,11,12,15	2,4,8,15	
9	9,10,14,15	1,2,3,4,5,6,7,8,9,11,12,13	9	
10	10,13,14,15	1,2,3,4,5,6,7,8,9,10,11,12	10	
11	4,7,8,9,10,11,12,13,14	1,2,3,6,11,15	11	
12	1,8,9,10,12,13,14,15	1,2,3,4,5,6,7,11,12	1,12	
13	9,13,15	1,2,3,4,5,6,7,8,10,11,12,13,14	13	
14	1,13,14,15	1,2,3,5,6,7,8,9,10,11,12,14	1,14	
15	4,8,11,15	1,2,3,4,5,6,7,8,9,10,12,13,14,15	4,8,15	I

Table 6 (Iteration 1): SF15 (Accreditation) emerged as the top-level factor with the highest dependence, indicating that successful accreditation relies on the achievement of other enabling factors.

Table 7. Iteration 2

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,3,4,7,8,9,10,11,12,13,14	1,3,6,12,14	1,3,12,14	
2	2,6,7,8,9,10,11,12,13,14	1,2,3,4,5,8	2,8	
3	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,3,5	1,3,5	
4	2,4,7,8,9,10,12,13	1,3,4,6,8,11	4,8	
5	2,3,7,9,10,12,13,14	3	3	
6	1,4,6,7,8,9,10,11,12,13,14	2,3,6	6	
7	7,9,10,12,13,14	1,2,3,4,5,6,7,8,11	7	
8	2,4,7,8,9,10,13,14	1,2,3,4,6,8,11,12	2,4,8	
9	9,10,14	1,2,3,4,5,6,7,8,9,11,12,13	9	II
10	10,13,14	1,2,3,4,5,6,7,8,9,10,11,12	10	II
11	4,7,8,9,10,11,12,13,14	1,2,3,6,11	11	
12	1,8,9,10,12,13,14	1,2,3,4,5,6,7,11,12	1,12	
13	9,13	1,2,3,4,5,6,7,8,10,11,12,13,14	13	II
14	1,13,14	1,2,3,5,6,7,8,9,10,11,12,14	1,14	II

Table 7 (Iteration 2): SF9 (Information & Communication Technology), SF10 (Risk Management), SF13 (Performance Measurement), and SF14 (Continuous Improvement) occupy Level 2, reflecting moderate driving power and high dependence.

Table 8. Iteration 3

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,3,4,7,8,11,12	1,3,6,12	1,3,12	
2	2,6,7,8,11,12	1,2,3,4,5,8	2,8	
3	1,2,3,4,5,6,7,8,11,12	1,3,5	1,3,5	
4	2,4,7,8,12	1,3,4,6,8,11	4,8	
5	2,3,7,12	3	3	
6	1,4,6,7,8,11,12	2,3,6	6	
7	7,12	1,2,3,4,5,6,7,8,11	7	III
8	2,4,7,8	1,2,3,4,6,8,11,12	2,4,8	III
11	4,7,8,11,12	1,2,3,6,11	11	
12	1,8,12	1,2,3,4,5,6,7,11,12	1,12	III

Table 8 (Iteration 3): SF7 (Equipment & Facility Upgrading), SF8 (Strategic Planning), and SF12 (Work Environment) form Level 3 as essential linkages connecting drivers and dependent variables.

Table 9. Iteration 4

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,3,4,11	1,3,6	1,3	
2	2,6,11	1,2,3,4,5	2	
3	1,2,3,4,5,6,11	1,3,5	1,3,5	
4	2,4	1,3,4,6,11	4	IV
5	2,3	3	3	IV
6	1,4,6,11	2,3,6	6	
11	4,11	1,2,3,6,11	11	IV

Table 9 (Iteration 4): SF4 (Strategic Decision-Making), SF5 (Resources and Training), and SF11 (Customer Focus) were classified into Level 4, demonstrating a balance between influence and dependency.

Table 10. Iteration 5

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,3	1,3,6	1,3	V
2	2,6	1,2,3	2	V
3	1,2,3,6	1,3	1,3	
6	1,4,6	2,3,6	6	

Table 10 (Iteration 5): SF1 (Teamwork Effectiveness) and SF2 (Contract Management) were identified as Level 5 factors, functioning as key drivers in FM implementation.

