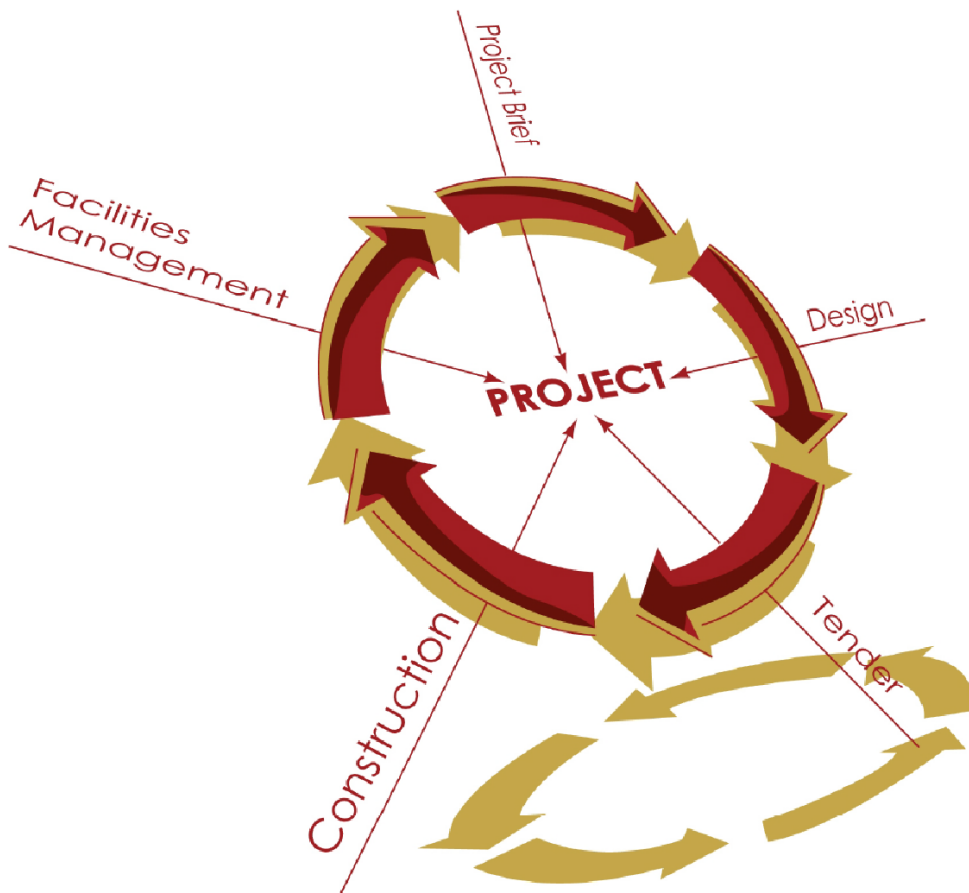


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Introduction

Welcome to this special issue in Malaysian Construction Research Journal (MCRJ) for the 2nd International e-Conference on Green and Safe Cities (IeGRESAFE) 2024. This conference was organised by the Green Safe Cities Research Group (GreSafe), UiTM Perak Branch in collaboration with Universitas Syiah Kuala Banda Aceh, Indonesia; Kyoto Institute of Technology Matsugasaki, Sakyo-ku, Kyoto, Japan; Universiti Teknologi Malaysia (UTM); and Universiti Tun Hussein Onn Malaysia (UTHM). It has been an avant-garde platform successfully hosted under the theme ‘Resilient Urban Futures: Sustainable Solutions for Tomorrow’.

This seminar, which is held virtually on 19 and 20 September 2024, seeks to provide a dynamic forum for academics, researchers, industry practitioners, and policymakers to deliberate on the challenges and opportunities of shaping sustainable construction, inclusive, and resilient cities. The discussions are intended to highlight innovative approaches and cross-disciplinary solutions that address pressing built environment sustainability issues such as climate adaptation, disaster risk reduction, smart infrastructure, green procurement, energy efficiency, and sustainable construction practices.

The theme underscores the urgent need to rethink urban development strategies that not only safeguard communities but also enhance quality of life and environmental stewardship. IeGRESAFE 2024 aims to foster collaboration, knowledge exchange, and actionable insights that will guide the transformation of cities towards a safer and greener future by bringing together global perspectives and local experiences.

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Editorial

Welcome from the Editors

Welcome to this special issue in Malaysian Construction Research Journal (MCRJ) for the 2nd International e-Conference on Green and Safe Cities (IeGRESAFE) 2024. We would like to express our sincere gratitude to our contributing authors, reviewers, organisers, and readers.

This special issue in MCRJ for 2nd International e-Conference on Green and Safe Cities (IeGRESAFE) 2024 contains twenty (20) interesting papers covering the theme of “Resilient Urban Futures: Sustainable Solutions for Tomorrow”. It is our sincere hope that this special issue will serve as a valuable resource for readers, whether they are scholars, practitioners, policymakers, or students, in expanding their understanding of the multifaceted dimensions of sustainable and safe urban development. The articles compiled here reflect diverse perspectives and innovative research outcomes presented during IeGRESAFE 2024, and together they highlight the collective commitment towards building greener, safer, and more resilient cities.

We aspire that the insights shared within these pages will inspire further research, spark new collaborations, and encourage practical applications in the real world of construction, planning, and policymaking. Ultimately, it is our expectation that this special issue will not only contribute to academic discourse but also empower readers to play an active role in shaping sustainable urban futures for generations to come.

Brief introduction of each article is given as hereunder:

Muhammad Suhail Azmin Tuah and Sallehan Ismail have explored the potential of bamboo fibre textile-reinforced mortar (BTRM) as a sustainable strengthening method for reinforced concrete slabs. The finding focuses on mesh size variations and their effects on flexural behaviour, which confirmed the suitability and effectiveness of BTRM for structural strengthening.

Elma Dewiyana Ismail et al. have identified the barriers—organizational, technical, and financial—that prevent small and medium-sized enterprises (SMEs) from fully adopting BIM, while suggesting strategies to accelerate its implementation. This review emphasises the importance of government interventions and initiatives as part of a strategy to overcome the barriers SMEs face.

Norhafizah Yusop et al. have investigated how Competency-Based Education (CBE) can improve problem-solving skills in quantity surveying students, highlighting both challenges and effective teaching approaches. The results underscore the importance of understanding students’ learning experiences to address competency gaps and support the advancement of QS CBE programmes.

Kageishieny Nadarason et al. have assessed recycling initiatives in construction projects, ranking key practices using Analytical Hierarchy Process (AHP) and Relative Importance Index (RII) methods to promote better waste management and sustainability in the industry. This study exclusively examined on four categories of C&D waste: timber, metal, concrete, and packaging material.

Syarifah Nur Shaqina Syed Shabahar et al. have executed a comparative study of facilities management and maintenance contracts across five countries; the United States, the United Kingdom, Australia, Hong Kong, and Malaysia. This paper uncovers diverse procurement approaches and highlights global best practices, including tendering methods, contract types, durations, payment methodologies, and its evaluation criteria.

Nuradila Izzaty Halim et al. have examined the use of POFA (MicPOFA) and nano-sized POFA (NaPOFA) as cement substitutes in SCHPC, demonstrating their potential to enhance flexural strength and sustainability. The findings suggest that MicPOFA and NaPOFA enhance concrete's mechanical properties, facilitating environmentally responsible solutions for the structural demands of modern high-rise buildings, bridges, and infrastructure projects.

Muhammad Suhail Azmin Tuah et al. have investigated the impact of bamboo textile mesh sizes (M1–M5) on bond characteristics and flexural behaviour as an eco-friendly alternative for structural reinforcement. The study delves into failure modes, showcasing a shift from brittle to ductile behaviour in BTRM, with bamboo textiles controlling crack widths, enhancing post-crack behaviour, and improving structural safety

Nurhidayah Md Isa et al. have reviewed cost management challenges in Malaysian rail projects using a systematic literature review (SLR). The study has identified gaps in planning and budgeting practices and proposing improvements to minimise overruns.

Nadira Ahzahar et al. have identified management and financial barriers that hinder the adoption of lean construction practices in Malaysia. Through surveys and literature review, the study has suggested ways to increase the implementation of sustainable lean practices in improving project efficiency, reducing costs, and enhancing project outcomes.

Sheikh Ali Azzran Sh Said and Nur Liyana Amer Hamzah have discussed how organisational development strategies can enhance the effective implementation of BIM in construction firms, particularly culture and human capital management. The findings reveal three organisational development approaches conducive to BIM implementation: aligning organisational culture and values with individuals; developing organisational strategies to enhance BIM utilisation; and fostering organisational innovation.

Adeeb Zulkifli et al. have evaluated worker accommodations against national standards, revealing compliance gaps and calling for improved design, safety, and welfare measures. The findings highlighted recurring deficiencies that pose health and safety risks, including overcrowding, poor ventilation, inadequate sanitation, and weak fire prevention measures.

Mohd Syahrul Hisyam Mohd Sani et al. have analysed experimental results which are presented on the use of washed bottom ash concrete in cold-formed steel sections, showing its potential to improve structural performance. The compression behaviour of all specimens is documented, and the failure mode of each specimen is examined in this study.

Nurulhuda Ali et al. have identified 31 economic indicators for assessing TOD performance in the Malaysian context and validated them using expert consensus. This study has addressed a critical gap by providing evaluated economic indicators tailored to assess TOD's role in sustainable urban development in Malaysia

Siti Nurul Ainun Mohd Mustafa et al. have evaluated critical design performance criteria for green office buildings, refining sustainability benchmarks for practice through expert interviews. The findings summarised twenty-eight (28) criteria that were considered relevant, and eight (8) were excluded as the criteria were reviewed as irrelevant to design performance criteria in green buildings.

Nurul Diyana Mohd Dahari et al. have introduced a risk-based maintenance management model to improve decision-making and resource allocation in public school facilities. The results were validated through SEM-PLS approach. Results demonstrate that all four perceived risk factors significantly influence maintenance management performance, supporting the model's theoretical framework

Alivia Rosy Walidonna et al. have carried out a comparative analysis of physical and non-physical building features of UNESCO World Heritage Sites of Melaka and George Town: Historic City of the Straits of Malacca in Malaysia and the Historic City of Vigan in the Philippines. This paper highlights how both physical and cultural features contribute to heritage conservation and urban resilience.

Yuhainis Abdul Talib et al. have assessed facility satisfaction in two (2) case studies of elderly housing institutions (Pondok Villages). The study has proposed strategies to align them with sustainable management practices, that foster cultural sustainability.

Annisa Qadrunnada et al. have evaluated the sustainability of a low-income housing estate in West Aceh, Indonesia, using the Greenship Neighbourhood rating system by the Green Building Council Indonesia (GBCI). The study offered interventions on design improvements for better environmental performance.

Noor Ainsyah Zulkifli et al. have investigated the causes and effects of mid-project design changes. This paper highlights their impact on costs and schedules and recommends best management practices. The results underscore the importance of adopting proactive and strategic management approaches to reduce mid-project design disruptions.

Yan Yan et al. have identified key design principles in smart home design construction with human computer integration elements in Hefei, China. Using semi-structured interview, the study revealed usability, security, and fault tolerance are among the criteria needed for improving user experience in smart home systems.

ENHANCING FLEXURAL PERFORMANCE OF REINFORCED CONCRETE SLABS CONSTRUCTION THROUGH BAMBOO FIBER TEXTILE-REINFORCED MORTAR (BTRM) STRENGTHENING: A MESH SIZE INVESTIGATION

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Abstract

This study investigates the flexural behaviour of reinforced concrete (RC) slabs strengthened using bamboo fibre textile-reinforced mortar (BTRM), focusing on the effect of varying bamboo textile mesh sizes. Bamboo, a renewable and widely available material, is explored as a sustainable alternative for enhancing cementitious composites. The study addresses a research gap in the use of bamboo textiles in textile-reinforced mortar (TRM), particularly for RC slab applications. The experimental setup involves four-point bending tests with instrumentation including load cells, displacement transducers, and strain gauges. Performance indicators such as load capacity, deflection, ductility, and crack propagation under static loading are evaluated. Results demonstrate that BTRM enhances load-deflection characteristics, improves crack resistance, and contributes to greater ductility through gradual deformation and energy absorption. Stress-strain responses confirm improved tensile behaviour and delayed crack formation. Overall, the findings confirm the suitability and effectiveness of BTRM for structural strengthening, offering guidance for sustainable retrofitting practices.

Keywords: *Bamboo Fiber Textile-Reinforced Mortar (BTRM); bond characteristics; mesh size optimization; Textile Reinforced Mortar (TRM)*

INTRODUCTION

Cement-based materials, particularly mortar and concrete, are the most widely used construction materials globally. Despite their advantages, their low tensile strength and brittle nature limit structural performance under dynamic loading such as impacts or earthquakes. Fiber reinforcement is commonly employed to enhance strength and ductility. Recent advancements have led to the development of textile-reinforced mortar (TRM) composites, where non-corrosive textiles are embedded in a fine cementitious matrix (De Munck et al., 2018). TRM offers advantages such as lightweight and corrosion-resistant systems, ease of handling, and a high strength-to-weight ratio. Compared to fibre-reinforced polymers (FRPs), TRMs avoid issues like high costs and poor fire resistance associated with epoxy resins (Goldfeld, 2020).

TRM has shown promise in improving tensile strength, ductility, and energy absorption—crucial for structures subjected to dynamic loads (Goldfeld, 2020; Irshidat & Al-Shannaq, 2018; Wastiels, Van Ackeren, Tysmans & Van Paepegem, 2018). Strategically positioning technical textiles along the primary stress directions of the composite demonstrates greater efficacy compared to randomly dispersing short fibres within the concrete mix (Zhu, Peled, & Mobasher, 2011). Moreover, the use of textiles as reinforcement allows for the precise

arrangement of fibres according to specifications, unlike the constraints imposed by short fibres.

Several studies have explored the application of TRM in retrofitting RC and masonry structures, encompassing flexural (Scheerer et al., 2019) and shear strengthening (Bielak, Adam, Hegger, & Classen, 2019), confinement of RC columns (Al-Gemeel & Zhuge, 2019), and seismic retrofitting (Bournas, 2018). TRM has also been successfully used for retrofitting masonry structures (e.g., out-of plane strengthening (Bournas, 2018) and shear strengthening of masonry walls (Shabdin, Zargaran & Attari, 2018)). Traditionally, TRM has incorporated synthetic fibres, but concerns regarding the high embodied energy of steel and synthetic fibres, as well as recycling challenges, present obstacles to global sustainability goals. In response, there is a growing interest in composites reinforced with natural fibres, often referred to as green, biodegradable, or bio-composites. While extensive research has explored the potential of short natural fibres in reinforced cementitious composites, limited attention has been dedicated to natural TRM, particularly regarding its tensile or flexural behaviour in strengthening RC structures. In current TRM development, only a few studies have investigated the performance of natural TRM (Ferrara, Pepe, Martinelli & Tolêdo Filho, 2021; Fidelis et al., 2016; Sadrolodabae, Claramunt, Ardanuy & de la Fuente, 2021; Trochoutsou, Di Benedetti, Pilakoutas & Guadagnini, 2021). Notably, these studies have revealed highly ductile tensile behaviour with distinctive characteristics.

Maria Ernestina Alves Fidelis et al. (2016) conducted an extensive study to understand the degradation mechanisms of concrete reinforced with natural jute textiles. The research emphasized the impact of polymer-coated versus uncoated jute fabrics, demonstrating that coated fabrics exhibited a stronger bond. The study found that polymer coatings significantly enhance the bond between the fibre and matrix, thereby reducing fibre degradation. In another study, Giuseppe Ferrara et al. (2021) conducted experimental research on TRMs incorporating flax textiles within a lime-based matrix. The study revealed significant insights, with impregnation treatment of dry textiles emerging as a key factor. Despite a marginal reduction in tensile strength, impregnated textiles enhanced the mechanical response under tensile loads, leading to improved performance.

Payam Sadrolodabae et al. (2021) evaluated the mechanical and durability characteristics of short randomly oriented textile waste fibres (TWF) as potential reinforcements for cement composites. Concentrating on non-structural building components such as aesthetic façade panels and cladding, the research highlighted that TWF composites displayed post-cracking behaviour and enhanced energy absorption, making them suitable for these applications. On average, the compressive strength and flexural stiffness of TWF composites surpassed those of reference samples by 12%.

Niki Trochoutsou et al. (2021) conducted a study investigating the tensile performance of flax- and jute-TRM in strengthening masonry structures. Their findings indicated that both flax and jute fibres were viable for structural applications, with flax demonstrating superior strength and elongation capacity. Flax-TRM exhibited enhanced strength and ductility attributed to the effective interaction between the dense flax textile and lime mortar, enabling multiple cracks and uniform stress distribution. In contrast, Jute-TRM displayed suboptimal fibre-matrix interaction, resulting in unsatisfactory composite behaviour, even at higher reinforcement ratios. Notably, the research also highlighted that thicker mortar overlays did

not consistently improve mechanical performance and could prove detrimental, particularly with low mechanical reinforcement ratios.

Nevertheless, it's crucial to recognize that natural fibres, such as flax and hemp, may not consistently deliver the same high tensile strength as synthetic fibres like glass or carbon. This discrepancy could potentially impact the overall performance of TRM, particularly in applications demanding exceptionally high strength. When it comes to strengthening structures with TRM, various types of textile materials are commonly utilized, including steel and synthetic fibres such as glass and carbon (Raji, Mostofinejad & Eftekhari, 2022). The tensile and flexural behaviour of TRM, including aspects such as multiple cracking, toughness, and strength, depends on several factors. These factors include the properties of the reinforcing textiles, the characteristics of the cement matrix, the interface bond, and the anchorage of the textiles used in TRM (Gopinath, Prakash, & Ahmed, 2020).

While numerous studies have investigated synthetic fibre TRMs (e.g., glass, carbon), natural fibre-based TRMs remain underexplored for structural elements like RC slabs. Prior research has primarily focused on flax (Ferrara et al., 2021), jute (Fidelis et al., 2016) and textile waste (Sadrolodabae et al., 2021), often at small scale or in non-structural components. Foundational works (Papanicolaou, Triantafillou, Karlos & Papathanasiou, 2007; Triantafillou, 2001) established TRM principles, yet few studies have applied these to bamboo textiles in full-scale flexural retrofitting. This study extends the scope by incorporating bamboo—a locally abundant, low-cost fibre—into a structural retrofitting system, with a focus on textile mesh geometry and its role in ductility, crack control, and flexural strength. The mesh size of TRM plays a pivotal role in influencing its flexural behavior. This term refers to the spacing and arrangement of the textile reinforcement within the mortar matrix. The presence of perforations between the fibre rovings allows for a mechanical interlock between the reinforcement and the matrix (Koutas Lampros, Tetta, Bournas Dionysios & Triantafillou Thanasis, 2019). Research suggests that a well-established interlocking combination between mortar and reinforcement yields significant benefits in retrofitting applications, enhancing energy absorption, displacement, and load capacity by more than 100% (Coelho & Silva, 2023). Maintaining a uniform mesh size in reinforcement textiles is crucial for achieving mechanical interlock and ensuring even stress distribution throughout the TRM. It's worth emphasizing that the optimal mesh size can vary based on factors such as the specific application, the properties of the fibres utilized, and the desired performance criteria. Therefore, careful consideration of these factors is paramount in achieving the desired outcomes in TRM applications.