Table 11. Iteration 6

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
3	1,2,3,6	1,3	1,3	VI
6	1,4,6	2,3,6	6	VI

Table 11 (Iteration 6): SF3 (Knowledge & Competencies) and SF6 (Top Management Commitment and Support) form Level 6, representing the strongest drivers at the foundation of the model.

Following six rounds of level partitioning, the hierarchical structure of the CSFs was established. This structure served as the basis for developing the final ISM-based model.

Step 4: Result of MICMAC Analysis

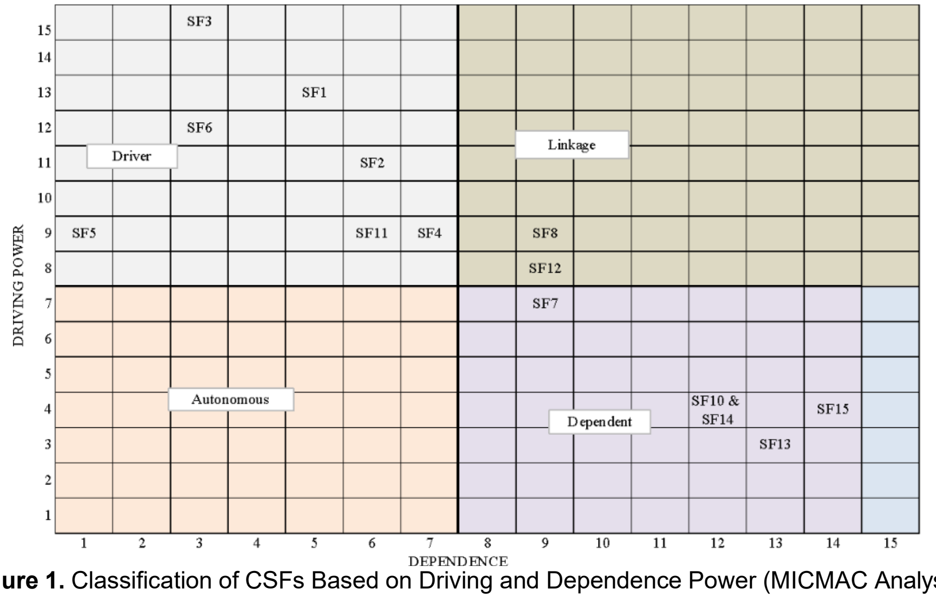

Figure 1. Classification of CSFs Based on Driving and Dependence Power (MICMAC Analysis)

The following section presents the results derived from the ISM and MICMAC analyses, highlighting the hierarchical structure and interdependencies among the 15 critical success factors. To validate and categorise the ISM results, a MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) analysis was conducted. MICMAC analysis classifies factors based on their driving power and dependence power, resulting in four quadrants:

1. Driver factors – high driving power, low dependence
2. Linkage factors – high driving and high dependence
3. Dependent factors – low driving power, high dependence
4. Autonomous factors – low driving and low dependence

The outcome of this analysis is illustrated in Figure 1, which shows how the critical success factors (CSFs) are classified according to their driving and dependence power in the healthcare FM system.

Step 5: Result of ISM-Based Model

Using the outcomes of level partitioning and MICMAC categorisation, an integrated ISM- based model was constructed to represent the hierarchical relationships among the CSFs. Based on the outcomes of the previous step, the hierarchical relationships among the CSFs were developed using Interpretive Structural Modelling (ISM). The resulting framework is shown in Figure 2, which presents the cascading influence of driver, linkage, and dependent factors in the healthcare FM implementation model.

This structured model enables a clear understanding of the cascading influence from leadership and capability-based drivers (such as Top Management Commitment and Knowledge & Competencies) through strategic and operational linkages, to final dependent outcomes like Continuous Improvement and Accreditation.