Thus, this study aims to investigate the flexural behaviours of an RC slab strengthened with BTRM. Bamboo, as a plant-based natural fibre, presents itself as a low-cost renewable material abundant in many countries, including Malaysia. Despite previous research demonstrating the suitability of short bamboo fibres as reinforcement in strengthening cementitious composites, studies on bamboo fibre/yarn for TRM composites, especially focusing on the characteristics and flexural behaviour of concrete slabs in strengthened RC structures, are still scarce. This research seeks to fill this gap by studying the suitability and effectiveness of BTRM in flexural strengthening of RC slabs, with a specific focus on the geometrical mesh size of bamboo textile. The study aims to evaluate the impact of different mesh sizes of bamboo textile on the strength of RC slabs concerning load-carrying capacity, deflection characteristics, ductility, and cracking patterns under static loads. The findings of

this study are essential for knowledge development, assessing feasibility, and providing guidance for future researchers in this field.

EXPERIMENTAL PROGRAM

Test Specimens and Material Properties

A total of three RC one-way slabs were prepared for testing purposes. All specimens had a length of 1000mm, with a rectangular cross-section measuring 400mm x 60mm. The concrete mixtures for the slabs were designed according to the Department of Environment method, with a constant water-to-cement ratio of 0.47 to achieve a target strength of 30 MPa at 28 days. The composition of the concrete mixture consisted of commercial Portland cement (ASTM C150 Type 1) with a specific gravity of 3.15 (see Table 1), crushed granite as coarse aggregate with a maximum particle size of 20 mm, and river sand as fine aggregate. Table 2 shows the grading size of aggregates used for this study. To ensure correct workability, a polycarboxylic ether-based superplasticizer (SP) was added during composite fabrication. The mix proportions for the RC slab materials are detailed in Table 3, along with the experimentally obtained strength properties of the concrete at 28 days. These results were derived from three cubes, each measuring 100 × 100 × 100 mm, in accordance with the BS EN 12390-3 standard.

In order to enhance tensile strength within each RC slab sample, BRC DA8 wire mesh reinforcement complying with BS4483 was employed. The general technical specifications of the reinforcement used are shown in Table 4. Notably, the surface of the BRC possesses a smooth contour to address potential bond slip issues between the BRC and the concrete matrix. Figure 1 shows the details of RC slab designs. Among the three slabs, two were strengthened, and one was left un-strengthened as the control specimen. The test parameters for this study aimed to investigate the effect of spacing mesh size of lateral bamboo textile for strengthening the slab. In this study, two types of bamboo textile, with the same properties but different weaving in mesh sizes for textile grids (10 × 10mm and 20 × 20mm), were used as the strengthening material, as shown in Figure 2. The properties of the bamboo yarn fibre used for textiles are listed in Table 5. A description of all slab specimens prepared for this study is as follows:

- 1) M0 – RC slab tested as built, without any strengthening layers.
- 2) M10 – RC slab strengthened with BTRM (mesh size 10x10mm).
- 3) M20 – RC slab strengthened with BTRM (mesh size 20x20mm).

Table 1. Typical Chemical Compositions of OPC and Silica Fume

Material	Composition (%)									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	SO ₂	P ₂ O ₅	TiO ₂	Others
OPC	16.00	3.60	2.90	72.00	1.50	0.34	3.10	0.06	0.17	0.34
Silica Fume	90.00	1.20	2.00	1.00	0.60	0.80	0.50	0.05	0.09	4.80

Table 2. Sieve Analysis of Aggregates

Aggregate	Aggregate Passing (%) According to Sieve Size (mm)								
	0.15	0.3	0.6	1.18	2.36	5	10	14	20
Sand	5	17	44	63	91	100	100	100	100
Coarse aggregate	0	0	0	0	0	5	25	56	88

Table 3. Mix Designs of RC Slab and Mortar

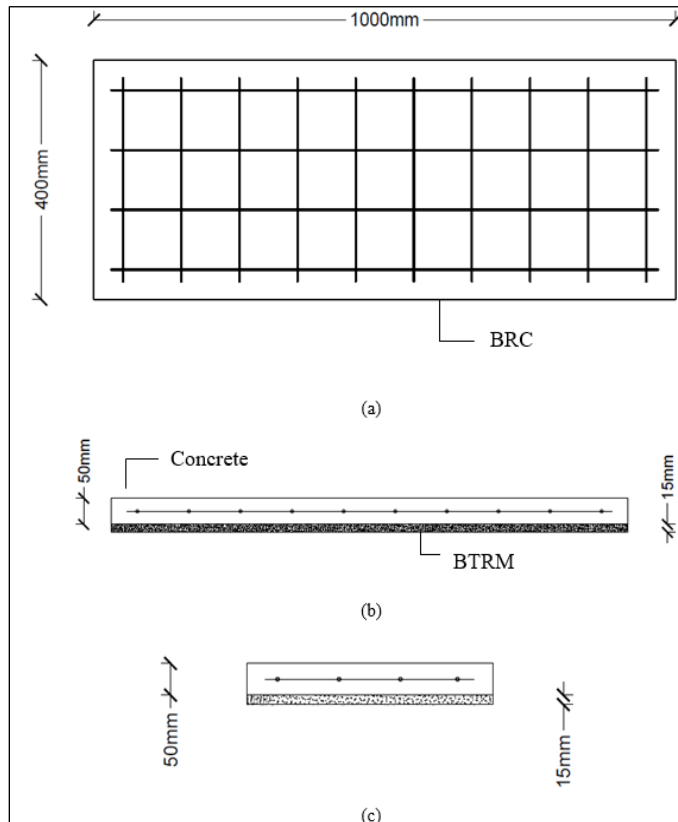
Types of Mixture	Cement (kg/m ³)	Water (kg/m ³)	Sand (kg/m ³)	Aggregate (kg/m ³)	Silica Fume (kg/m ³)	SP (1% from Mass of Cement)	f'_c (MPa)	Std Dev.
RC Slab	340	160	515	1385	-	0.34g	32.4	1
BTRM	470	168	1380	-	47	0.47g	40.0	1.52

Table 4. Specifications of BRC Reinforcement

Main Wire		Cross Wire		Steel Area		Mass Per Unit Area (kg/m ²)
Diameter (mm)	Pitch (mm)	Diameter (mm)	Pitch (mm)	Main (mm ² /m)	Cross (mm ² /m)	
8	100	8	100	503	503	7.90

Table 5. The Properties of Bamboo Yarn Fiber

Properties	Average Maximum Load (N)	Average Tensile Strength (MPa)	Average Tensile Modulus (MPa)	Average Tensile Modulus (GPa)	Average Elongation at Break (%)
Bamboo Fibre	37.089	47.22	49862.51	49.86	33.76

**Figure 1.** The Details of Slab Designs, Including: (a) The Plan View of The Slab, (b) The Front View of The Slab, and (c) The Side View of The Slab

In the production of BTRM for the strengthened slab, the textile fibres were embedded within a 15 mm thick mortar layer applied to the tensile face located below the concrete slab surface. In this study, the mortar mixture used for BTRM consists of ordinary Portland cement, fine river sand, and superplasticizer, with similar standard specifications as materials

used for concrete. However, in this mortar mix, silica fume (10% by weight of cement) was added as an additional mineral admixture to replace cement content and enhance the strength of the mortar binder. Table 1 shows the typical chemical composition of silica fume used for this experiment. Meanwhile, Table 3 shows the mix composition of materials for the mortar mixture. The average compressive strength of the mortar mix was 40 MPa, taken from three mortar cubes tested at 28 days according to the BS EN 12390-3 standard for use in this experiment.



Figure 2. Bamboo Textile Used in Strengthening of RC Slabs (a) 10 x 10mm (b) 20 x 20mm

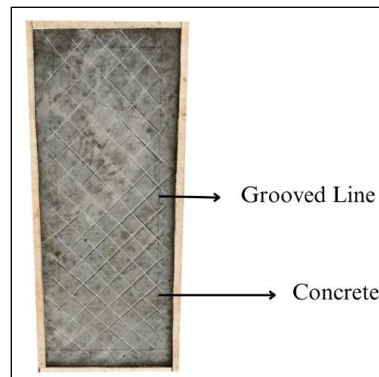


Figure 3. Creation of A Grid of Small Grooves on Slab Surface

In preparing the tested specimens, the RC slabs were first prepared and cast using timber formwork. Fresh concrete was then poured into the formwork and vibrated using a poker vibrator to ensure proper compaction of the mix. Subsequently, the cast concrete slabs were covered with a plastic sheet, demoulded after 7 days from casting, and then underwent the strengthening layer process. The procedure for applying the strengthening layer to the slab involved the following steps: (1) creating a grid of grooves on the bottom surface of the slab, as illustrated in Figure 3, with grooves ranging from 2–3 mm in width and depth. (2) For the BTRM application, the concrete surface was dampened with water to ensure good bonding conditions. (3) A 6–7 mm-thick layer of mortar was then applied to all BTRM-strengthened slabs using a smooth metal trowel. (4) After the first layer of mortar was applied to the dampened surface, the textile was embedded into the mortar by hand pressure. (5) Another layer of mortar was subsequently applied to completely cover the textile. After these steps, the specimens were stored under laboratory conditions until the testing phase.

Test Setup and Instrumentation

The RC slabs were subjected to four-point loading conditions to examine their flexural behaviour, as depicted in Figure 4. The test specimens were simply supported around their perimeter on a rigid frame consisting of four hollow-section steel beams. A servo-hydraulic

actuator mounted on a steel reaction frame applied the load monotonically, with vertical displacements controlled at a rate of 1 mm/min. The applied load's magnitude was monitored using a 300 kN capacity load cell and increased in 2 kN intervals. Concurrently, the vertical deflections of the slabs were recorded using a linear variable displacement transducer (LVDT). Electrical strain gauges, with a gauge length of 60 mm, a gauge resistance of $112 \pm 0.3 \Omega$, and a gauge factor of 2.13%, were installed on the top surface of the slabs at the pure bending region (near mid-span) to measure compressive strain. All deflection and strain data during loading were monitored via a data logger and an automatic data acquisition system. Crack widths and patterns were observed and documented at each load stage until failure occurred.

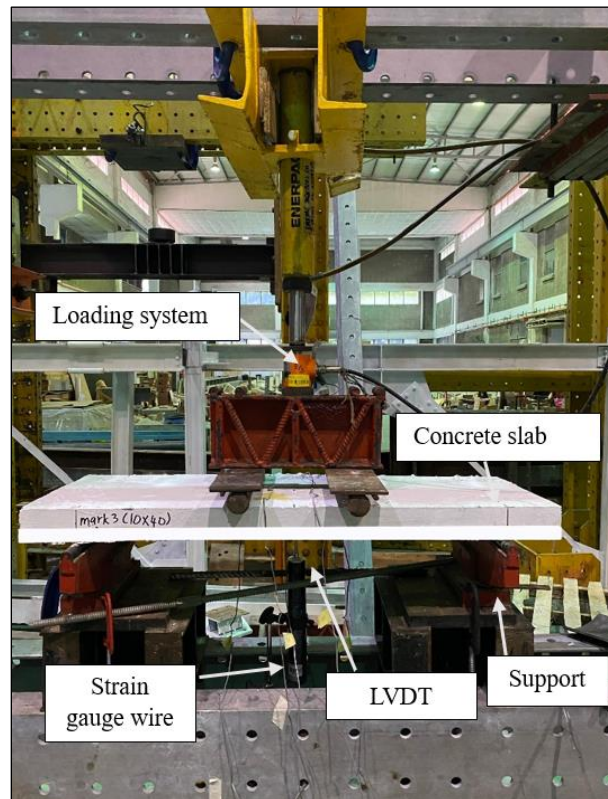


Figure 4. Test Setup of The Flexural Test in Laboratory

Limitations

It is important to note that only one specimen was prepared and tested for each slab configuration (M0, M10, and M20). This decision was made due to constraints in cost, time, and testing logistics, especially considering the large-scale nature of the slab specimens and the complexity of instrumentation (e.g., strain gauges, data loggers). While this approach allowed for a comprehensive investigation of load-deflection characteristics, stress-strain behaviour, ductility, and crack patterns, the findings should be interpreted as exploratory in nature. Future studies should incorporate multiple replicates per configuration to enable statistical averaging and improve the reliability and generalisability of the conclusions.

RESULTS AND DISCUSSION

Load-Deflection Characteristics

The load-deflection behaviour of the RC slab specimens is depicted in Figure 5, which can be classified into three primary phases: In the initial phase, as illustrated in Figure 5, the slabs exhibit an elastic response, where the relationship between load and deflection follows a linear pattern until the point of cracking. This phase is primarily influenced by the concrete matrix's stiffness. Notably, Slab M0 displayed its first crack at a load of 1.0 kN, resulting in a deflection of 0.13 mm. For Slab M10, a similar crack was observed at 1.2 kN with a deflection of 0.04 mm. Meanwhile, Slab M20 experienced its initial crack at 1.4 kN, resulting in a deflection of 0.1 mm. Consequently, the first crack load in Slabs M10 and M20 increased by approximately 20% and 40% respectively, compared to Slab M0.

Transitioning to the second phase, there's a noticeable surge in load, accompanied by the formation of additional cracks. During this phase, both the steel and textile reinforcement bear the tensile load, eventually leading to the steel reinforcement reaching its yield point. The yield loads at this stage for Slabs M0, M10, and M20 were documented as 2.8 kN, 4.9 kN, and 6.6 kN, respectively. Notably, the yield load of steel reinforcement in M10 and M20 increased by approximately 75% and 136%, respectively, compared to M0, owing to the contribution of textile reinforcement in load-bearing. Moreover, corresponding yield deflections of 0.45 mm, 0.33 mm, and 0.51 mm were observed for M0, M10, and M20, respectively.

In the third phase, the textile reinforcement contributes additional load-carrying capacity during the post-yield stage. Cracks tend to stabilise in this phase, possibly due to the textile reinforcement's ability to bridge microcracks. Subsequently, there's a rapid drop in load, indicating the failure of the textile reinforcement layer. Here, the stiffness of the textile reinforcement increases, a phenomenon known as deformation hardening in flexure. Ultimate capacities for Slabs M0, M10, and M20 were observed as 4.1 kN, 5.8 kN, and 7.5 kN, respectively, contributing to ultimate deflections of 0.72 mm, 0.58 mm, and 0.66 mm, respectively. It's important to note that in the case of Slab M0, the third phase was not observed due to the absence of a textile reinforcement layer, leading to the failure of the steel reinforcement after initial cracking.

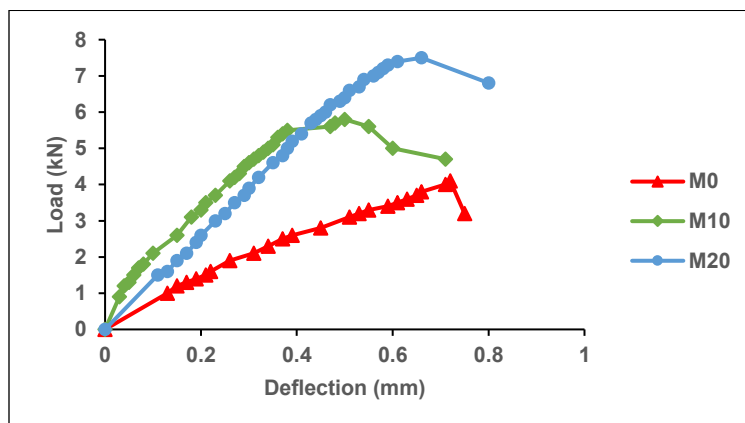


Figure 5. Load Deflection Curves of All Slabs

Stress-Strain Behaviour

The stress-strain behaviour of the concrete slab specimens, illustrated through stress-strain curves (refer to Figure 6), offers valuable insights into the mechanical response of the material under various loading conditions. In the initial elastic phase, the stress-strain curves for both the BTRM-strengthened slabs (M10 and M20) and the non-strengthened slab (M0) display linear patterns up to the point of cracking. This linear behaviour is supported by the finding that the strain changes relative to the gauge position remained linear during the elastic state. After cracking, the tension in the textile layer increases rapidly, contributing to the observed changes in the stress-strain curves.

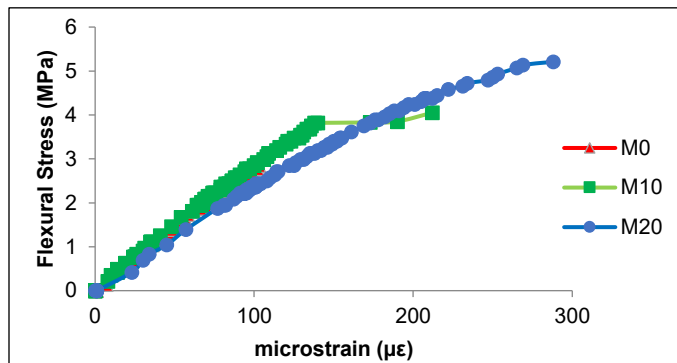


Figure 6. Stress Versus Strain Curves of All Slabs

The observation that slab M20 exhibits lower concrete strain compared to M10 at each corresponding load underscores an intriguing aspect of the stress-strain behaviour. This difference in concrete strain between M20 and M10 can be attributed to the more effective bridging mechanism provided by the textile layer in M20. In M10, stresses were transferred directly from the steel reinforcement to the concrete, leading to higher increments in concrete strain. The M10 curve concludes with a sharp increase in concrete strain, as shown in Figure 6, indicating the rupture of the steel reinforcement upon reaching its critical strain.

Furthermore, the stress-strain curves for both M20 and M10 exhibit a slower decrease than the M0 curve, emphasizing the sustained contribution of the textile reinforcement in the post-yield stage. This observation aligns with the idea that the textile layer acts as a bridge for microcracks, leading to stabilised cracks and a gradual drop in load. The stress-strain curves, thus, visually represent the intricate interplay between steel and textile reinforcement in the BTRM-strengthened slabs, offering a comprehensive understanding of the material's response to loading conditions and highlighting the positive influence of textile reinforcement on the structural performance of the concrete slab.

Ductility

Ductility, a pivotal attribute in structural engineering, denotes a material's inherent ability to deform and elongate prior to reaching the point of failure. This characteristic assumes paramount importance as it empowers structures to absorb energy and deform gradually, consequently mitigating the risk of sudden and brittle failure. In this investigation, the determination of slab ductility was guided by the model established by Naaman and Jeong (1995).

To quantify the ductility index of structural slabs, Naaman and Jeong (1995) introduced the following formula. This equation takes into consideration the correlation between inelastic absorbed energy and elastic stored energy, providing a comprehensive metric for ductility within the context of structural analysis.

$$\text{Ductility Index, } \mu_e = \frac{1}{2} \left(\frac{E_{\text{tot}}}{E_{\text{el}}} + 1 \right)$$

(1)

where μ_e is the ductility index, E_{tot} is the total energy calculated as the area under the load-deflection curve up to the defined failure load and E_{el} is the elastic stored energy which is a portion of the total energy. The elastic stored energy is computed as the area under the slope of the elastic behaviour (area beneath line S, up to the point of intersection with P_{failure} ; see Figure 7).

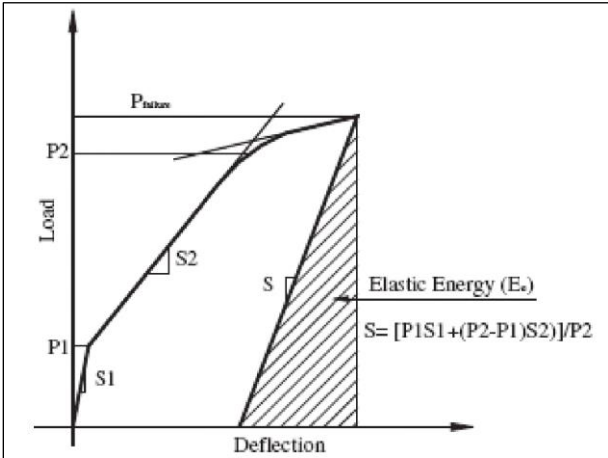


Figure 7. Ductility Index According to Naaman and Jeong (1995)

In the conducted investigation, the ductility of various slabs was evaluated, with the ductility index computed based on the assumption that the failure load was 80% of the ultimate attained load value, as presented in Table 6.