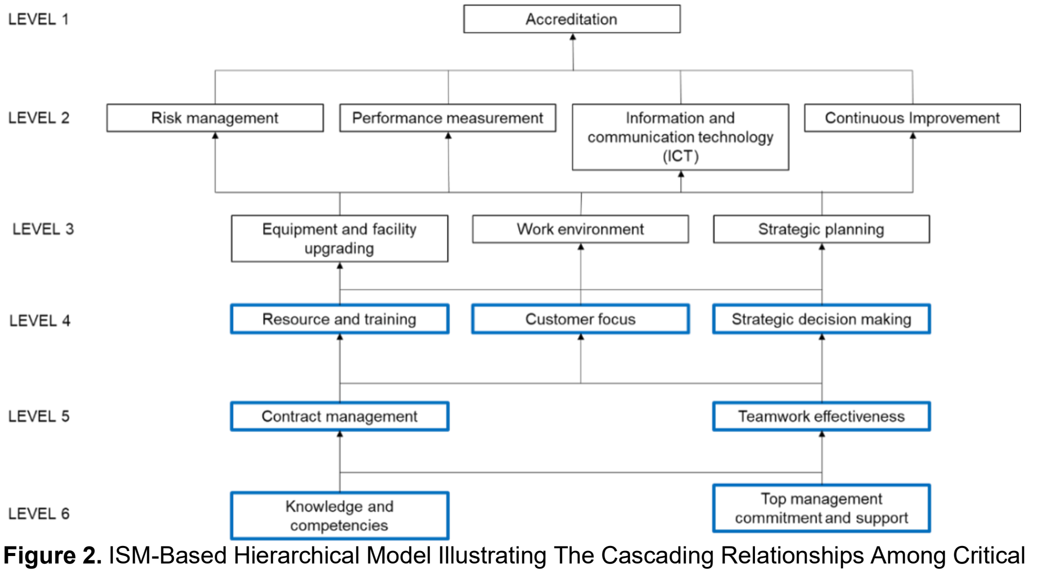

Figure 2. ISM-Based Hierarchical Model Illustrating The Cascading Relationships Among Critical Success Factors in Healthcare FM Implementation

Step 6: Model Validation and Interpretation

The ISM model was reviewed and validated by the same group of experts to ensure interpretive accuracy and contextual relevance. The experts confirmed that the hierarchical structure aligns with real-world FM implementation dynamics in healthcare organisations. The validated ISM–MICMAC framework thus provides a reliable analytical foundation for both academic interpretation and practical application in FM performance enhancement.

This research followed a systematic six-step ISM process integrated with MICMAC validation to derive a hierarchical and interdependent model of success factors. The methodology not only identifies *which* factors are critical but also explains *how* they interact, thereby contributing to a more structured understanding of FM implementation success in healthcare environments.

The preceding methodological process established a structured framework for analysing the interrelationships among the fifteen identified success factors for Facilities Management (FM) implementation in healthcare. Through the Interpretive Structural Modelling (ISM) approach, qualitative expert inputs were systematically transformed into a hierarchical model, enabling a visual and analytical understanding of causal linkages among the factors.

The resulting reachability matrix and level partitioning exercises (Tables 5–11) provided a foundation for classifying each success factor according to its level of influence and dependency. To further validate and interpret these hierarchical relationships, the MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) analysis was applied, categorising the factors into four groups: driver, linkage, dependent, and autonomous. This dual analytical approach ISM for structural mapping and MICMAC for classification ensures that the findings are both methodologically robust and strategically meaningful. The following section presents the results derived from this integrated analysis, highlighting how key driver factors such as Top Management Commitment, Knowledge and Competencies, Teamwork, and Contract Management shape the broader system of FM implementation in healthcare.

FINDINGS AND DISCUSSION

The findings from both MICMAC and ISM analyses indicate a coherent structure among the success factors of FM implementation in the healthcare sector.

The driver factors (e.g., knowledge and competencies, teamwork, contract management, and top management support) serve as the key enablers that propel successful implementation.

1. The linkage factors (strategic planning and work environment) operate as connecting bridges between the strong drivers and the dependent outcomes, reinforcing the dynamic nature of healthcare FM systems.
2. The dependent factors (risk management, continuous improvement, and accreditation) emerge as outcomes resulting from the effective integration of the preceding layers.

The correspondence between the literature review (Table 1) and the MICMAC and ISM results is significant, demonstrating the theoretical coherence and empirical consistency of the findings.