Table 6. Ductility Index of All Slabs						
Slab Specimens	S1	S2	S	E_{tot}	E_{el}	Ductility index
M0	7.7	4.3	5.4	3.18	1	2.10
M10	30	12	16.41	3.1	0.65	2.89
M20	14	8.57	9.6	5.83	0.93	3.65

The results indicate that the M20 slab, reinforced with bamboo textile, exhibited a notably ductile behaviour when compared to the other slabs. In contrast, the M0 slab, lacking bamboo textile reinforcement, displayed the lowest stiffness and toughness, resulting in reduced energy absorption and a ductility index lower than that of the BTRM slabs. Specifically, the M0 slab achieved the lowest ductility index value of 2.10, representing a 38% and 74% reduction compared to the M10 and M20 slabs, respectively. These findings underscore the significant enhancement in ductility brought about by the inclusion of BTRM for retrofit reinforcement. This reinforcement aids in distributing bending stresses and facilitating

material deformation without abrupt and catastrophic failure, thereby enhancing the ductility of the concrete structural slab.

Furthermore, within the context of BTRM, the study highlights the influential role of geometrical mesh size in determining ductility. Specifically, it was observed that a high level of ductility can be attained when incorporating BTRM with M20, as opposed to M10. This phenomenon may be attributed to the finer mesh size or higher fibre density of the textile, which restricts cement paste penetration. Smaller mesh sizes create narrower spaces between fibres, making it more challenging for the cement paste to infiltrate. This penetration and interlocking mechanism between the cementitious matrix and textile reinforcement are essential for establishing a robust bond and enhancing the overall mechanical properties of BTRM, contributing to improved ductility when used for reinforced structural slabs.

Mode of Failure and Crack Pattern

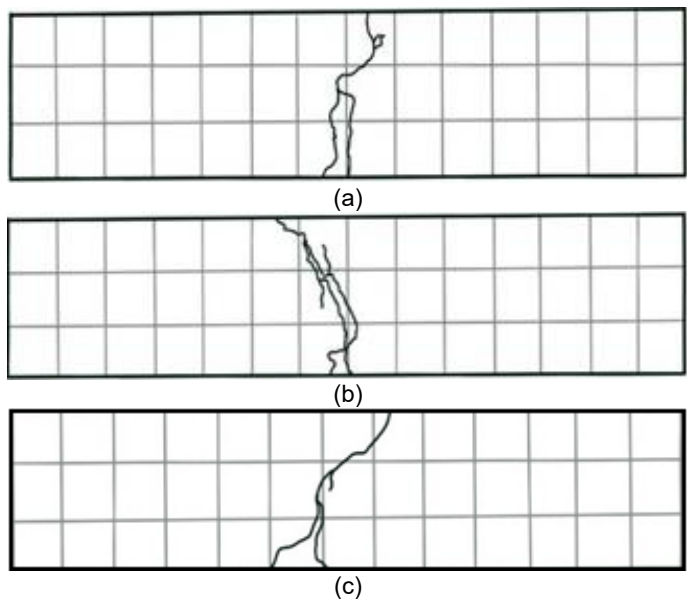


Figure 8. Crack Pattern for All Specimen at Concrete Crushing (a) M0 (b) M10 (c) M20

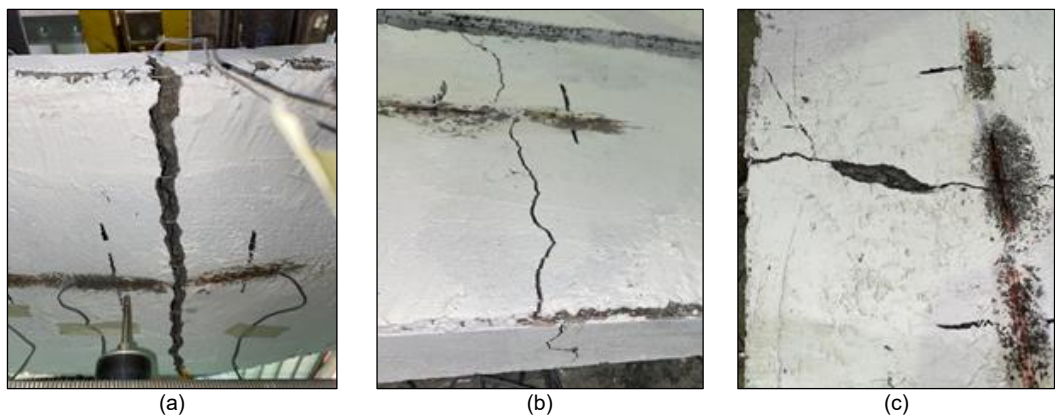


Figure 9. Failure Modes of Slab (a) M0 (b) M10 (c) M20

The initiation of tensile cracking on the soffit of the slab was determined through visual inspection, while the yielding point of the longitudinal reinforcement was identified using tensile strain readings from strain gauges attached to the mid-span reinforcement during testing. All cracks were carefully examined and marked, and Figure 8 illustrates the typical crack patterns observed in the specimens at the point of failure. A comparison between a concrete slab reinforced with BTRM and a non-strengthened or control sample anticipates distinct differences in crack patterns. In the non-strengthened slab, cracks are expected to be more extensive, wider, and less controlled, especially in areas subjected to bending stresses.

Conversely, the BTRM-strengthened slab is expected to exhibit a more controlled and confined crack pattern, particularly in the pure bending segment, where the reinforcement's properties act as effective crack arrestors (Giese, Giese, Dutra & Da Silva Filho, 2021). This expectation is supported by Figure 9, which visually confirms that failure mode and crack patterns in the BTRM-strengthened slab are less extensive, more confined, and follow a more predictable pattern. When subjected to loading conditions, the BTRM-strengthened slab undergoes a failure mode that is notably controlled and localized, in contrast to the potential sudden and catastrophic failure observed in non-strengthened slabs. The crack patterns in the BTRM-strengthened slab exhibit a coordinated response to applied loads, with initial cracks manifesting within the pure bending segment and propagating bilaterally. This controlled response is attributed to the concentration of flexural stress at the BTRM cracks, promoting the development of tensile strength in the concrete slab. A crucial observation is the reduction in the number and severity of cracks, particularly within the critical pure bending region, in comparison to non-strengthened slabs. The textile bamboo fibres in BTRM act as effective crack arrestors, limiting the extent and width of cracks and preventing their uncontrolled propagation. This underscores the effectiveness of BTRM reinforcement in enhancing crack resistance and structural performance, as evidenced by the reduced number and severity of cracks in the critical pure bending region. Additionally, Table 7 provides details on crack characteristics, revealing distinctive responses in crack spacing for the M0 slab compared to others and significantly smaller crack widths in slabs reinforced with BTRM. The study concludes that textile fibres, particularly in M10 and M20 slabs, exert control over crack widths, acting as effective crack arrestors and enhancing the post-crack behaviour of the slab. This reinforcement contributes to maintaining load-carrying capacity and reducing the likelihood of spalling and fragmentation during failure events, ultimately improving the safety of the structure.

Table 7. Number of Cracks and Spacing Results

Slab Specimens	No of Cracks	Spacing Between Cracks (mm)	
		Min	Max
M0	16	30	60
M10	31	10	20
M20	23	12	26

CONCLUSION

This study examined the flexural performance of reinforced concrete slabs retrofitted with bamboo textile-reinforced mortar (BTRM), focusing on the influence of different mesh sizes. Key conclusions are as follows:

- i. Load-deflection analysis revealed three behavioural phases. Slabs M10 and M20 showed enhanced first crack and yield loads compared to the control slab (M0), with M20 achieving the highest ultimate load and deflection due to the contribution of textile reinforcement.
- ii. Stress-strain behaviour demonstrated improved crack control and lower strain in BTRM slabs, particularly M20, which displayed better crack bridging and sustained post-yield strength.
- iii. Ductility increased significantly in slabs strengthened with BTRM. The M20 slab exhibited a ductility index of 3.65, outperforming M10 (2.89) and M0 (2.10). The finer textile mesh in M20 improved bonding and deformation capacity.
- iv. Crack pattern and failure mode observations confirmed that BTRM reinforcement reduced crack width and spacing, resulting in more predictable and less brittle failure. Textile fibres in M10 and M20 acted as crack arrestors, enhancing post-cracking behaviour and structural safety.

In summary, the use of BTRM—especially with optimised mesh size—significantly improved the load-bearing capacity, ductility, and crack resistance of RC slabs. The findings support the viability of BTRM as a sustainable, cost-effective retrofitting solution for enhanced structural performance in flexural elements. This study offers important insights into the flexural performance of RC slabs retrofitted with BTRM using bamboo textile, but its exploratory nature is limited by the use of a single test specimen per configuration. To strengthen the validity and statistical significance of the results, future research should include multiple specimens for each variable configuration and perform statistical analysis of the outcomes. This would provide more robust comparisons, reduce variability, and confirm the trends observed in this preliminary investigation.

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BUILDING INFORMATION MODELLING (BIM): WHAT'S HINDERING SMEs FROM ADOPTING BIM?

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Abstract

Building Information Modelling (BIM) has emerged as an advanced technology in the construction sector, indicating to improve efficiency, cut expenses, and enhance project outcomes. Many benefits could be gained by implementing BIM in construction projects, for instance, visualisation of 3D models, enhancement in collaboration and communication, and systematic and live updated information data, to name a few. Despite its ability and advantages, the adoption of BIM within Small and Medium-sized Enterprises (SMEs) has been rather slow. This review paper explores the barriers that hinder SMEs from adopting BIM in their construction projects. Through an extensive literature review, the barriers could be identified and categorised into organizational, technical, financial, and other related challenges. Every category is analysed in order to understand its impact on BIM adoption. Based on the results, several factors hinder the adoption of BIM in SMEs. This review emphasises the importance of government interventions and initiatives as part of a strategy to overcome the barriers SMEs face. This article seeks to aid academics and industry leaders in crafting a constructive climate for BIM adoption in SMEs by providing a thorough analysis of the barriers and obstacles to BIM adoption in SMEs.

Keywords: *Building Information Modelling (BIM); barriers; BIM adoption; challenges; Small and Medium-sized Enterprises (SME).*

INTRODUCTION

Building Information Modelling (BIM) has been widely known in the architecture, engineering and construction (AEC) sector as a transformative technology with the potential to reduce costs, enhance collaboration, increase efficiency, and optimise decision-making among construction players (Eastman et al., 2008; Abanda et al., 2017). Despite these advantages, the adoption of BIM among Small and Medium-sized Enterprises (SMEs) remains limited (Saka & Chan, 2021). Globally, several countries have introduced BIM mandates to standardise its use across the construction industry. In line with these global initiatives, Malaysia has launched the Public Works Department (JKR) Strategic Plan 2021–2025, targeting 80% BIM implementation by 2025. However, the pace of BIM adoption, particularly among SMEs in Malaysia, has not aligned with this national ambition. This disconnect underscores the importance of identifying the unique challenges faced by SMEs in embracing BIM.

This paper explores the possible factors that hinder SMEs from adopting BIM. By examining past studies and recognising the barriers faced by SMEs, this review paper aims to deliver insights that could help other researchers in formulating effective strategies in order to encourage wider BIM adoption among SMEs, and this is due to the fact that most large organizations are the ones implementing BIM which creates a digital divide. The term digital divide has emerged within the construction industry several years ago. The digital divide is the meaning of separation between large firms and small firms even from the same industry, in this case, the construction industry (Ayinla & Adamu, 2018; van Dijk, 2006).

The significance of this research is centred on the difficulties that are faced by SMEs in the construction industry, mainly in BIM adoption. It is known that SMEs play a huge role in the economy, specifically in the construction sector, where SMEs contribute to innovation, employability and social development (Ismail et al., 2021). However, SMEs face limited resources, in terms of technical and financial. These often hinder their ability to try and adopt new advanced technologies such as BIM. Therefore, it is crucial to understand the challenges that prevent SMEs from adopting BIM so that SMEs too, could leverage the benefits of BIM.

This study has twofold: first, it reviews the current state of BIM adoption among SMEs by looking at previously done research; second, it highlights specific barriers that hinder SMEs from adopting BIM. By synthesising the findings from prior studies, it discusses the reasons why SMEs are not adopting BIM in their projects yet. Ultimately, this research aims to shed light on what could be done in the future to help SMEs adopt BIM.

Overview of Building Information Modelling (BIM)

Building Information Modelling (BIM) is a digital presentation method and platform for information integration and collaboration used widely in the architecture, engineering, and construction (AEC) sector worldwide. BIM is considered a cutting-edge approach to conventional and traditional Computer-Aided Design (CAD), whereas most 2D drawings use CAD for technical drawings and representations (Biswas et al., 2023).

BIM allows stakeholders to share and access centralised data throughout the building life cycle (Shilkina, 2023). Some of the benefits of BIM are that it aids in optimising project management strategies, energy efficiency enhancement, and offers comprehensive design and construction processes within the systems and structures of the buildings. In addition, BIM plays a vital role in improving the efficiency of construction projects. By leveraging the usage of BIM, operational expenses could be minimised, and it also facilitates decision-making based on current data from digitalised models (Liu & Zhang, 2023). The significance of BIM lies in its capability to assist cooperation among various professionals, improve communication, and enhance the overall integration of building designs by merging knowledge and technical processes (Mahran et al., 2022). Succar (2009) indicates BIM as a group of processes, technologies and policies which allows multiple stakeholders to collaborate in designing, constructing and operating. The BIM technology was first introduced in Malaysia in the year 2007 (Enegbuma et al., 2014; Latiffi et al., 2013; Mohammad et al., 2019).

Small Medium-Sized Enterprises

Small and medium-sized enterprises (SMEs) play a crucial role in the worldwide economy and contribute to employment, economic growth, and innovation (Gherghina et al., 2020). Until this moment, there is no fixed definition of SMEs (Omar et al., 2009). However, even though there is no specific definition, most SMEs have similar characteristics. In construction, SMEs range from small family businesses to medium-sized businesses responsible for projects such as commercial, residential and infrastructure developments (Anzagira et al., 2021). Besides that, SMEs could be defined by the size of their employees and the amount of annual revenues (Sidek et al., 2020). Table 1 shows the definition of SMEs

from different countries. The definition of SMEs in Malaysia is based on the total number of full-time employees and annual sales turnover (Hashim & Abdullah, 2000).

Table 1. Definitions of SMEs

Country	SMEs	Size of Employees	Annual Turnover
Australia	98%	<200	-
Canada	98%	<499	<5 million
France	98%	<250	<50 million
Indonesia	98%	<100	-
Italy	98%	<250	-
Malaysia	98.5%	<200	<50 million
The Netherlands	99%	<250	<40 million
Nigeria	96%	<200	<499 million
United Kingdom	98%	<250	-
USA	98%	<500	-

(Source: Saka & Chan, 2020)

Due to the smaller scale of SMEs, there are advantages and disadvantages. Positively, SMEs are more flexible and agile, which allows them to adapt quickly to market changes or project requirements (Giudice et al., 2021). While their small size obviously works in certain situations, there are also difficulties, particularly when it relates to resource acquisition. Financial drawbacks are major challenges for SMEs due to the limitation of resources and funding (Ullah, 2020). In contrast to larger organizations that have the privilege of solid capital and credit, SMEs frequently face constraints which hinder their success and growth (Liu et al., 2022). This financial shortcoming impacts the SMEs' ability to make investments toward new technology advancements, enlarge their operations or commit to big projects (Indrawati, 2020).

BIM Adoption Among SMEs

It is fair enough to say that SMEs are mostly involved in every part of the AEC industry, including procurement, design, on-site production, offsite manufacturing and support services (Rezgui & Zarli, 2006; Zou et al., 2022). However, there are several challenges that SMEs face when it relates to the adoption of technology, as they always lack financial stability and resources compared to larger firms (Abanda et al., 2014; Gamage et al., 2020). This makes it difficult for SMEs to be exposed to new technology such as BIM. Due to these circumstances, most SMEs may have a hard time coping with recent technological advancements. Apart from that, they also may tend to lose opportunities to be more competitive and improve their operations. Before implementing BIM, SMEs may be involved in a few gradual innovations in order to improve their BIM capabilities (Poirier et al., 2015a). Moreover, significant training and effectively cost investment is needed for the implementation and adoption of BIM (Eadie et al., 2013a; Babatunde et al., 2021). Additionally, the application and adoption of BIM are influenced by uncertainties and risks which relate to unclear roles, legal issues, resistance to change and absence of awareness and personnel training (Sun et al., 2017; Khoshfetrat et al., 2022). For these reasons, it is apparent that SMEs must contemplate important decisions before intending to adopt BIM.

Recognising the reasons for the low adoption of BIM within SMEs in the AEC sector needs a comprehensive understanding of the factors that are affecting the decisions towards BIM adoption in AEC organizations (Hong et al., 2016; Abbasnejad et al., 2021). A number of studies have investigated BIM adoption within large organizations ((Davies & Harty, 2013; Nguyen et al., 2004)). However, only a few studies were found to investigate BIM adoption among small firms (Makabate et al., 2022; Saka & Chan, 2021). The size of an organization affects its organizational structure (Parida et al., 2010), leading to significant variations in the challenges of BIM implementation, the perceived benefits of BIM, and the level of motivation related to the organization's decision-making. As a result, little attention is paid to the implementation and adoption of BIM in SMEs despite evidence that SMEs contribute the most to economic growth (Surya et al., 2021; Gherghina et al., 2020). By adopting BIM in projects, several advantages could be gained for SMEs. Based on their role as one of the significant in market share, they could gain potential productivity and this could boost the productivity as a whole (Succar & Kassem, 2015; Vidalakis et al., 2020).

METHODOLOGY

The data and sources were obtained from Scopus, WoS and Google Scholar databases, including journal articles and established conference papers related to BIM adoption and SMEs in the construction sector. The selection of sources was based on the relevancy of the research objective. The sources were assessed carefully, and the main focus is on: Identifying the barriers hindering BIM adoption among SMEs in the construction industry. To maximize the scope of the selection, a systematic approach to keywords was utilised. Keywords such as "BIM adoption," "BIM adoption and SMEs," BIM and SMEs," and other related combinations of keywords were employed in the information-search process. This strategy allows us to focus on the identification of literature dealing with the barriers to BIM adoption in SMEs. The review followed a systematic screening process, where titles and abstracts were first assessed for relevance. Selected articles were then reviewed in full. Data from the studies were coded thematically based on identified barriers. These barriers were categorised under financial, organizational, technical, legal, and environmental themes to facilitate synthesis. Additionally, the scope of the chosen review papers is within a 5-year time frame to ensure that the information and presented data are relevant and current. By reviewing recent literature, this study aims to shed light on the obstacles faced by SMEs in adopting BIM.



Figure 1. Factors Hindering SMEs from BIM Adoption

Table 2. Inclusion and Exclusion Criteria for Literature Selection

Criteria Type	Inclusion Criteria	Exclusion Criteria
Publication Type	Peer-reviewed journal articles and conference papers	Books, theses, editorials, news articles, blog posts
Database Source	Scopus, Web of Science (WoS), Google Scholar	Non-academic databases, unpublished sources
Relevance	Studies focusing on BIM adoption among SMEs in the construction industry	Studies not related to SMEs or BIM, or not focused on the construction sector
Language	English-language publications	Non-English publications
Time Frame	Published within the last 5 years (e.g., 2019–2024)	Studies published before 2019
Focus	Studies that identify barriers or challenges to BIM adoption	Studies focused purely on BIM benefits, technology types, or unrelated frameworks
Access	Full-text available	Abstract-only papers or paywalled inaccessible documents

DISCUSSION

BIM adoption among SMEs presents interrelated challenges. Based on seven main articles that have been reviewed, each study unveils different aspects of difficulties that SMEs face. Makabate et al. (2022) emphasised several main obstacles towards BIM adoption. These comprise high investment costs, limited resources, reluctance to change within companies, lack of expertise, cultural resistance and a shortage of sub-contractors with BIM experience. The financial barriers are particularly acute due to the tighter budgets of SMEs, and this may be the reason why SMEs are hesitant to invest in new technologies without a clear strategy for return on investment (Saah et al., 2023). Furthermore, the internal reluctance to change within the company suggests that there are organizational challenges that need to be addressed (Kindstrom et al., 2024). The financial constraints faced by SMEs are supported by Ismail et al. (2019), who in their study, have confirmed that the cost of investments for technology hardware, BIM software, certifications, and licensing is a burden to SMEs. Besides that, financial investments are necessary for training and employing new staff who have technology experience. The emphasis on concerns related to cost indicates that there is a need for government bodies to offer support in financial and incentives in order to overcome these challenges.

Furthermore, Saka and Chan (2020) expanded the discussion by distinguishing process and people-related barriers; for instance, lack of guidance and implementation strategies, insufficient client demand towards BIM, shortage of experts, lack of awareness among stakeholders and resistance to change are the main reasons for the hindrance of BIM adoption. Their study emphasises the significance of strategic planning and the need for frameworks and comprehensive guidelines for SMEs to ease the BIM adoption process. In addition, the lack of client demand towards BIM also gives a clear vision that some market forces are not really supportive of BIM adoption, and this may discourage SMEs from adopting new technology.

A recent study by Sarvari et al. (2024) classifies four main areas of barriers for SMEs to adopt BIM; namely technology, legal, management and financial. Technological barriers, such as the complexity of BIM tools and software integration issues, are the main obstacles. Legal barriers, such as regulatory compliance and contractual issues, may require clear guidelines. On the other hand, the management and financial barriers show that strategic

financial support from the government is required. A study by Hall et al. (2023) identifies evidence of challenges by highlighting technological, resource and cultural-related barriers and governmental issues. Some of the main factors for reluctance are the lack of compatibility of the software used, the high initial cost of hardware due to the need for high-end technology devices, the licensing process and the lack of client demand for BIM projects. The findings suggest that the government should intervene to support and encourage the adoption of BIM by SMEs. In addition, the implementation of policies and mandates on BIM usage could encourage SMEs to adopt BIM.

Table 3. Key Findings of SMEs Barrier in BIM Adoption

Source	Key Findings
Li et al. (2019)	Critical barriers include a lack of legal environment, BIM perception and software standards.
Ismail et al. (2019)	The main challenge is related to cost issues, which include the cost of investment in technology hardware and software, certification, and licencing requirements. In addition, training and employing new staff with technology experience also requires high investments.
Saka & Chan (2020)	The most severe challenges are process/people-related barriers, a lack of implementation strategies and guides, a lack of BIM demands from clients, a shortage of experts, a lack of awareness of stakeholders, and resistance to change.
Murphy et al (2022)	Company buy-in, lack of education and resources are reasons why SMEs resist BIM
Makabate et al. (2022)	The primary challenge for SMEs in adopting BIM is the high cost of investment, as they doubt, they will gain their return on investment (ROI). Other challenges include limited resources, change reluctance in the company, lack of expertise, cultural resistance, and a lack of subcontractors with BIM experience.
Hall et al. (2023)	This paper reveals 4 main obstacles: technological, governmental, resource and cultural.
Sarvari et al. (2024)	Reveals that the barriers holding back BIM adoption are management's hesitance to adopt BIM, reluctance to change by stakeholders and lack of technicality understanding towards BIM. Identified four categories of barriers: technology, legal, management, and financial.

Due to the identified barriers, a practical roadmap is suggested for SMEs as a guide to adopt BIM. This roadmap consists of three stages; short term action that focuses on awareness, BIM training from technology vendors and financial subsidies and incentives. Mid-term stage could include having partnership with organizations that has opted BIM and for long term action, it should aim at integrating BIM technology into SMEs projects and aligning them with the national BIM standard. By following these stages, SMEs could move forward and support the national goals for digital transformation in the construction industry.

LIMITATION

This study is based entirely on secondary data collected from existing literature, without the inclusion of primary data such as interviews or surveys. As a result, the findings rely on the interpretations and scope of previous studies, which may vary in context and methodology.

CONCLUSION

This review focuses on identifying barriers that hinder SMEs from adopting BIM by reviewing previous studies. An extensive review of selected papers indicates that several multifaceted challenges restrict SMEs from engaging BIM in their organization. One of the

most frequent barriers is financial-related factors, such as high implementation and upfront cost, which indicate new hardware and software installation, licensing, and certification. In addition to cost-related hurdles, organizational challenges such as unskilled personnel, change resistance, and limited management commitment also affect the integration of BIM in SME workflows. Low awareness of BIM benefits also contributes to the slow pace of adoption. Technological issues like software compatibility and the perceived complexity of BIM add to the reluctance, especially among firms that lack technical support. The lack of support by the government is one reason for the slow adoption of BIM among SMEs. To conclude, overcoming these challenges requires a roadmap and a comprehensive strategic approach. Support towards financial investments, strategic planning, extensive training and programmes are essential. By addressing these issues and challenges holistically, SMEs may have the opportunity to leverage the advantages of BIM usage and, at the same time, enhance their efficiency, productivity and competitiveness in the construction industry.

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CONSTRUCTION QUANTIFICATION PROBLEM-SOLVING SKILLS ENHANCEMENT: STUDENTS' PERSPECTIVES ON TECHNICAL COMPETENCY-BASED EDUCATION (CBE)

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Abstract

Problem-solving skills are crucial for the professional development of individuals, particularly within Competency-Based Education (CBE) for construction professionals. The application of CBE in construction quantification has emerged as an effective instructional approach to improve learning outcomes. In Quantity Surveying (QS) CBE training, it is essential to identify effective methods that enhance students' problem-solving abilities in construction quantification to meet industry expectations. This study adopts a qualitative methodology to explore students' perspectives on the issues, challenges, and critical success factors in implementing CBE in construction quantification. A total of 83 participants were selected from accredited QS diploma programmes at Malaysian public higher education institutions, as listed by the Board of Quantity Surveyors Malaysia (BQSM). The findings reveal key challenges such as difficulties in interpreting drawings, limited understanding of construction elements, weak visualisation skills, and the underutilisation of construction technology knowledge. Additionally, students emphasised the importance of practical and interactive teaching methods. These insights are vital for improving the implementation of CBE in QS education within Malaysian higher learning institutions. The results underscore the importance of understanding students' learning experiences to address competency gaps and support the advancement of QS CBE programmes. The outcomes offer valuable guidance for educators, policymakers, and stakeholders in shaping the future of CBE in construction quantification.

Keywords: *Competency-Based Education (CBE); Construction Quantification; Cognitive Challenges; Instructional Challenges; Adaptive Instructional Methods*

INTRODUCTION

Quantity Surveying (QS) is a professional discipline that demands precision and accuracy, particularly in cost estimation (Ali, Mustaffa, Keat & Enebuma, 2016; Fortune & Skitmore, 1994). Malaysian public higher education institutions offer diploma and degree programmes in QS, producing both sub-professional and professional graduates who are expected to manage and control the financial aspects of construction projects (Perera, Babatunde, Pearson & Ekundayo, 2017; Yogeshwaran, Perera & Ariyachandra, 2018). Although a significant number of students graduate from QS programmes each year, concerns remain about their competency and readiness to meet industry expectations (Ainsworth, 2006; Chong, Lee & Lim, 2012; Malik & Venkatraman, 2017; Perera et al., 2017; Zakaria, Munaaim & Khan, 2006). The Construction 4.0 Strategic Plan 2021–2025 identifies that the Malaysian construction workforce continues to be dominated by low-skilled occupations and stresses the importance of developing technically capable graduates who are well-prepared for professional roles (Construction Industry Development Board Malaysia, 2020). While practical skills can be gradually developed through industrial training and on-site experience

(Mu, 2010), employers increasingly seek graduates who are work-ready and able to perform competently upon entering employment (Perera, Pearson & Dodds, 2010; Zoysa, Nadeetharu & Kulatunga, 2024). Consequently, Malaysian public higher education institutions play a critical role in producing graduates who are competent, adaptable, and prepared to address the multifaceted challenges of the construction sector. Efforts to improve student outcomes and align academic training with professional demands have intensified (Economic Planning Unit, 2021; Ministry of Education Malaysia, 2024).

The development of Competency-Based Education (CBE) framework and instructional benchmarking tools, designed collaboratively with industry stakeholders, offers a strategic means of addressing these gaps in graduate preparedness (Liu, Chen & Zhang, 2025). At the same time, it is essential to consider students' experiences with instructional methods, particularly in courses that demand advanced technical and cognitive skills such as construction quantification. Instructional design models highlight the importance of aligning teaching strategies with students' abilities, learning demands, and developmental needs (Baturay, 2008; Hamzah, Abdullah & Ma, 2024). This highlights the need to evaluate whether traditional methods are adequate for fostering the problem-solving competencies required in technical disciplines.

In response to these concerns, this study aims to explore students' perspectives on the implementation of CBE in the construction quantification course. Specifically, it investigates the challenges students encounter in acquiring quantification skills, identifies effective instructional strategies that support problem-solving, and examines the extent to which their learning experiences align with industry-defined competency standards.

LITERATURE REVIEW

The risk of academic underperformance and limited technical proficiency remains a significant concern in technical education. Practical instructional support is essential to foster academic success, particularly in skill-intensive environments like construction education (Gao & Mohamad, 2024; Liu et al., 2025). However, diverse learning styles often conflict with traditional, one-size-fits-all pedagogies, making it difficult to ensure effective knowledge transfer (Chasokela, 2025; Hamzah et al., 2024). In the context of ongoing skills gaps and workforce shortages (Construction Industry Development Board Malaysia, 2020), there is a clear need for instructional reforms that align academic outcomes with industry standards. This study responds to these challenges by investigating QS students' experiences with problem-solving in construction quantification within a CBE framework.

Challenges in Developing Construction Quantification Competencies

Construction quantification remains a cornerstone of QS education and practice (Abdul Aziz, 2003; Rashid, 2002). Achieving proficiency in this area is essential for ensuring that graduates possess the technical and managerial competencies required by the profession (Nkado, 2000a; Nkado, 2000b; Noor, Tobi & Salim, 2020). Despite the established recognition of its importance, a substantial number of graduates continue to fall short of the skill levels demanded by employers (Chong et al., 2012). A major contributor to the skills gap in construction quantification is students' difficulty in interpreting technical drawings and visualising construction elements. Studies highlight two-dimensional (2D) and three-

dimensional (3D) visualisation as persistent challenges in this area (Hodgson, Sher & Mak, 2008; Osman, Mazlina, Khuzzan & Razaksapian, 2015). These skills are essential for understanding complex drawings and the interaction of building components. Aligned with these challenges, a strong foundation in construction technology further supports visualisation and quantification accuracy (Yogeshwaran et al., 2018; Perera et al., 2010; Royal Institution of Chartered Surveyors, 2022). Despite its recognised instructional value, the integration of construction technology into quantification courses remains inconsistent and insufficiently developed. The lack of instructional coherence makes it difficult for students to connect theoretical knowledge with practical application, leading to persistent cognitive challenges in solving quantification tasks. More importantly, construction technology and quantification are often taught as separate subjects, which limits opportunities for integrated and context-based learning. This fragmented approach creates a significant barrier to preparing students for the demands of modern professional practice. Studies have shown that incorporating construction technology into quantification instruction, especially through interactive tools and digital simulations, can substantially improve students' problem-solving abilities (Ali et al., 2016; Chasokela, 2025). This study therefore investigates how such integration can improve competency development and better align learning outcomes with professional standards.

Aligning CBE with Technical Demands in QS

Unlike traditional knowledge-based training, QS programmes are structured within a technical CBE framework that prioritises measurable learning outcomes and skill mastery (Ekundayo, 2020; Foster & Jones, 2020). This approach aims to produce graduates equipped with the technical skills and problem-solving abilities required by the construction industry (Chandramohan, Perera & Dewagoda, 2020). However, despite this intended emphasis on practical competency, recent research indicates persistent implementation inconsistencies. These shortcomings have contributed to a disconnect between students' academic achievements and their readiness for industry demands (Liu et al., 2025; Victar, Perera, Palihakkara & Dewagoda, 2024). Employers continue to express concerns regarding graduates' technical estimation capabilities, which are critical for effective construction project development. Several studies have highlighted industry dissatisfaction, particularly with the proficiency of some CBE graduates in core areas such as construction quantification (Guo, Gonzalez, Puolitaival, Enebuma & Zou, 2023; Oladotun & Edosa, 2016; Perera et al., 2017). These ongoing misalignments between educational outcomes and professional expectations indicate the need for more responsive, integrated, and adaptive competency-based learning models. Although recent advancements in competency assessment and digital learning technologies offer potential solutions to these challenges (Hamzah et al., 2024; Jamil, Idris, Zalli, Rakami & Putra, 2024; Liu et al., 2025), their adoption within QS education remains limited.

Adaptive Instructional Strategies within The CBE Framework

Learning theories and instructional models significantly influence knowledge acquisition, processing, and retention, yet their practical application in technical education remains inconsistent (Simandan, 2013; Wasserman, Wasserman, Wasserman & Wasserman, 2016). Teaching theory provides an important framework to support the relationship between instructional practices and learning outcomes (Chaudhary, 2013). However, the increasing

diversity of student characteristics and learning abilities presents substantial challenges for traditional teaching methods (Hamzah et al., 2024). The failure to accommodate varied learning styles often leads to educational experiences that do not translate into industry-ready competencies (Ainsworth, 2006; Malik & Venkatraman, 2017; Zakaria et al., 2006; Ziemkiewicz et al., 2012). Misalignments between academic training and industry expectations suggest the need for an instructional shift towards more adaptable and interactive learning environments (Liu et al., 2025). Digital platforms, interactive simulations, and adaptive learning technologies have been shown to significantly enhance student engagement and conceptual understanding in technical education settings (Chasokela, 2025; Hamzah et al., 2024; Naji, Gunduz, Alhenzab, Al-Hababi & Al-Qahtani, 2024). Yet, their integration within construction quantification education remains limited. By prioritising adaptive learning systems, educators could more effectively accommodate diverse learning needs and promote deeper technical skill acquisition (Jamil et al., 2024).

This paper aims to investigate how adaptive instructional strategies, when aligned with CBE framework, can better prepare students for industry expectations, thereby addressing existing shortcomings in QS education.

Instructional Strategies for Spatial Visualisation in QS Education

Considering the cognitive difficulties students encounter in interpreting technical drawings and visualising construction elements, spatial visualisation is consistently regarded as a fundamental competency in construction quantification education. Effective problem-solving in this area requires students to mentally manipulate spatial relationships and extract meaningful information from technical drawings (Fortune & Skitmore, 1994; Fung, 2015; Kymmel, 2008). However, the development of spatial visualisation skills is often underemphasised in traditional instruction. Olkun (2003) argues that targeted instructional strategies are essential for fostering 3D thinking. Emerging evidence suggests that the use of virtual reality, interactive visualisation and simulation tools can significantly enhance students' spatial reasoning and technical comprehension (Chasokela, 2025). Therefore, investigates how spatial visualisation competencies impact students' learning experiences and performance in construction quantification. Insights from QS diploma students provide a deeper understanding of the challenges they encounter and highlight the potential of adaptive instructional strategies to foster their professional development.

METHODOLOGY

This study employed a qualitative approach using semi-structured interviews to explore the challenges faced by students in developing construction quantification problem-solving skills and to identify instructional strategies aligned with the principles of CBE. A total of 83 diploma students enrolled in sub-professional QS programmes at public higher education institutions in Malaysia were selected through purposive sampling. All participants met the minimum academic entry requirements established by these institutions, ensuring a consistent academic background. Selection was based on students' willingness to engage in face-to-face interviews, where responses were captured both verbally and in writing, with guided support when necessary (Taylor & Bogdan, 1984). The purposive inclusion criteria ensured the selection of participants who were most relevant to the study's objectives (Rozmi, 2012). Although the sample size was limited, the purposeful selection enhanced the relevance of the

data, and the qualitative approach enabled the collection of in-depth insights into the instructional and professional challenges faced by students (Creswell, 2014).

To ensure alignment with the study's aims, interview questions were developed from a comprehensive review of literature concerning construction quantification competencies, challenges in technical education and instructional approaches within competency-based frameworks. The questions aimed to capture students' experiences in interpreting technical drawings, performing quantification tasks, and identifying instructional needs. Participants were also encouraged to propose teaching strategies and reflect on competencies they considered essential for their professional development. The interview protocol was reviewed by a panel of academic experts to ensure clarity and relevance. Interviews were conducted in either Malay or English, depending on the participants' preference, to encourage open and accurate expression of their views. Allowing the use of the preferred language enhanced the depth and authenticity of the responses, facilitating a more comprehensive understanding of the students' learning experiences (Silverman, 2007; Schensul, Schensul & LeCompte, 1999).

Data were analysed using inductive content analysis to uncover meaningful insights aligned with the study's objectives. Interview transcripts were read repeatedly to ensure familiarity with the data, from which codes were developed based on recurring patterns. These codes were then organised into categories and refined into core themes and sub-themes (Mohd Tobi, 2017). For instance, difficulties in interpreting drawings and the lack of visual support were categorised under spatial visualisation challenges. This analysis formed the basis for identifying instructional gaps and strategies to enhance technical competency in construction quantification. Credibility was strengthened through the development of a literature-based interview protocol, purposeful participant selection, and rigorous data analysis. While the focus on Malaysian public higher education institutions may limit the transferability of the findings, the study offers valuable insights into the instructional and cognitive challenges in technical education. The methodological approach was guided by established qualitative research principles outlined by Creswell (2014) and Patton (2015).

RESULTS AND DISCUSSION

The analysis identified three core themes that are significant to enhancing construction education within a CBE framework. Table 1 presents a summary of these themes, which form the foundation for the subsequent discussion.

Table 1. Summary of Core Themes and Sub-Themes from Thematic Analysis

Core Theme	Sub-Theme	Sample Code / Interpretation
Learning Difficulties	Cognitive Challenges	Internal learning difficulties such as poor spatial visualisation, difficulty in interpreting technical drawings, and limited mental translation from 2D to 3D.
Learning Process	Instructional Challenges: Shortcomings	Teaching-related problems like limited visual support, weak integration of content into the instruction, and the continued use of outdated or non-contextual materials.
Learning Strategies	Instructional Methods: Intervention, Integration & Innovation	Adaptive approaches (solutions) including 3D visual tools, simulation-based learning, real-life project, technology-enhance instruction and student-centred approaches.

(Source: Developed for this study)

As outlined in Table 1, the themes of learning difficulties, learning process, and learning strategies offer a structured basis for interpreting students' learning experiences. These themes are further detailed through sub-themes that capture cognitive challenges, instructional shortcomings, and instructional methods. The findings underscore the importance of spatial visualisation and technical competency in shaping students' engagement with construction quantification.

Learning Difficulties in Construction Quantification: Cognitive Challenges

The findings reveal that many students experience difficulty in construction quantification due to poor visual-spatial ability and limited capacity to interpret 2D technical drawings. These cognitive challenges hinder their understanding of construction components and compromise their accuracy in quantifying elements, despite familiarity with procedures or formulas. The qualitative data consistently highlighted these concerns, indicating strong thematic saturation and reinforcing the credibility and relevance of cognitive challenges as a dominant internal learning issue.