Top management commitment, strategic planning, teamwork, and customer focus were consistently recognised as essential for FM success, validating previous findings by Shohet et al. (2004), Olanrewaju et al. (2019), and Amos (2022). These results are further supported by more recent studies such as Adegoriola et al. (2023) and Ali et al. (2023), who found that leadership capability, management support, and team competency play pivotal roles in driving

FM performance across healthcare facilities. Similarly, Salem and Elwakil (2023) emphasised that top management commitment and staff knowledge are critical to sustaining FM innovation and digital transformation in the healthcare environment.

However, the ISM analysis offers a deeper structural understanding showing not just which factors are important, but how they influence one another within a hierarchical framework. As illustrated in Figure 1, Strategic Planning (SF8) and Work Environment (SF12) occupy the linkage quadrant, connecting driver factors such as Top Management Commitment (SF6) and Knowledge & Competencies (SF3) to dependent results like Accreditation (SF15) and Continuous Improvement (SF14). This interconnected structure demonstrates that effective FM implementation in healthcare is not linear but relational where leadership, capability, and teamwork collectively drive performance and outcomes.

The ISM-based model provides healthcare facility managers with a clear roadmap for prioritising strategic actions. Strengthening top management commitment and staff competencies forms the foundation for building cohesive teamwork and effective contract management. These, in turn, support strategic decision-making and resource planning, ultimately enhancing risk control, continuous improvement, and accreditation outcomes. Thus, the model can be applied as both a diagnostic tool and a strategic planning framework to guide FM implementation in hospitals and similar institutions.

Beyond theoretical interpretation, these findings have important implications for healthcare FM practice.

In practice, healthcare facility administrators can use the ISM-based model as a strategic decision-support tool to prioritise leadership commitment, competency development, and interdepartmental collaboration. The hierarchical structure enables managers to align training programs, contract management standards, and performance evaluation frameworks with the key driver factors identified in this study. By focusing on these foundational enablers, organisations can enhance decision-making, strengthen FM policy alignment, and achieve sustainable operational performance. Moreover, policymakers may utilise the model to develop competency frameworks and national guidelines that reinforce leadership accountability, standardise contract governance, and promote continuous FM improvement across healthcare institutions These findings align with Jenuwa et al. (2024), who proposed a model for assessing facility manager competencies within Malaysian hospital projects, highlighting that professional capability and strategic decision-making are fundamental drivers of successful FM implementation.

CONCLUSION, LIMITATIONS AND FUTURE RESEARCH AGENDA

This study examined the critical success factors (CSFs) influencing the implementation of Facilities Management (FM) in the healthcare sector using the Interpretive Structural Modelling (ISM) and MICMAC analytical approaches. Fifteen CSFs were identified and analysed to determine their hierarchical relationships and interdependencies. The ISM–MICMAC framework revealed that driver factors such as Top Management Commitment, Knowledge and Competencies, Teamwork, and Contract Management exert the greatest influence on FM implementation outcomes. Linkage factors such as Strategic Planning and Work Environment serve as mediators connecting leadership and operational domains, while dependent factors including Risk Management, Continuous Improvement, and Accreditation emerge as the resulting performance outcomes.

The research contributes to both theory and practice by presenting an empirically validated structural model that clarifies the interrelationships among the key CSFs in healthcare FM. The model offers a system-based perspective, moving beyond isolated factor analysis to explain how managerial, organisational, and operational elements interact to shape FM performance. This structured understanding fills a significant gap in FM literature, where previous studies often focused on individual success determinants without exploring their hierarchical influence.

From a practical standpoint, the ISM-based model provides healthcare facility administrators and policymakers with a strategic planning and diagnostic tool for prioritising FM improvement initiatives. Organisations are encouraged to strengthen leadership commitment, invest in competency development, and foster teamwork across departments to ensure effective policy implementation and operational alignment. By using this model, managers can link strategic planning with performance evaluation systems, thereby improving decision- making and ensuring sustainable FM outcomes in healthcare environments.