Students frequently reported difficulty forming mental images from drawings, which affected their confidence and performance. For instance, R5 found it difficult to visualise side and ground beams, while R12 mentioned challenges interpreting drawings due to low spatial ability. R3 noted that complex roof elements were hard to measure, and R14 struggled with quantifying reinforcement for staircases and WBLFF frames. R1 stressed that construction quantification demands high levels of imagination, posing particular difficulty for those with limited visual reasoning abilities. These experiences align with established literature, which recognises spatial visualisation as essential in technical disciplines (Elliot & Smith, 1983; Hsi, Linn & Bell, 1997; Miller & Bertoline, 1991; Sorby & Baartmans, 2000). Furthermore, R10 reported confusion when visualising beam-to-column connections, while R26 had difficulty distinguishing between beams and lintels in 2D views. R45 noted that interpreting roof truss structures was nearly impossible without visual aids. These findings correspond with previous research identifying visual reasoning as key to understanding spatial relationships (Hodgson et al., 2008) and linking visualisation to improved accuracy in problem-solving (McDonnell, 2010). These concerns further emphasise the importance of structured interventions aimed at developing spatial skills in technical education (Sorby & Baartmans, 2000).

Students also expressed challenges navigating complex technical drawings. R9 found it difficult to visualise different sides of a structure, and R21 explained that interpreting sectional views was time-consuming due to limited prior experience. R68 struggled with understanding unlabelled partitions, while R30 had difficulty imagining curved components. R24 and R38 highlighted how low confidence in interpreting drawings led to frequent errors and missed elements. R53 added that limited imagination impeded understanding of how structural components fit together. These difficulties reflect not only individual limitations but also instructional weaknesses in teaching design, where traditional approaches often emphasise procedural knowledge over visual reasoning. This was confirmed by R6 and R34, who struggled to mentally reconstruct real-world structures from flat drawings, and by R15, who encountered difficulty quantifying multi-directional staircases.

These findings highlight the need for instructional reform and policy enhancement to address visual-spatial challenges. Visual reasoning should be systematically integrated into instructional design, with adaptive strategies such as drawing-based tasks, digital modelling, and progressive visualisation proven to improve spatial abilities (Chasokela, 2025; Guo et al., 2023; Hamzah et al., 2024). Sorby (2009) emphasised the value of incremental visual training, while recent studies support the use of competency-based assessments and adaptive digital tools in technical education (Jamil et al., 2024; Liu et al., 2025). Policy frameworks should prioritise visual learning outcomes and performance-based assessments to better align education with industry needs. Investment in digital tools and collaboration with industry stakeholders can help ensure graduates are well-prepared for real-world quantification tasks. In summary, enhancing visualisation training through structured, responsive instructional practices is critical for improving student performance and professional competency in QS.

Learning Processes within CBE Framework: Instructional Shortcomings

Within the CBE framework, structured instructional practices are designed to promote performance-based learning through contextual, active, and student-centred approaches. However, the findings reveal that lecture-based delivery remains dominant in construction quantification education. Students commonly described the learning environment as passive and overly theoretical, with limited emphasis on hands-on engagement or real-world application. This contradicts the core aims of CBE, which emphasise skill development through experiential learning and measurable outcomes (Guo et al., 2023). A recurring concern among students was the lack of instructional clarity and support in developing drawing comprehension and spatial visualisation.

R58 noted that lectures often failed to clearly explain structural elements, while R19 reported difficulty visualising construction details despite attending construction technology classes. R23 and R28 further emphasised the limited focus on spatial visualisation, which affected their accuracy in quantity take-off tasks. These challenges reflect the cognitive demands involved in quantification and support earlier findings (Sorby & Baartmans, 2000; Hsi et al., 1997), who highlighted the importance of spatial visualisation for mentally transforming 2D drawings into accurate 3D understanding. Although construction technology is included in the syllabus, its integration with construction quantification instruction appears insufficient. R43 and R50 stated that the subject offered minimal support in developing quantification skills. R61 noted that certain lecturers presumed students possessed prior knowledge of technical drawings, which placed those without such background at a disadvantage. R13 and R62 criticised the rapid speed of lessons and the reliance on formulas without adequate visual explanation. R49 and R51 added that instructional materials lacked clarity, making it difficult to interpret construction details. These findings are consistent with previous research that emphasises the need for scaffolded visual reasoning to develop spatial and conceptual understanding (Hamzah et al., 2024; Chasokela, 2025). Students also expressed concerns over the lack of contextualised practice exercises aligned with real-world quantification tasks. R46 and R66 highlighted inconsistencies in drawing types and the absence of industry-relevant practice. R41 and R66 noted that the continued reliance on textbook-based 2D drawings, rather than actual project documentation, reduced the instructional value of lessons. R27 further observed that limited exposure to applied learning activities reduced engagement and hindered skill development.

These views are supported by studies that advocate embedding industry-relevant resources and visual reasoning into instructional design (Hamzah et al., 2024; Jamil et al., 2024; Liu et al., 2025). To address these instructional shortcomings, educators should adopt competency-based methods that incorporate digital visual tools and real-world project documentation. Continuous professional development is also necessary to enhance instructors' ability to implement such tools effectively. For policymakers, reform efforts should prioritise performance-based assessments, digital readiness, and alignment with industry standards to ensure students acquire the technical competencies required for professional practice.

In summary, the findings highlight persistent instructional weaknesses in construction quantification education under the CBE framework. These include insufficient visual support, weak integration of construction technology, and reliance on outdated or non-contextualised materials. Incorporating visual reasoning and contextual learning into instructional strategies, along with structured spatial training and conceptual development, is essential to strengthen technical competence and better prepare students for professional application (Chasokela, 2025; Guo et al., 2023).

Adaptive Instructional Methods for Construction Quantification Challenges

Traditional teaching and training methods often fail to bridge the gap between academic instruction and industry practice, resulting in graduates who are theoretically proficient but underprepared for real-world application. As previously discussed, students reported a lack of clarity, limited visual support, and minimal practical engagement in their learning process, particularly in understanding construction drawings and applying quantification techniques. While cognitive challenges limited students' initial understanding, the teaching strategies explored under the learning process theme revealed that these difficulties were further deepened by shortcomings in instructional delivery. This highlights the need for targeted strategies that not only address cognitive limitations but also foster the development of practical skills aligned with real-world demands. In response to these limitations, students shared insights into instructional practices that could support problem-solving development in construction quantification. The key theme that emerged is the importance of purposeful instructional design that addresses both cognitive and practical learning needs. This theme is examined through three interconnected sub-themes, namely instructional interventions for digital and active learning, integration of digital and traditional learning methods, and innovation in instructional approaches. Together, these sub-themes reflect a progressive instructional cycle that begins with structured support, moves toward integrated learning, and evolves into innovative teaching practices.

Digital and Active Learning Methods: Instructional Interventions

One of the key instructional interventions identified by students was targeted support from educators, which addressed persistent learning challenges and enhanced engagement through the use of visual tools. Students articulated clear expectations regarding the educator's role, emphasising the importance of facilitating comprehension rather than delivering content passively. They expected lecturers to incorporate digital technologies such as 3D visualisation tools into the teaching process and to demonstrate their relevance to both academic content and professional practice. This emphasis reflects a broader instructional shift toward student-

centred learning, where educators guide and adapt instruction based on individual learner needs (Zheng, Leow, Veerappan, & Koh, 2020).

Students consistently called for structured guidance using annotated drawings and simplified visual sequences. For example, R35 highlighted the value of hands-on instruction with digital drawings, while R55 and R57 emphasised the need for clear annotations and brief quizzes to support drawing interpretation. These responses suggest that digital visualisation is viewed as an essential instructional tool, particularly for cognitively demanding tasks such as interpreting drawings and performing quantity take-off. R50 noted that digital applications could enhance understanding of construction forms, while R3 stated that early exposure to 3D tools would improve technical accuracy. Similarly, R53 recommended introducing 3D content early in the course structure to reinforce conceptual foundations. Many students also stressed the importance of a structured instructional sequence that begins with 2D drawings and progresses to 3D tasks. R12 explained that moving from sketches to 3D renderings improved spatial awareness, and R20 supported sequencing drawing exercises according to students' cognitive development. These insights align with experiential learning principles, particularly when students actively apply theoretical knowledge to practical tasks. R43 expressed the need for clearer demonstrations and step-by-step explanations in drawing interpretation. Similarly, R6, R8, and R17 reported that digital sketches significantly enhanced their understanding and ability to apply design concepts in quantification tasks. These practices reinforce the value of guided visual instruction in developing cognitive engagement and problem-solving skills. This aligns with Sorby and Baartmans (2000), who emphasised structured spatial training as essential in visually intensive technical programmes. In this regard, remedial sessions that include progressive visual explanations, as suggested by R12, can be particularly effective for students with weaker spatial or technical backgrounds. By incorporating responsive visual and digital instruction, educators can address fundamental gaps that often hinder learning in construction quantification.

Experiential learning further emerged as a critical instructional intervention, particularly through exposure to real-world environments. Students described site visits and project case studies as instrumental in linking classroom learning with industry practice. R6 and R34 cited the role of site visits in providing context, while R76 observed that real-life project examples improved the relevance of theoretical content. These activities fostered greater engagement and supported the development of critical thinking, practical problem-solving, and industry readiness. Such findings align with earlier research that supports integrating real-world learning contexts and digital competencies to meet professional expectations in the built environment sector (Nkado, 2000a; Nkado, 2000b; Perera et al., 2010). This approach is consistent with Kolb's Experiential Learning Cycle, particularly through active experimentation, where students apply theoretical concepts in real contexts and reflect on the outcomes (Kolb, 1984). When combined with structured digital instruction and guided facilitation, experiential learning plays a vital role in addressing both instructional and cognitive challenges in technical education.

These findings emphasise the need for educators to adopt responsive and student-centred approaches that prioritise clear guidance, timely feedback, and adaptive support mechanisms. Incorporating experiential and active learning practices, such as visual-based remediation and site-based applications, can significantly enhance student competencies in construction quantification. For policymakers, the study highlights the importance of institutional

strategies that support instructional training, encourage blended learning environments, and promote continuous improvement of teaching methods aligned with technical competency development. These measures are essential for ensuring that educational interventions are both effective and sustainable in addressing persistent learning challenges in QS and other technical disciplines.

Digital and Traditional Learning Methods: Instructional Integration

The integration of digital and traditional learning methods enhances instructional practices in construction quantification. This blended approach, which combines manual drawing exercises with digital tools such as AutoCAD, SketchUp, and Revit, provides students with a cohesive and supportive learning environment. Through this integration, students are better able to translate theoretical knowledge into practical application and develop essential technical competencies.

Student responses further highlighted the instructional value of combining traditional and digital methods to improve comprehension, particularly in technically demanding content. R9 and R18 noted that construction elements became more understandable when 3D representations were used alongside manual drawings, aiding their ability to interpret complex structures. Rather than viewing digital tools as replacements for manual techniques, students saw them as complementary aids that enhanced the learning process. This preference for dual-modality instruction aligns with the perspectives of Slavin (2003) and Parsons et al. (2001), who emphasised the benefits of aligning instructional strategies with learners' cognitive preferences to improve academic achievement.

In addition to the combination of digital and traditional tools, students also highlighted the significant role of subject integration, particularly between construction technology and construction quantification. R25 found construction technology very helpful, while R42 and R57 noted its support in understanding technical drawings and construction quantification tasks. R47 explained that construction technology deepened their grasp of construction elements by clarifying both their functions and classifications. R83 and R78 recognised the subject's relevance, with R78 emphasising its connection to painting work within construction quantification tasks. Similarly, R37 and R20 acknowledged that construction technology enhanced their understanding of components and elements relevant to construction quantification. While R72 found the subject only somewhat helpful, the overall consensus affirms that construction technology plays a crucial role in providing foundational knowledge necessary for accurate quantification. These insights reinforce the importance of construction technology as a complementary subject in developing technical competence. However, the findings also reveal instructional shortcomings in the delivery of construction technology and quantification content, which appear to limit student performance and hinder the development of technical fluency. The absence of synergistic integration between these core subject's points to a structural weakness in instructional design. Students' perspectives clearly indicate the need for a more coherent and aligned instructional framework that ensures consistent reinforcement of key concepts across related modules. The integration of construction technology with construction quantification is essential to improving both conceptual understanding and the application of technical knowledge in QS education.

Instructional integration and technical reinforcement are necessary to strengthen learning outcomes (Ogunkola & Knight, 2018). Emphasising a unified instructional approach that connects construction quantification with related technical modules supports both conceptual clarity and practical application. These findings align with the observations of previous studies, which highlighted the need for a CBE framework that embeds relevant learning resources, visual reasoning strategies, and conceptual development to enhance teaching effectiveness (Hamzah et al., 2024; Jamil et al., 2024; Liu et al., 2025). Similarly, Chasokela (2025) emphasised the importance of embedding spatial and conceptual skills through structured instructional strategies. Professional competency standards further reinforce this need. In the context of QS, most professional bodies categorise required competencies into three main areas mandatory, core, and optional. These categories are structured to ensure that graduates are adequately prepared to practise as competent professionals while maintaining high standards of practice. These competencies also serve as benchmarks for the technical and managerial capabilities expected within the construction industry and provide a basis for developing robust competency models (Noor et al., 2020). By exploring students' perspectives on these educational and professional issues, this study establishes a clear framework for professional development to address the disconnect between theoretical competency frameworks and the practical skills necessary for effective performance in the field. In particular, the Royal Institution of Chartered Surveyors (2022) underlined the importance of technical proficiency in areas such as construction technology and quantification as essential for global employability and accreditation, reflecting the growing need for these skills to be strongly embedded in curriculum design.

These findings present valuable insights for both educators and policymakers in advancing instructional practices. For educators, integrating digital visualisation tools with traditional methods enhances student understanding, particularly in complex tasks such as construction quantification and drawing interpretation. Aligning content between construction technology and construction quantification strengthens conceptual clarity and supports applied learning. These elements should be viewed as integral to instructional practices rather than as supplementary features. Continuous professional development is essential to ensure educators are equipped to implement these strategies effectively. For policymakers, the findings emphasise the need for instructional reform that promotes digital readiness and the effective adoption of the CBE framework. Technical education in the built environment should be guided by systematic instructional design and learning strategies that reflect current industry needs. As noted by Perera et al. (2010) and Zakaria et al. (2006), targeted investment in educational technology, instructional alignment, and faculty development is critical to ensuring learning outcomes meet professional standards.

Innovations in Instructional Approaches

While integration focuses on combining traditional and digital learning methods to create a consistent learning environment, innovation enhances instructional effectiveness by adopting emerging technologies and updated teaching approaches. Innovation addresses persistent cognitive and visualisation challenges by reforming how technical content is delivered and understood. Adaptive instructional strategies involve the use of virtual reality simulations to explore building components, the incorporation of augmented reality to visualise construction details in context, and the development of 3D application-based

modules to strengthen spatial reasoning and construction quantification accuracy. Technological advancement is recognised as a crucial element in this innovation.

Students in this study consistently highlighted the value of visual and interactive tools, not only as supplementary aids but as essential components of a more effective instructional framework. Virtual reality, for example, was frequently mentioned by both students and scholars as a powerful tool in construction quantification. R19 proposed using physical models to make abstract concepts more visible, while R80 suggested using a 3D animation system as an effective training tool, especially beneficial for those involved in construction-related applications. R83 emphasised the importance of high-impact instructional tools such as construction simulation software, which can offer immediate, animated visual experiences to support deeper learning. Additionally, R50 recommended augmented reality tools to simplify the understanding of complex construction elements, while R34 recognised the usefulness of 3D animation in demonstrating the construction process.

Positive student feedback on adaptive instructional strategies in construction quantification supports the idea that these tools help bridge theoretical learning with practical understanding. Consistent with these findings, prior research highlights the value of digital innovation in addressing cognitive and visualisation challenges within technical education (Ali et al., 2016; Hamzah et al., 2024). Korkut and Surer (2023) demonstrated that virtual reality allows students to visualise and manipulate engineering designs in ways that traditional 2D representations cannot. Chasokela (2025) found that this immersive approach strengthens spatial awareness and problem-solving skills by simulating real-world conditions. Similarly, Jamil et al. (2024) and Liu et al. (2025) supported the concept that innovative instructional methods contribute to higher-order learning, engagement, and knowledge retention. Overall, the findings indicate that the application of digital innovation tools, particularly virtual reality, represents a significant advancement in instructional practices within the CBE framework. These tools enhance students' visualisation and quantification skills while fostering adaptable learning environments, better preparing graduates to meet the evolving demands of the construction industry.

CONCLUSION

This study explored QS students' experiences in developing construction quantification skills within a CBE framework, focusing on learning difficulties, learning processes, and instructional strategies. The findings reveal that many students struggle to interpret technical drawings and mentally convert 2D representations into 3D forms. These difficulties highlight not only individual cognitive challenges but also broader limitations in instructional design and delivery. As such, there is a critical need for teaching approaches that actively develop visual reasoning and spatial awareness, extending beyond the passive transmission of technical content. The analysis also indicates that students benefit most from structured learning environments that incorporate experiential activities, problem-based learning, and progressively supported instruction. Students exposed to such strategies reported increased confidence and improved accuracy in handling complex quantification tasks.

The results affirm that successful implementation of CBE in QS depends on teaching practices that simultaneously deliver technical content and build the cognitive capacities required for real-world problem-solving. These insights reinforce calls for instructional

reform that embraces visual learning tools, digital technologies, and contemporary instructional strategies aligned with industry standards. Additionally, the findings demonstrate strong student agreement with the identified sub-themes on learning difficulties, learning processes, and adaptive instructional strategies. The theme of learning strategies emphasises how intervention, integration, and innovation collectively enhance construction quantification learning. This consistency across responses indicates a high degree of thematic saturation and strengthens the credibility of the data, suggesting that the challenges and proposed solutions are broadly experienced by the student cohort.

By providing qualitative evidence on the intersection of cognitive development, instructional practice, and technical skill acquisition, this study contributes to ongoing efforts to improve the effectiveness of QS education. Advancing construction quantification learning requires deliberate alignment between instructional strategies, cognitive development, and professional standards. Through such alignment, QS programmes can better prepare graduates to meet the complex and evolving demands of the construction industry in Malaysia and beyond.

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AUTHOR CONTRIBUTION

All authors contributed to the study's design, methodology development, writing, and data analysis, as well as reviewed and edited the article to enhance its quality.

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EVALUATING RECYCLING PRACTICES IN CONSTRUCTION PROJECTS USING AN ANALYTICAL HIERARCHY PROCESS (AHP)

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Abstract

The rapid expansion of the construction industry in developing countries has resulted in an increase in the proliferation of construction and demolition (C&D) waste. A small number of negligent contractors unlawfully disposed of an excessive amount of C&D waste in the forest, mangrove swamps, oil palm plantations, roadside, and sea or lake. Nevertheless, a few diligent contractors implemented recycling initiatives at construction sites to decrease the amount of waste that was sent to gazette landfills designated by local authorities or government agencies. Therefore, this study aims to outline a complete assessment of recycling practices. This study exclusively examined on four categories of C&D waste: timber, metal, concrete, and packaging material. A pilot survey with industry professionals was used to finalise 24 recycling practices practiced at construction sites. Subsequently, a questionnaire was disseminated among construction practitioners, yielding complete responses from 125 surveys. Analytic Hierarchy Process (AHP) and Relative Importance Index (RII) were employed to evaluate the responses. Key findings that highlight the prominence of recycling practices at construction sites are 'metals sold to recycling centres', 'excess concrete used for paving temporary site accesses', and 'concrete used as filling for road bases. The outcomes of this research not only contribute valuable insights to industry professionals but also aim to raise awareness regarding the critical importance of recycling practices in curbing the proliferation of C&D waste sent to landfills. Overall, this paper seeks to foster a sense of responsibility among construction practitioners and promote sustainable waste management practices within the industry.

Keywords: *Environment; Recycling; Construction and Demolition; Analytical Hierarchy Process; Relative Importance Index*

INTRODUCTION

The construction industry is considered a key part of any nation's socio-economic growth. The worldwide construction industry experiences an average growth rate of 2.8% (Yuan, 2023). The construction industry is currently experiencing significant expansion, yet it is widely recognized for having detrimental effects on the environment (Ginga *et al.*, 2020). This industry considerably enhances environmental problems such as the exploration of natural resources, irretrievable environmental conversion, and increased contaminants in the atmosphere. Construction waste is produced through site clearance, inefficient material usage, excessive material acquisition, and human errors occurring on construction sites. Between 10% and 30% of the waste originates from construction works (Vilventhan *et al.*, 2019). The global production of C&D waste is estimated to exceed 10 billion tonnes, with nearly 9.5 million tonnes generated in Malaysia alone (Ghafourian *et al.*, 2021). Consequently, it is essential to establish the standard recycling practices applied at the construction site to reduce the material waste generation rate.

Table 1. Recycling Practices with References

Group	Recycling Practices	References
Timber	Recycled in next projects	(Nadarason, 2019), (Kofoworola & Gheewala, 2009)
Timber	Used as a bulking medium	(Nadarason, 2019), (Kofoworola & Gheewala, 2009)
Timber	Used as hoardings	(Nadarason, 2019), (Ponnada et al., 2015)
Timber	Used as energy for power generation	(Lin et al., 2021); (Cramer & Ridley, 2020); (Nadarason, 2019); (Lai et al., 2016); (Aiyewalwhinmi et al., 2016); (Zhao et al., 2010); (Kofoworola & Gheewala, 2009); (Tam et al., 2006a); (Peng et al., 1997)
Timber	Used as decorative products	(Nadarason, 2019); (Tam et al., 2011); (Tam et al., 2006b)
Timber	Used as piles	(Nadarason, 2019); (Tam et al., 2006b)
Timber	Used for furniture	(Nadarason, 2019); (Tam et al., 2011); (Kofoworola & Gheewala, 2009); (Tam et al., 2006b)
Timber	Used to improve soil texture	(Nadarason, 2019); (Kofoworola & Gheewala, 2009); (Tam et al., 2006b)
Timber	Used as temporary works	(Nadarason, 2019); (Tam et al., 2011)
Timber	Used as landscaping mulch	(Nadarason, 2019); (Tam et al., 2011)
Timber	Used for erosion control and groundcover	(Nadarason, 2019); (Zhao et al., 2010)
Timber	Chipboard production	(Cramer & Ridley, 2020); (Nadarason, 2019); (Zhao et al., 2010); (Tam et al., 2006a)
Timber	Used as fertilizer in composting	(Nadarason, 2019)
Timber	Ground timber used as sewage sludge bulking medium	(Nadarason, 2019); (Kofoworola & Gheewala, 2009)
Metal	Sold to recycling centres	(Hoang et al., 2020); (Nadarason, 2019); (Malik et al., 2017); (Lockerey et al., 2016); (Lai et al., 2016); (Tam et al., 2011); (Zhao et al., 2010); (Kofoworola & Gheewala, 2009); (Huang et al., 2002); (Tam et al., 2006a)
Metal	Sent to other construction sites	(Nadarason, 2019); (Lai et al., 2016); (Okeyinka et al., 2015); (Tam et al., 2006b)
Metal	Cut steel corners for shelves	(Yuan et al., 2011a)
Metal	Used for roof cladding	(Nadarason, 2019); (Tam et al., 2006b)
Concrete	Used as filling for road base	(Hoang et al., 2020); (Nadarason, 2019); (Lockerey et al., 2016); (Aiyewalwhinmi et al., 2016); (Tam et al., 2011); (Kofoworola & Gheewala, 2009); (Tam et al., 2006a)
Concrete	Used to build kicker blocks	(Nadarason, 2019); (Zhao et al., 2010); (Kofoworola & Gheewala, 2009)
Concrete	Used for paving temporary site access	(Nadarason, 2019); (Lockerey et al., 2016); (Aiyewalwhinmi et al., 2016); (Tam et al., 2011); (Zhao et al., 2010)
Concrete	Replaced as aggregates	(Hoang et al., 2020); (Nadarason, 2019); (Lockerey et al., 2016); (Aiyewalwhinmi et al., 2016); (Akinkurole et al., 2013); (Tam et al., 2011); (Kofoworola & Gheewala, 2009); (Tam et al., 2006b); (Peng et al., 1997)
Packaging Material	Excess packaging materials are sold to recycling centers	(Hoang et al., 2020); (Nadarason, 2019); (Lockerey et al., 2016); (Tam et al., 2011); (Tam et al., 2006b)
Packaging Material	Sack bags are used as pots to grow small plants	(Nadarason, 2019); (Tam et al., 2006b)

The AHP is a highly adaptable method that can be used for decision-making, ranking, prioritisation, and allocating resources (Szadoczek & Duleba, 2022). The researchers widely utilized AHP to organise and assess complex decisions (Torre & Saloman, 2022). There is

lack of prior research work on the recycling strategies using AHP in Malaysian construction industry (Ghafourian *et al.*, 2021). This study is essential to strengthen recycling practices for construction and demolition waste. Only four types of C&D waste were focused upon, i.e. metal waste, concrete waste, packaging material and timber as they were highly generated in the construction industry. The aim of this study is to provide a comprehensive overview of the recycling practices implemented for C&D waste at construction sites. The literature review was used to ascertain and validate 24 recycling practices. A questionnaire was disseminated to industry specialists to collect their perspectives on recycling practices. 125 surveys were fully completed. Relative Important Index (RII) and Analytic Hierarchy Process (AHP) were employed to analyse the responses. In this study, an interactive tool developed in Python language that enabled the resolution of decision-making problems using the AHP method, from an online environment of free access.

LITERATURE REVIEW

This study compiled the recycling practices in the Malaysian construction industry after an extensive literature review. Note that by using the mean analysis approach there are 24 recycling techniques in the Malaysia construction industry, there are 24 recycling techniques in the Malaysian construction industry that have achieved a score of higher than 3.00 mean scores, indicating their position in term of effectiveness. Table 1 shows the recycling practices and their corresponding references. The subsequent sections of this paper will analyse and evaluate these 24 recycling practices to determine their level of priority using the AHP.

A questionnaire was distributed to construction industry personnel based on the collected recycling strategies. The questionnaire facilitated the identification of the most notable recycling practices in construction sites.

METHODOLOGY

A survey was devised and disseminated to construction industry professionals to assess the implementation of recycling strategies at construction sites. The first part of the questionnaire covers the respondent's information such as position, type of project, working experience, contract amount of project, and highest academic qualification. The second part includes the recycling practices carried out in construction sites and the rank of impact factors. A likert-scale of five was employed (5-very high impact, 3-medium impact, and 1-very low impact). A total of 125 responses were obtained from the respondents. The Spearman's Rank Correlation Test and RII were utilized. Thus, the ranking of all recycling techniques was determined utilising the AHP method. This study is notable for employing the AHP to evaluate recycling methods at construction sites.

DATA CHARACTERISTICS

A Google form was distributed to construction professionals to collect demographic information from the respondents. The data was gathered during the period January – July 2023. 125 answers were collected. The online questionnaire did not permit incomplete submissions. Respondents were categorised into six groups based on their total years of experience. The distribution is illustrated in Figure 1. The majority, or 35.2% of the respondents have experience between 16 – 20 years in the construction industry.

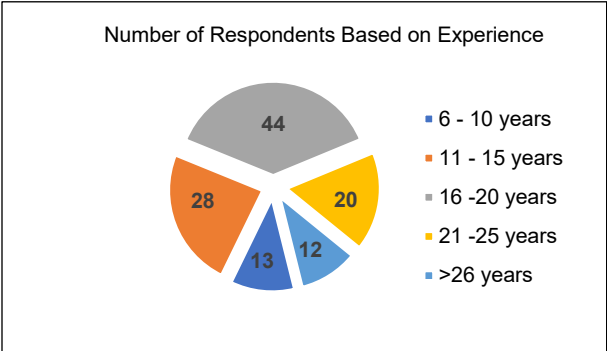


Figure 1. Number of Respondents Based on Total Years of Construction Experience

The percentage of respondents with 21–25 years of experience is 12%, while approximately 22.4% have experience between 11 and 15 years. 20% had more than 26 years of working experience. The smallest working experience group was 6–10 years, which is 10.4%. Hence, approximately 89.6% of the respondents have over 10 years of experience. This indicates that most of the respondents possess significant expertise and extensive knowledge in the area of the construction industry in Malaysia.

Figure 2 exhibits the respondent’s types of organisations. Most of the respondents, 70.4%, are from the contractors’ organisation. Next, 21.6% of the respondents are from consultant agencies whereas 8% are clients.

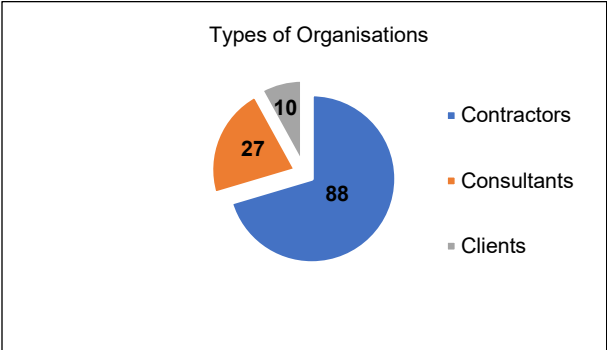


Figure 2. Types of Organisations

The contractor’s responses were more significant due to their superior comprehension of recycling practices and C&D waste generation rate. Besides, contractors will serve as a valuable source of input due to their extended on-site presence (Ahn et al., 2022). Therefore, the input for this survey is beneficial for this study.

RESULTS

The participants were required to evaluate the frequency of recycling practices at construction sites. This questionnaire implemented a five-point Likert scale (5- very high impact, 3- medium impact, and 1- very low impact). The Likert scale scores has been converted for use in AHP analysis by converting the Likert scale values into AHP’s pairwise comparison scale. The data was analysed using Spearman’s Test and relative importance index, as will be discussed in the next sections.

Relative Importance Index (RII)

The RII method evaluates the response data and provides an initial ranking.

$$RII = \frac{(\sum P_i X_i)}{N(n)}$$

Where RII = relative importance index, P_i = weight given to each attribute (1 to 5); X_i =number of respondents chose the same weight P_i ; n = the highest scale weight (5 in this case); N = total number of participants (125).

RII results for the recycling strategies at construction sites are listed in Table 2 below.

Table 2. Results and Ranking of RII Values for Recycling Strategies

Code	Recycling Practices	Timber		Metal		Concrete		Packaging Materials	
		RII	Rank	RII	Rank	RII	Rank	RII	Rank
T1	Recycled in next projects	0.91	2						
T2	Used as a bulking medium	0.58	13						
T3	Used as hoardings	0.89	3						
T4	Used as energy for power generation	0.88	4						
T5	Used as decorative products	0.86	5						
T6	Used as piles	0.68	10						
T7	Used for furniture	0.80	9						
T8	Used to improve soil texture	0.64	11						
T9	Used as temporary works	0.96	1						
T10	Used as landscaping mulch	0.81	6						
T11	Used for erosion control and groundcover	0.81	7						
T12	Chipboard production	0.81	8						
T13	Used as fertilizer amendment for composting	0.23	14						
T14	Ground timber used as sewage sludge bulking medium	0.63	12						
M15	Sold to recycling centres			0.98	1				
M16	Sent to other projects			0.95	2				
M17	Cut steel corners for shelves			0.67	4				
M18	Used for roof cladding			0.79	3				
C19	Used as filling for road base					0.98	2		
C20	Used to build kicker blocks					0.84	4		
C21	Used for paving temporary site access					0.98	1		
C22	Replaced as aggregates					0.93	3		
P23	Excess packaging materials are sold to recycling centres							0.93	1
P24	Sack bags as small pots to grow small plants							0.84	2

Moreover, the participants were requested to rank the occurrence of recycling practices at construction sites. The finding is shown in Table 2. Table 3 shows the findings of RII values, and the prevalence of recycling techniques based on the ranking of C&D waste produced. The generation of concrete C&D waste was high, and contractors practiced

recycling technique to reduce the waste generation. For instance, the contractors layed excess concrete as temporary site access to ensure the workers safety. The relative weights of AHP analysis are determined by these values.

Table 3. RII Results and Ranking for Recycling Practices Based on The Waste Generation

ID	Type of C&D Waste	RII	Rank
W01	Timber	0.75	4
W02	Metal	0.85	3
W03	Concrete	0.93	1
W04	Packaging Material	0.89	2

These RII values are utilised for Spearman's Rank Correlation and then allocate relative weights in AHP analysis.

Spearman's Rank Correlation Test

The Spearman Test was employed to compare different recycling practices using a specific formula in order to assess the accuracy and precision of the data.

$$\rho = 1 - 6 * \frac{\sum d_i^2}{n(n^2 - 1)}$$

Where ρ = Spearman correlation coefficient; d_i = difference between parties' rank assigned to each factor; n = the impact factor total number (24 in this study).

The Spearman's test was utilized to evaluate and compare various categories. The rank was obtained using the relative importance index. Spearman's coefficient ranges from -1 to +1. A positive sign indicates a positive correlation, and a negative sign indicates a negative correlation. Table 4 presents an overview of Spearman's correlation coefficients for different comparison cases.

Table 4. Spearman's Rank Correlation Values

Comparison Criteria	Timber	Metal	Concrete	Packaging Material
Contractor vs others	0.89	0.85	0.87	0.88
Less vs more than 15 years' experience	0.75	0.78	0.79	0.73
Less vs more than 50% of C&D waste generation	0.95	0.99	0.98	1.00

A brief calculation of "Less vs more than 50% of C&D waste generation" for timber with a value of 0.95 in Table 4 is shown in Table 5 as a reference.

Table 5. RII Value Results and Ranking for Recycling Practices

Code	Recycling Practices	Less than 50%	More than 50%	(Difference) ²
T1	Recycled in next projects	6	1	25
T2	Used as a bulking medium	11	12	1
T3	Used as hoardings	2	3	1
T4	Used as energy for power generation	10	7	9
T5	Used as decorative products	3	9	36
T6	Used as piles	13	11	4
T7	Used for furniture	9	10	1

Code	Recycling Practices	Less than 50%	More than 50%	(Difference) ²
T8	Used to improve soil texture	7	6	1
T9	Used as temporary works	1	2	1
T10	Used as landscaping mulch	8	4	16
T11	Used for erosion control and groundcover	4	8	16
T12	Chipboard production	14	14	0
T13	Used as fertilizer amendment for composting	5	5	0
T14	Ground timber used as sewage sludge bulking medium	12	13	1
			Spearman value	0.95

Analytical Hierarchy Process (AHP)

```

D:\rest\pythonProject\.venv\Scripts\python.exe D:\rest\
pythonProject\test2.py
Enter the Method (Range from 1 to 10): 3
Enter the Method name for AA3 =
AA
Enter the Method name for BB3 =
BB
Enter the Method name for CC3 =
DD
Choose your Item:
1) AA
2) BB
3) DD
Enter the chosen item No:2
You have Chooosen : BB
Enter the percentage of materials need: [format: Sugar
 20% ]
Enter the Method name for AA3
Enter the Compound Name:aa
Enter the Compound Percentage [Format: 10%, 20%]15%
Enter the Method name for BB3
Enter the Compound Name:bb
Enter the Compound Percentage [Format: 10%, 20%]35%
Enter the Method name for CC3
Enter the Compound Name:cc
Enter the Compound Percentage [Format: 10%, 20%]25%
Enter the Method name for DD3
Enter the Compound Name:dd
Enter the Compound Percentage [Format: 10%, 20%]11%
-----We have Suggestion about your method-----
Our Suggestion about your materials and it's proportion
is: GOOD_COMBINATION
Your product differs 15 % from our threshold value
Please make sure you need to have to choose the Method
as AA, BB, CC, DD and the ingredients name should be aa
,bb,cc,dd

```

Figure 3. Python Software Screenshot

The analytic hierarchy process (AHP) is a commonly employed and proven method in Multi-Criteria Decision Making (MCDM) applicable across various sectors. AHP offers a practical method for analysing decision problems. It is a technique used to assess both subjective and objective functions in the process of making decisions involving several criteria. Its purpose is to assist users in reaching a mutually acceptable answer. A vital feature of the AHP is its capacity to foster consensus among participants in collective decision-making. AHP empowers decision-makers to attain the advantageous and optimal judgement for their problem, rather than simply obtaining “correct” responses. Decision-makers can utilise the AHP to evaluate and rank criteria by assigning numerical values to determine their relative relevance within a hierarchical framework. This allows for efficient identification and prioritisation of key aspects (Torre & Saloman, 2022; Baric & Zeljko, 2021; Huang, 2021).

An inconsistency index with a value greater than 0.10 is considered inappropriate, requiring a reassessment of the calculations (Escobar et al., 2022). This index is an essential measure for decision-makers to evaluate the reliability of their judgments. If the consistency index exceeds the threshold of 0.10, it indicates the necessity of a reassessment to guarantee the dependability and precision of the decision-making process. The criteria were four types of C&D waste, and the alternatives are recycling practices. Python software was used to determine the consistency ratio (CR) and to prioritise each element. Figure 3 displays a screenshot from the software.

Figure 4 illustrates the AHP hierarchical structure, which consists of three layers. The initial level denotes the alternatives, which are the recycling strategies. The second level denotes the selection criteria, namely, the categories of C&D waste while the final level signifies the analysis goal, which is the final ranking.

The AHP method is delineated in the following steps:

1. Identify the problem objective.
2. Identify the problem criteria.
3. Assign relative weights for each criterion.
4. Develop the AHP multiple-level hierarchical structure.
5. Develop pairwise matrices for comparisons. The formula for developing a pairwise matrix is as follows:

$$[A_{ij}], \text{ where } i, j = 1, 2, \dots, \quad (1)$$

where A = pairwise comparison value, i = impact factors (i = 24); j = types of C&D waste (j = 4).

6. Check the consistency ratio and revise the pairwise comparison matrix if the ratio is below 0.1. This step was carried out using Python software.
7. Calculate priority values to establish the overall ranking of the alternatives. The total of each column for every pairwise comparison matrix was computed and normalised with the sum of each column.