This research also highlights opportunities for future studies. Subsequent work could expand the ISM–MICMAC framework to encompass other healthcare facility contexts, such as primary care clinics or long-term care centres, to assess the model's generalisability. Furthermore, integrating this framework with quantitative approaches such as Structural Equation Modelling (SEM) or the Rasch Measurement Model may provide statistical validation and deeper insight into the strength of causal relationships. Future studies could also explore the influence of digitalisation, artificial intelligence, and post-pandemic FM practices, extending this model towards a more data-driven and adaptive Facilities Management framework.

In conclusion, the study establishes a structured and evidence-based framework that not only enhances understanding of how success factors interact within healthcare FM but also provides a practical foundation for strategic decision-making, leadership development, and performance optimisation. By applying the proposed ISM–MICMAC model, healthcare organisations can move towards more sustainable, resilient, and intelligent FM systems that support both operational excellence and long-term institutional value. This study extends the insights of previous Malaysian research (Au-Yong et al., 2017; Hashim et al., 2024; Jenuwa et al., 2024), by presenting a structured ISM–MICMAC framework that aligns with national FM practice trends and informs policy-level strategies for strengthening healthcare facility management in Malaysia.

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The Malaysian Construction Research Journal (MCRJ) is the journal dedicated to the documentation of R&D achievements and technological development relevant to the construction industry within Malaysia and elsewhere in the world. It is a collation of research papers and other academic publications produced by researchers, practitioners, industrialists, academicians, and all those involved in the construction industry. The papers cover a wide spectrum encompassing building technology, materials science, information technology, environment, quality, economics and many relevant disciplines that can contribute to the enhancement of knowledge in the construction field. The MCRJ aspire to become the premier communication media amongst knowledge professionals in the construction industry and shall hopefully, breach the knowledge gap currently prevalent between and amongst the knowledge producers and the construction practitioners.

Articles submitted will be reviewed and accepted on the understanding that they have not been published elsewhere. The authors have to fill out the **Declaration of the Authors** form and return the form via fax/email to the secretariat. The length of articles should be **between 3,500 and 8,000 words** or **approximately 8 – 15 printed pages (final version)**. **The similarity index must be lower than 20% and proofread in UK English.** The Similarity Report and summary of the article (less than 250 words) for editorial must be submitted together with the manuscript.

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CODIFICATION AND APPLICATION OF SEMI-LOOF ELEMENTS FOR COMPLEX STRUCTURES

(FULL NAME) Ahmad Abd Rahman[1,2], Maria Diyana Musa[2] and Sumiana Yusoff[2]
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Abstract (Arial Bold, 9pt)
Damage assessment …… ……(Arial, 9pt. Left and right indent 0.64 cm, it should be single paragraph of about 100 – 250 words.)

Keywords:(Arial Bold, 9pt) *Finite Element Analysis; Modal Analysis; Mode Shape; Natural Frequency; Plate Structure (Time New Roman, 9pt)*

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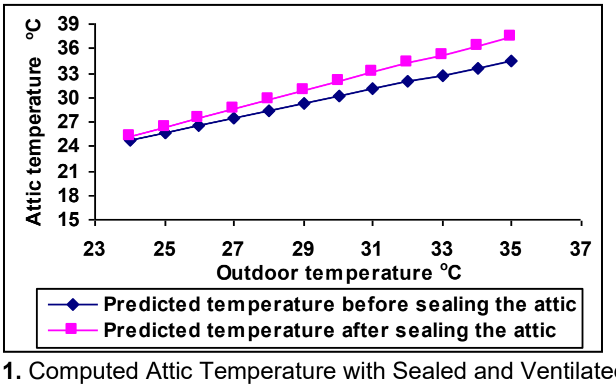

Figure 1. Computed Attic Temperature with Sealed and Ventilated Attic

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Table caption: Arial Bold + Arial, 9pt. + Capitalize Each Word. Captions should be written above the table.

Table Line: 0.5pt.

Table 1. Recommended/Acceptable Physical Water Quality Criteria

Parameter	Raw Water Quality	Drinking Water Quality
Total coliform (MPN/100ml)	500	0
Turbidity (NTU)	1000	5
Color (Hazen)	300	15
pH	5.5-9.0	6.5-9.0

(Source: Twort et al., 1985; MWA,1994)

Units: All units and abbreviations of dimensions should conform to **SI standards.**

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