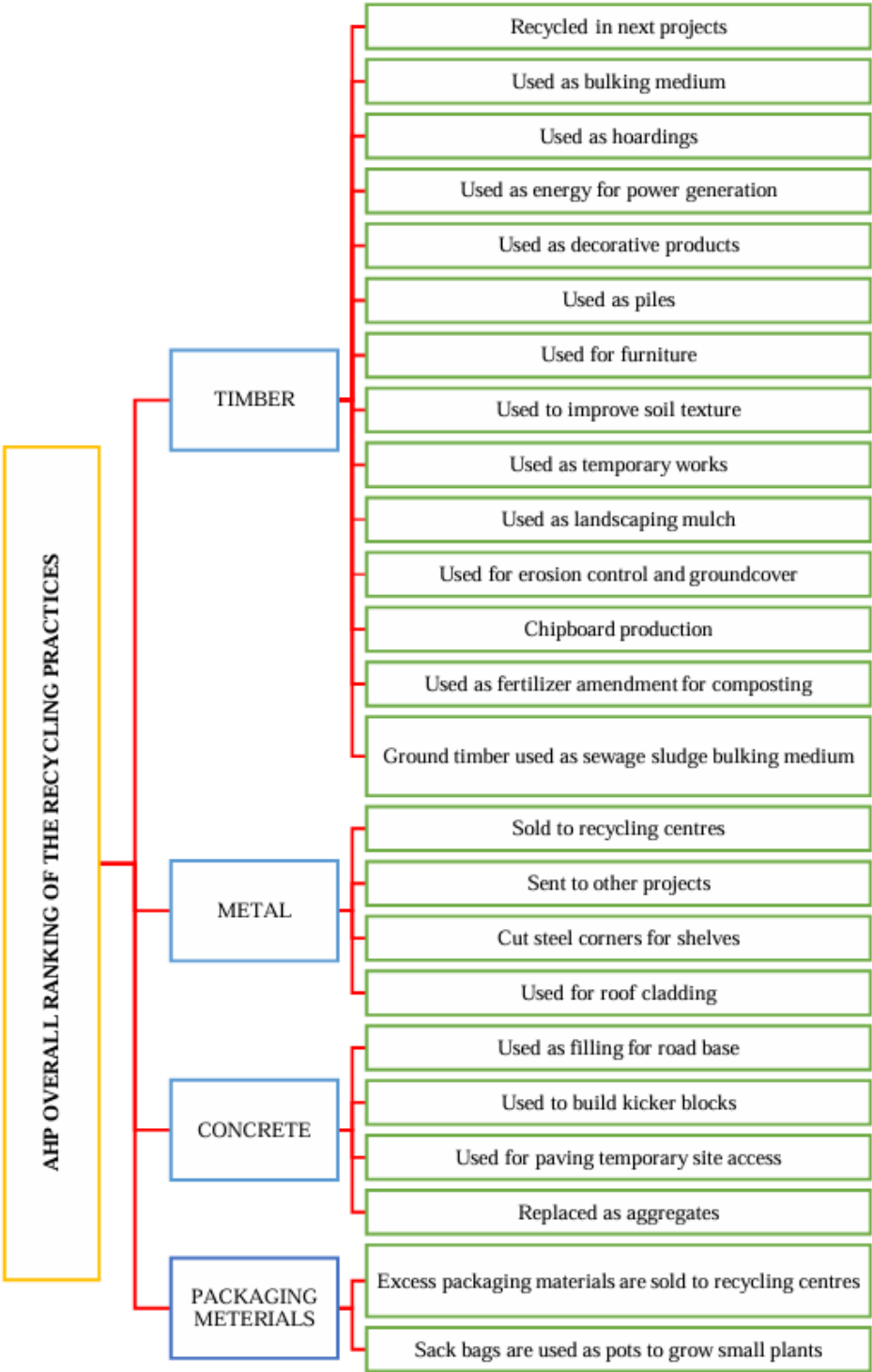


Figure 4. Model for AHP Overall Ranking

This section includes the aforementioned steps and their corresponding sample calculations. A size of 14*14 matrices was developed. As a sample, Table 6 shows recycling practices for timber and consistency ratio normalised pairwise comparisons.

Table 6. Recycling Practices for Timber – AHP Normalized Pairwise Comparisons

ID	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	Priority Value
T1	0.09	0.08	0.10	0.09	0.09	0.08	0.10	0.07	0.06	0.08	0.05	0.08	0.09	0.08	0.081
T2	0.03	0.03	0.05	0.02	0.02	0.03	0.04	0.02	0.02	0.03	0.04	0.02	0.03	0.02	0.029
T3	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.014
T4	0.11	0.11	0.12	0.10	0.08	0.10	0.08	0.08	0.09	0.09	0.10	0.10	0.09	0.09	0.096
T5	0.06	0.07	0.08	0.06	0.06	0.07	0.08	0.05	0.05	0.06	0.06	0.07	0.05	0.06	0.063
T6	0.17	0.20	0.23	0.20	0.25	0.24	0.18	0.21	0.21	0.16	0.14	0.16	0.21	0.22	0.199
T7	0.11	0.10	0.12	0.08	0.08	0.12	0.11	0.08	0.12	0.11	0.11	0.11	0.12	0.10	0.105
T8	0.03	0.02	0.02	0.01	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.023
T9	0.10	0.09	0.08	0.08	0.07	0.07	0.08	0.08	0.09	0.08	0.08	0.09	0.09	0.07	0.082
T10	0.07	0.07	0.07	0.08	0.08	0.06	0.06	0.08	0.07	0.09	0.08	0.08	0.07	0.08	0.074
T11	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.01	0.015
T12	0.03	0.03	0.04	0.02	0.02	0.03	0.04	0.03	0.02	0.04	0.03	0.02	0.03	0.04	0.030
T13	0.07	0.08	0.09	0.09	0.07	0.08	0.09	0.07	0.07	0.08	0.08	0.09	0.10	0.06	0.080
T14	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.022
Summation	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Consistency Ratio = 0.00923 < 0.1															

Additionally, a 4x4 matrix for recycling processes was constructed for the AHP analysis presented in Table 7. The matrices were normalized by dividing the values of each column by the column total, and the priority values (the average of each row) were computed.

Table 7. C&D Waste Generation – AHP Normalized Pairwise Comparisons

ID	W01	W02	W03	W04	Priority value
W01 Timber	0.32	0.33	0.32	0.34	0.328
W02 Metal	0.35	0.35	0.36	0.33	0.348
W03 Concrete	0.32	0.33	0.33	0.34	0.330
W04 Packaging Material	0.06	0.06	0.07	0.08	0.068
Summation =	1.00	1.00	1.00	1.00	1.00
Consistency Ratio = 0.0258 < 0.1					

At the end, the final ranking of factors was determined by multiplying the priority matrix by the recycling practices, as illustrated in Figure 5.

	W01	W02	W03	W04				Overall	Rank		
T1	0.081	0	0	0				T1	0.035	14	
T2	0.029	0	0	0				T2	0.011	24	
T3	0.014	0	0	0				T3	0.048	9	
T4	0.096	0	0	0				T4	0.028	17	
T5	0.063	0	0	0				T5	0.029	16	
T6	0.199	0	0	0				T6	0.012	23	
T7	0.105	0	0	0				T7	0.057	7	
T8	0.023	0	0	0				T8	0.053	8	
T9	0.082	0	0	0				T9	0.122	2	
T10	0.074	0	0	0				T10	0.037	13	
T11	0.015	0	0	0	W01	0.328		T11	0.041	12	
T12	0.030	0	0	0	X	W02	0.348	=	T12	0.013	22
T13	0.080	0	0	0		W03	0.330		T13	0.026	18
T14	0.022	0	0	0		W04	0.068		T14	0.015	20
M15	0	0.198	0	0				M15	0.181	1	
M16	0	0.106	0	0				M16	0.074	4	
M17	0	0.056	0	0				M17	0.014	21	
M18	0	0.734	0	0				M18	0.021	19	
C19	0	0	0.082	0				C19	0.059	6	
C20	0	0	0.075	0				C20	0.033	15	

Figure 5. Model for AHP Overall Ranking

DISCUSSION

Table 8 discusses the ranking for each recycling practice practiced at the construction sites based on Figure 5.

Table 8. Ranking of Each Recycling Practice

ID	Recycling Practices	Priority	Rank
M15	Sold to recycling centres	0.181	1
T9	Used as temporary works	0.122	2
C21	Used for paving temporary site access	0.088	3
M16	Sent to other projects	0.074	4
P23	Excess packaging materials are sold to recycling centres	0.063	5
C19	Used as filling for road base	0.059	6
T7	Used for furniture	0.057	7
T8	Used to improve soil texture	0.053	8
T3	Used as hoardings	0.048	9
P24	Sack bags as small pots to grow small plants	0.048	10
C22	Replaced as aggregates	0.047	11
T11	Used for erosion control and groundcover	0.041	12
T10	Used as landscaping mulch	0.037	13
T1	Recycled in next projects	0.035	14
C20	Used to build kicker blocks	0.033	15
T5	Used as decorative products	0.029	16
T4	Used as energy for power generation	0.028	17
T13	Used as fertilizer amendment for composting	0.026	18
M18	Used for roof cladding	0.021	19
T14	Ground timber used as sewage sludge bulking medium	0.015	20
M17	Cut steel corners for shelves	0.014	21
T12	Chipboard production	0.013	22
T6	Used as piles	0.012	23
T2	Used as a bulking medium	0.011	24

The most common recycling practice at construction sites involves selling excess metals to recycling centres. The priority value of this recycling practice is 0.181, positioning it as the highest-ranked method. This not only reduces the C&D waste but also generates additional revenue. The recycling practice ranked second, with a priority value of 0.122, involves using timber for temporary works, such as timber steps. These temporary solutions are implemented during construction to mitigate slips, trips, and falls.

The next highest-ranked recycling practice, with a priority value of 0.088, involves using excess concrete to pave temporary site access. This practice involves pouring surplus concrete at the construction site to create pavements for workers, thereby ensuring their safety and reducing the risk of injuries. The recycling practice of sending metals to other projects is ranked fourth highest, with a priority value of 0.074. Metals such as scaffolding are transferred to subsequent or different projects. The fifth-ranked, with a priority value of 0.063, involves selling excess packaging materials to recycling centres. These materials, including cardboard, are directed to recycling centres instead of being indiscriminately disposed of or consigned to landfills. This approach also offers the potential to augment the contractor's revenue.

CONCLUSION

This paper studied the types of recycling practices applied at construction sites based on the 4 types of C&D waste: timber, metal, concrete, and packaging material waste. The construction industry professionals would use the rankings to manage the construction sites. The recycling practices were quantified through a questionnaire. The recycling techniques of C&D waste were evaluated both individually and in conjunction with AHP. The most highly ranked recycling practices are metal recycling to recycling centres, timber used for temporary works, concrete used for paving temporary access, metal sent to other projects, and packaging material waste sold to recycling centres. This study differs from other past researchers by analysing the recycling practices through AHP.

This article suggested a general ranking that could help the experts comprehend the various recycling practices. The construction practitioners need to comprehend and mitigate the recycling practices based on the generation of C&D waste. Communication among construction professionals could reduce the amount of C&D waste generated at construction sites. The contractors should implement recycling strategies at their construction sites to reduce C&D waste and ensure environmental safety. Finally, the recycling techniques outlined in this paper could be examined as a case study in a construction project for future research by comparing contractors', consultants' and clients' point of view.

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AUTHOR CONTRIBUTION

Kageishieny Nadarason and Kanesh Kumar Kasvar conceived the study and developed the theoretical framework. Saitharan Nagapan aided in the analysis and supervised the project. All authors deliberated on the results and contributed to the final manuscript.

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COMPARATIVE ANALYSIS OF FACILITIES MANAGEMENT MAINTENANCE CONTRACT DOCUMENT AND PROCUREMENT ACROSS THE GLOBE

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Abstract

Understanding procurement and contract practices in different countries is essential for organisations and professionals involved in Facilities Management Maintenance (FMM) on a global scale. This comparative analysis explores key elements of contract documents and procurement practices for FMM in five distinct countries: the United States, the United Kingdom, Australia, Hong Kong, and Malaysia. The research focuses specifically on contract documents and procurement processes, aiming to better understand the various strategies implemented by each country to optimise FMM operations and improve organisational efficiencies. This analysis compares FMM contract documents and procurement globally, drawing insights from an extensive review of relevant literature. The data gathered from the literature review were then analysed by using thematic analysis. It emphasises the growing need to understand global differences in facility management and maintenance. The research reveals significant factors in how each region approaches tendering methods, contract types, durations, payment methodologies, and its evaluation criteria. Through this comprehensive review, stakeholders gain a deeper understanding of the dynamic landscape of FMM practices, enabling them to make informed decisions and strategically navigate the complexities of global FMM contract documents and procurement.

Keywords: *Contract Document; Facilities Management and Maintenance; Global Perspective; Outsourcing; Procurement*

INTRODUCTION

To maintain its value, appeal to users, and function as intended, a project must undergo proper operation and maintenance (O&M). Facility Management Maintenance (FMM) is an interdisciplinary domain focused on the administration of facilities, services, and personnel to optimise the operational efficiency of an organisation's workplace. In the early 20th century, Wiggins (2021) claimed that the growth of FMM could be attributed to the expansion of office management. With the increasing adoption of professional office administration practices by various organisations, including clerical tasks, record-keeping, and supervision, the need to effectively manage the workspace emerged. Therefore, implementing FMM practices became essential for ensuring proper operation. FMM involves the coordination and supervision of various activities related to the O&M of facilities. This is supported by Zhan et al. (2023), where the O&M phase accounts for the largest proportion of the overall life cycle cost, with FMM contributing 65%–85% of the total expenditure. FMM plays a crucial role in optimising the efficiency and effectiveness of a facility, influencing both the productivity and satisfaction of its occupants. This aligns with the International Facility Management Association's (IFMA, 2022) definition, which describes FMM as the integration of people, location, and process to enhance business productivity and quality of life.

Atkin and Brooks (2015) further defined FMM as comprising an extensive array of services, including utility provision and real estate administration. In the realm of FMM, organisations have two main options between providing services in-house or outsourcing them. FMM outsourcing refers to the practice of involving the expertise of a third-party organisation to assume the obligations associated with FMM, while in-house FMM entails the organisation itself taking on the responsibility of maintaining and operating its facilities using its internal personnel (Zalejska-Jonsson, 2020). The decision to choose between in-house or outsourced services is a pivotal strategic choice, influenced by factors like cost-effectiveness, required expertise, and alignment with the company's goals, as noted by Zalejska-Jonsson (2020). While Ifediora et al. (2021) observed that most organizations tend to favour in-house services, the choice depends on the organization's specific needs and priorities.

FMM is a dynamic, multifaceted domain, orchestrating a symphony of activities that maintaining the functionality and longevity of facilities (Milala et al., 2022). Kureshi (2020) highlighted that the procurement process is central to these activities, the gateway through which organisations acquire the services and expertise necessary to ensure the seamless operation of their built environments. The procurement process involves multiple stages, from competitive tendering to the selection of contractors responsible for delivering the services (Saikat & de Almeida, 2023). While procurement process establishes the foundation, contract documents form the framework that defines the relationships, terms, and expectations that bind stakeholders together (Almarri, 2020). These documents can range from service-level agreements to comprehensive contracts and cover procurement practices, such as the details of tendering methods, contractor selection processes, a variety of contract types, contract durations, and payment methods.

However, while many studies have examined procurement process and contract types in separation or within national context, there remains a lack of comprehensive comparative research that critically analyse how FMM contracts and procurement practices vary globally. Comparative procurement research such as Aboelazm et al. (2025) legal comparison of Egypt, UAE, India, Kenya and other countries illustrates both the usefulness and infrequency of cross-country analysis. This research aims to address the gap by offering a cross-country comparison of FMM contract documentation and procurement strategies.

LITERATURE REVIEW

FMM Contract Documents

A contract document is a legally binding agreement between two or more parties. According to Almarri (2020), a contract document usually contains definitions, terms and conditions, and specific offers made by one party to another. Greenberg et al. (2023) stated that contracts serve as the foundation for business and interpersonal connections within the developed world. Hasan and Salwa (2021) emphasize that contracts as an essential part of safeguarding the financial interests of the involved parties, ensuring that no party suffers losses, as long all the obligations and rights have been established and documented. These documents, ranging from comprehensive service-level agreements (SLAs) to maintenance contracts and complex outsourcing arrangements, provide the legal, operational, and procedural framework within which FMM services operate. One of the distinctive features of

FMM contracts is their adaptability to diverse global contexts. Greenberg et al. (2023) emphasise that contracts are not uniform but adapt to regional influences, regulatory frameworks, and cultural factors. This adaptability is essential in addressing the unique needs of different regions and industries. For instance, in regions with stringent environmental regulations, FMM contracts often include sustainability clauses that promote eco-friendly practices (Uysal, 2024).

Elements of FMM Contract Documents

FMM contract documents are comprehensive roadmaps that outline the full scope of FMM activities. The documents contain a well-coordinated set of elements designed to ensure the agreement is reliable, precise, and legally enforceable for all parties involved. Bartholomew (2022) highlights that a comprehensive contract typically comprises several key documents, each playing a distinct role in shaping the agreement. These documents are meticulously crafted to address various facets of the FMM process. Among the notable documents within a FMM contract, as highlighted by Bartholomew (2022), are:

1. **Bidding Documents**
Bidding documents represent the main point of every contract. It is the document that invites prospective service providers to submit their proposals, outlining their capabilities, pricing, and approach to fulfilling the contract requirements (Asian Development Bank, 2022). Bidding documents typically include an advertisement, invitation to bid, instruction to bidders, and bid form.
2. **General Conditions of Contract**
The General Conditions of Contract (CoC) section provides the overarching framework within which the FMM agreement operates. It lays the fundamental rules, rights, and obligations of the contracting parties (Bartholomew, 2022). This section typically covers broad principles, such as dispute resolution mechanisms, contract termination, and legal jurisdiction. It ensures that the contract operates within a defined and equitable legal framework.
3. **Supplementary Conditions of Contract**
El-Hoteiby et al. (2017) define Supplementary Conditions of Contract as a document that tailor the general framework to the specific needs of the facility and the agreement. These conditions provide flexibility, allowing the contract to adapt unique circumstances and requirements. Supplementary conditions may include additional clauses, specifications, or amendments that cater to the distinct characteristics of the facility and the services to be delivered. This section ensures that the contract is customised to meet the facility's specific needs.
4. **Specification**
The specification component offers a detailed breakdown of the technical requirements and performance standards for FMM services. It outlines expectations for equipment maintenance, cleanliness standards, energy efficiency, and other technical aspects. Specifications are highly detailed and serve as a reference point for quality assurance, ensuring that the contracted services meet the facility's exacting technical and performance requirements (Graics et al., 2021).

5. Drawings

Drawings provide visual documentation of the facility, depicting the layout, equipment, systems, and other key elements that are part of the FMM services. These visual aids are critical for ensuring that service providers have a clear understanding of the facility's physical layout, the specific areas, and assets that require maintenance. Drawings enhance precision in service delivery, support better planning, and resource allocation (Albtoush et al., 2022).

6. Report of Investigation of Physical Condition

The Report of Investigation of Physical Condition is an essential component, especially for existing facilities or those with complex systems. It provides a detailed assessment of the remaining useful life and functionality of its assets, as well as any maintenance needs and potential risks (Re Cecconi et al., 2019). This report provides insights into the current condition of the facility. It includes details about the physical state of the building, equipment, and systems, including any defects, damage, or issues that require attention. This component helps service providers understand the challenges they may face and informs their maintenance and repair strategies.

Collectively, these components ensure that FMM contracts are robust, detailed, and customised to the unique requirements of the facility in question. They provide a comprehensive and reliable framework that guides the operation of FMM services.

FMM Procurement

Procuring FMM services is critical to ensuring the efficient and smooth operation of buildings and facilities worldwide (RICS, 2020). Nevertheless, the procurement procedures of FMM vary significantly in worldwide, depending on various aspects, including the size, complexity of the facility, and the degree of services outsourcing. Ancarani and Capaldo (2005) pointed out that, while FMM processes and principles are generally similar worldwide, regional differences still exist. Mokhtar and Myeda (2023) emphasized that procuring FMM services is a multifaceted and intricate procedure, encompassing several stages and considerations. To achieve a successful and efficient procurement process, it is essential to aligning with best practices and recommendations from experts and authoritative organizations. The guidelines for FMM procurement have been developed by various reputable organisations, each emphasising key principles and essential aspects of the procurement process (Mokhtar & Myeda, 2022). Notably, the Royal Institution of Chartered Surveyors (RICS, 2020) structured its guidelines around four main components, which are key principles, planning, procurement, and post-procurement phases. Similarly, the Chartered Institute of Procurement and Supply (CIPS, 2021), in its framework, has outlined a comprehensive set of knowledge, skills, and competencies necessary for effective procurement and supply management. This framework is focusing on four pillars critical to efficient procurement and supply, including infrastructure, process, performance, and people development. Furthermore, the International Organisation for Standardisation (ISO) has introduced ISO 41001:2018, which provides a detailed explanation of the key steps in ensuring effective FM sourcing and procurement. These steps encompass a range of critical considerations, from cover sourcing strategies, aligning with business contexts, identifying current and future needs, defining service levels, exploring service delivery options, developing a business case, selecting a preferred delivery method, and managing facilities

services (ISO, 2018). Additionally, it covers aspects of FMM agreements and procurement practices, concluding with performance measurement in service delivery. According to Heinis et al. (2022), these comprehensive guidelines and frameworks collectively provide a roadmap for organisations engaged in FMM procurement, enabling them to adhere best practices, streamline processes, and enhance the efficiency and effectiveness of their procurement and supply management operations.

METHODOLOGY

The methodology for this research is primarily based on an extensive literature review focusing on FMM contract documents and procurement practices across countries. According to Snyder (2019), literature review is useful to conceptualising fragmented fields, clarifying the key themes and identify gaps in the existing knowledge. The research began with a detailed exploration of existing academic articles, industry reports, government publications, and global expert opinions. The objectives were to build a comprehensive knowledge-based that incorporates the latest developments, best practices, and critical insights in FMM procurement and contract documentation. Following the literature review, the information was synthesised to develop a structured understanding of global and regional FMM practices.

A thematic analysis approach was applied to identify patterns across the literature and documents. Themes were developed inductively by manually coding the recurring topics and keywords related to contract types, procurement procedures, payment mechanisms and evaluation methods. The selected countries, the United States (US), the United Kingdom (UK), Singapore, Australia, and Malaysia, were strategically selected to provide a comprehensive view of global FMM practices. The US, UK, Singapore, and Australia were selected due to their significant advancement in the FMM sector, while Malaysia was selected to observe the growth of FMM in a developing market.

In addition to the literature review, the research involved a focused analysis of actual FMM contract documents from each selected country. Document analysis was employed to interpret the structure and content of these documents. As Bowen (2009) highlights, document analysis is an effective qualitative method for systematically reviewing and interpreting textual data, particularly when examining organisational policies, procedures and legal records. This method provides deeper understanding on how FMM contracts are structured and applied in practice. Throughout the research process, various data sources were being reviewed, including government publications, official procurement guidelines, academic databases, industry reports, publications from industry associations, and additional authoritative sources.

FINDINGS

FMM Contract Documents and Procurement Across the Globe

The procurement process and the contract documentation for FMM services are important steps in establishing effective and efficient partnerships between contractors and clients, improving service delivery outcomes (Bett & Achuora, 2021). Both the procurement process and contract documentation should be carefully designed and implemented, reflecting qualities such as transparency, adaptability, and clarity. These are critical in ensuring that the

responsibilities and requirements of the project are fulfilled. Table 1 below summarizes the findings of FMM contract documents and procurement practices globally, illustrating diverse methods and techniques used to optimise FMM services.

FMM Contract Documents

Type of Contract

Contract type selection reflects a balance between predictability and adaptability. While all five countries use fixed price contracts as a key mechanism to ensure cost transparency and administrative simplicity. Developed countries such as the United States (US) and the United Kingdom (UK) go beyond this by having job order contract (JOC), target plus, cost-plus and performance-based models. These options offer a level of flexibility for evolving service requirements and are particularly effective in overseeing long-term facilities with diverse maintenance needs (Anwar et al., 2016; Gunnoe et al., 2016). In contrast, Malaysia and Singapore despite being operationally efficient, adhere more closely to fixed-price methods. This inflexibility may suppress the needs for changes in the contract scope and at the same time reduce the possibility of cost growth where fixed price contract can motivate the contractor to control the costs and avoid behaviours that will lead to increase in cost (Callaway et al., 2018).

Contract Period

Contract durations in developed nations are often structured with built-in extension mechanism, allowing for adjustments based on contractor performance or shifting needs. The UK's 2+2 or 5+2 model, and Singapore's 3+3 approach are example of contract structure designed for both administrative control and service continuity. This flexibility reflects a more mature contract governance practices, which are less prevalent in Malaysia's shorter and fixed terms. Heiland et al. (2024) support this approach where flexible contract terms that have performance review enable a better risk management and lifecycle alignment in the FMM contract.

Payment Method

Across various countries in the field of FMM, the Key Performance Indicators (KPIs) payment method is a widely adopted and used as a core payment mechanism, reflecting the global-shift toward performance-based procurement (Bakhrom, 2024). KPIs play an important role in assessing and evaluating the performance of service providers and it can encompass factors such as service efficiency, customer satisfaction levels, adherence to safety and standards, and other relevant metrics that measure overall performance. However, their effectiveness is contingent upon organisational capacity to define, measure and enforce such indicators. For instance, Australia and Singapore implement a robust performance monitoring system that link KPIs with payment deductions or incentives, enabling a clearer accountability (Jamaluddin et al., 2019). In contrast, in countries like Malaysia, where KPI implementation have risk becoming symbolic rather than impactful (Abdullah et al., 2022).

Table 1. Summary of FMM Contract Documents and Procurement Across The Globe

Item	USA (National Academies of Sciences Engineering and Medicine, 2020)	UK (ECDC, 2017; RICS, 2020)	Singapore (Building and Construction Authority, 2021)	Australia (Department of Finance, 2022)	Malaysia (Isa et al., 2016)
Contract Document	Types of Contracts • Job Order Contract • Fixed Price • Labour-hour • Times and Materials • Performance based	• Fixed Price contract • Cost plus • Target plus	• Fixed Price contract	• Fixed Price contract	• Fixed Price contract
	Contract Period • One base year to 9-year renewal	• 2-5 years (Also include extension clause e.g., 2+2, 5+2)	• 3–5 years. At least 3 years with the option of extending another 3 years	• 2-9 years	• 2-5 years
	Payment Method • Key Performance Indicator (KPI)	• KPI	• KPI	• KPI	• KPI
Procurement	Tendering Method • Negotiated • Competitive Open Tendering	• Open tender • Selective tender	• Open Tender • Selective tender	• Open tender • Limited tender • Prequalified tender • Two stage tenders	• Open Tender • Pre-qualified • Limited Tender
	Procurement Document • Request for Bid (RFB) • Request for Information (RFI) • Indefinite Delivery/Indefinite Quantity (IDIQ)	• Request for Proposal (RFP) • Intention to Tender (ITT) • RFI	• RFP	• Request for Quote (RFQ) • Expression of Interest (EOI) • Request for tender (RFT) • RFI • RFP	• Tender document
	Evaluation • Pricing • Experience and qualification • Management Plan • Reference • Personnel	1) Group can discuss the strengths, weaknesses, and risks of the submissions and agree a score by consensus 2) an average score can be calculated from the evaluator's individual scores • Legal capacity • Economic and Financial capacity • Technical and professional capacity	• Total score of: 1. Price score 2. Quality score • Deter price diving using. "Abnormally-low-bid Curbing Mechanism" (ACM)	• Relevant experience • Appreciation of the task • Past performance • Management and technical skills • Resources • Management systems • Methodology • Price	• Technical capacity • Financial evaluation • Personnel • Price offered

(Source: Author's own compilation)

FMM Procurement

Tendering Method

Selecting the appropriate tendering method is essential to ensure that service providers are chosen in a way that suits the specific needs and dynamics of different countries. In the United States, there are two primary approaches to procurement, which are Negotiated and Competitive Open Tendering (National Academies of Sciences Engineering and Medicine, 2020). Negotiated approaches facilitate comprehensive negotiations with prospective providers, enabling a deeper exploration of various aspects, while Competitive Open Tendering ensures fair competition by allowing providers to submit bids for contracts. According to Wallis (2020), negotiated approaches can result in a cost savings of 5-10% more effective than competitive tendering with the right negotiation strategies. The UK employs a dual approach (RICS, 2020), utilising both Open Tendering for broad participation, and Selective Tender for situations that require specific, pre-qualified providers. Singapore follows similar practices, emphasizing both inclusivity and tailored selection through Open and Selective Tender method (Building and Construction Authority, 2021).

In a guideline by the Department of Finance (2022), Australia employs various methods for tendering, including Open, Limited, Prequalified, and Two-Stage Tenders. Open tenders are designed to promote widespread involvement from potential bidders, while Limited Tenders are suited for specific situations. Prequalified tenders are tailored to providers who possess established qualifications, and lastly, Two-Stage Tenders offer a structured approach to complex projects. Similar to the UK, Isa et al. (2016) reported that Malaysia employs the practice of Open Tenders to encourage broad participation, whereas Selective Tenders are utilised in circumstances necessitating pre-qualified vendors. These tendering methods reflect each country's commitment to adaptability and inclusivity in FMM practices. By aligning with its unique requirements, these methods ensure fair competition and the selection of high-quality service providers.

Procurement Document

The process of procurement in FMM involves a range of documents to solicit and evaluate proposals from service providers (Talamo & Atta, 2019). Although there may be differences in terminology and processes employed, the purpose remains the same across different countries. The US, UK and Australia deploy a diverse set of instruments such as RFPs, RFQs, EOIs and IDIQs where it allows for a stepwise filtering and deeper vetting of service providers. These procedural layers ensure a high degree of alignment between service specifications and provider competencies. On the other hands, Malaysia uses a standard tender document, although it is administratively efficient, it may restrict the procurement teams from conducting a more detailed comparative evaluations or iterative clarifications during the tendering phase.

Contractor Evaluation

In developed countries like the US, UK, Singapore and Australia, contractor evaluation generally employs a composite methodology, where it integrates technical, financial, managerial and in some cases, qualitative aspects. The US for instance, assesses proposal

based on a wide range of criteria including price, qualifications, experience references and management plans (National Academies of Sciences Engineering and Medicine, 2020). The UK uses a similar method of evaluation, where a group consider the benefits and drawbacks of proposals before coming to an agreement based on legal, technical and economic factors (RICS, 2020). Fawzy et al. (2024) supported this, stating that multidimensional evaluation models make it easier to choose the right contractor instead of choosing contractor that offer the lowest price. Singapore on the other hands, improves this method by focussing on both price and quality at the same time with a total scoring system. The Abnormally Low Bid Curbing Mechanism (ACM) is an important part of it since it prevents under-pricing that might negatively impact service quality. This system works best in contracts that are based on performance, where the quality of the work done is directly related to the contractor's skills (Building and Construction Authority, 2021).

Australia has similar complete models that consider things like task appreciation, post-performance, management system and techniques. This creates a strong framework goes beyond only pricing (Department of Finance, 2022). This illustrates a transition from conventional cost centric selection to value-based procurement, which considers long term asset performance and service delivery risk. On the other hand, Malaysia still mainly uses technical skill, financial stability, personnel qualifications and price offered as main factors for evaluating (Mohd Isa et al., 2016). These factors are important, but they tend to favour contractors who already have good financial and technical profiles. This could lead to missing out on new ideas, initiatives or flexibility to be offered in the FMM projects. Jasim (2021) states that contractor's evaluation is often misunderstood to judge the contractor's capability to do their works, but it depends on how well the criteria fits the project's goals.

Synthesis of FMM Contract Document and Procurement Across The Globe

The comparative findings across five countries show that the maturity of procurement process and contract documentation influences the achievement of FMM implementation. Based on the findings, flexible contract structures and evaluation based on performance metrics have become a trend among developed countries. These practices reflect the global FMM standards that show the importance of aligning a strategic procurement with long-term asset goals (Paul et al., 2024). For example, developed countries like US and UK have embraced job order and performance-based contract types where these types of contracts are designed to accommodate a more complex nature of FMM services. Findings from (Zou et al., 2019) shows that flexible contracts have a direct contribution to the value creation of FMM services, where it enables iterative performance adjustment. In contrast, countries that rely on fixed pricing and rigid contract may find it hard to deal with any changes in the operational needs, especially when there is a lack of performance feedback mechanism. When looking at the payment mechanism, it highlights the widespread use of KPI-based payment. According to Su et al. (2023), the success of these payment mechanisms depends on the supervision resources and the consistent interpretation of KPI standards. If these are insufficient, it may lead to unreasonable payment.

Additionally, findings also shows that the choices of document tendering play a significantly impact on the outcomes of FMM services. Multi-stage tendering or negotiated tendering are important and crucial to be used based on the complexity of the projects. The more complex the project, the more detailed and secured the procurement process will be

(Mohammad Idris, personal communication, 2023). This is due to the methods allow for a deeper evaluation of the service providers, not based on the cost alone but also alignment with the technical demands (Cheaitou et al., 2019). Equally important is the use and choices of the procurement documents where the absence of a consistent and details templates can result in varying interpretations of quality and service expectations. These documents form the basis for evaluating the contractor proposals where the clarity of the document directly influences how criteria such as pricing, technical requirements and the service standards are understood and assessed (Talamo & Atta, 2019). Consequently, the selection of the contractor depends on the evaluation processes that consider not only the price offered but also the contractor's technical capability and overall competence. Shukery et al. (2018) highlighted that the use of experience during evaluating that contractor enhance the decision-making process, where it reduces the subjectivity in contractor selection.

RECOMMENDATIONS

Evolving Trends in FMM Contract Documents

The consideration of emerging trends and innovative approaches within the FMM contract documents is crucial as the field continues to evolve. These trends are shaping the future of FMM, emphasising efficiency, sustainability, and adaptability to changing global dynamics. Through the integration of technology and the utilisation of data-driven solutions, professionals in facility management can optimise operational processes and improve the effectiveness of preventative and predictive maintenance programmes for facilities. The integration of intelligent building systems not only enhances energy efficiency but also remote monitoring and predictive maintenance (Nota et al., 2021). Other than that, in recent years, the digitalization of FMM contract documents has gained prominence. Ariffin et al. (2023) and Nojedehe et al. (2022) stated that the integration of digital tools, such as Computerised Maintenance Management Systems (CMMS) and Building Information Modelling (BIM), can result in FMM contracts being more dynamic and data driven.

Furthermore, a shift towards green practices and the use of renewable energy sources, ensuring the long-term sustainability of facilities and reducing their environmental impact (Ivanova & Datta, 2023). Although global efforts to reduce the carbon footprint and promote environmental responsibility have encouraged the incorporation of eco-friendly practices and energy-efficient solutions into contracts, progress in integrating sustainable concepts into construction contracts and contract administration has been slow (Hasan & Salwa, 2021). To stay competitive, it is important for FMM contract documents to effectively address current trends and actively promote the adoption of innovative practices within the field.

CONCLUSION

FMM plays a crucial role in ensuring the smooth operation of buildings and facilities worldwide. This article has explored the complex landscape of FMM contract documents and procurement practices across various countries, providing key findings that underscore the diversity in this field. FMM contract documents serve as a rulebook for facility maintenance, tailored to local laws and regulations. Procurement processes, however, vary from country to country. Despite these differences, the core objectives of FMM contracts and procurement remain consistent across nations, which is to provide inclusivity, transparency, and high-

quality services. Looking ahead, FMM is evolving with technology, data-driven solutions, and sustainability. These trends are focused on enhancing efficiency within the field. As the world emphasises environmental responsibility and energy efficiency, FMM contracts are expected to play a central role in promoting these positive changes. In summary, FMM is a dynamic and critical field that ensures the functionality of the buildings and facilities, while continuously adapting to new challenges and opportunities.

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STRUCTURAL PERFORMANCE OF RC BEAMS WITH MICPOFA AND NAPOFA AS CEMENT REPLACEMENTS IN SELF-CONSOLIDATING HIGH-PERFORMANCE CONCRETE: AN IRWIN'S MODIFICATION METHOD ANALYSIS

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Abstract

The use of waste materials in concrete production has gained significant attention in the construction sector, promoting sustainability and reducing environmental impact. As the construction of high-rise buildings increases, there is a growing demand for specialized concrete incorporating sustainable materials to address this concern effectively. This research investigates the performance of micro-sized POFA (MicPOFA) and nano-sized POFA (NaPOFA) as cement substitutes in SCHPC, contributing to the development of environmentally friendly SCHPC. The research methodology includes a comprehensive experimental investigation, focusing on the mechanical properties of SCHPC through flexural testing. The study uses 100 mm x 100 mm x 500 mm concrete beams as specimens, representing various formulations, including plain SCHPC and SCHPC incorporating MicPOFA (SCHPCMP1) and NaPOFA (SCHPCNP1). Flexural strength was evaluated at 28 and 365 days. Furthermore, the results from the flexural test were used to analyse fracture energy using Irwin's modification method, providing a deeper understanding of the concrete structure's behaviour and strength characteristics. The findings showed that SCHPCMP1 and SCHPCNP1 demonstrated high load-carrying capacities compared to control SCHPC, with SCHPCNP1 exhibiting the highest ultimate load and significant ductility, especially at 365 days. The inclusion of MicPOFA and NaPOFA improved SCHPC's flexural strength, with SCHPCNP1 showing the greatest improvement over time. These findings suggest that MicPOFA and NaPOFA enhance concrete's mechanical properties, facilitating environmentally responsible solutions for the structural demands of modern high-rise buildings, bridges, and infrastructure projects.

Keywords: *Micro POFA; Nano POFA; SCHPC; Irwin's; Flexural Strength*

INTRODUCTION

The construction sector in Malaysia is increasingly prioritizing environmentally friendly projects by embracing sustainable development concepts. This shift highlights the use of high-performance concrete that incorporates eco-friendly cementitious materials produced at a reasonable cost. Concrete remains a crucial engineering material in construction, with the rapid pace of urbanization and industrialization amplifying its importance. The rising demand for concrete has, in turn, increased cement production, as cement is essential for concrete formulation. However, this growing demand raises concerns about depleting raw materials

for cement and increasing carbon dioxide emissions, which pose significant environmental and human health risks. Consequently, there is a strong need for alternative materials that can effectively replace cement, offer similar properties while make concrete more cost-effective. The palm oil industry is vital to Malaysia's economy, making the country the second-largest global producer after Indonesia, contributing approximately 19.96 million tonnes of palm oil annually (Zamri et al., 2019). Palm oil cultivation in Malaysia began in 1960, covering around 54,000 hectares. By 1980, this had expanded to 1.02 million hectares, and by 1990, to 2.03 million hectares. The area under cultivation continued to grow, reaching 3.37 million hectares in 2000, 4.85 million hectares in 2010, and 5.64 million hectares in 2015. The Malaysian Palm Oil Board reported that the plantation area further increased to 5.74 million hectares in 2016, 5.81 million hectares in 2017, 5.849 million hectares in 2018, and 5.90 million hectares in 2019. Along with this expansion, palm oil production has increased significantly, leading to substantial palm oil waste.

Felda Holdings Bhd., a major plantation company, has implemented Clean Development Mechanism (CDM) initiatives nationwide, including biogas, compost, and power plants using biomass waste from palm oil mills. These efforts aim to convert waste into renewable energy, reflecting Felda's commitment to environmental sustainability (Adnan, 2019). In 2019, Felda Palm Industries Sdn. Bhd. reported significant waste generation from their mills, underscoring the potential for eco-friendly practices. This initiative could contribute to the production of green concrete by replacing waste in cement manufacturing, aligning with Felda's environmental responsibility goals. Despite challenges such as decreased crude palm oil (CPO) production due to labour shortages and limited supply during the COVID-19 pandemic, the palm oil sector performed better in 2021 than in the previous year. As the industry recovers, research and development efforts continue to focus on sustainability and competitiveness (Malaysian Palm Oil Board, 2020). Malaysia's construction industry is moving towards green construction to achieve sustainability, particularly in buildings requiring high durability. This goal can be achieved by enhancing normal concrete into high-performance concrete (HPC) using eco-friendly supplementary cementitious materials (SCM). Various studies have demonstrated that SCMs, such as rice husk ash (Ambedkar et al., 2017; Sandhu & Siddique, 2017), fly ash (Hefni et al., 2018; Wang & Park, 2015), and POFA (Ahamed & Siddiraju, 2016; Safiuddin et al., 2011) significantly improve both fresh and hardened concrete properties, such as increased compressive strength and reduced permeability.

However, research specifically on the effects of MicPOFA and NaPOFA is still limited and needs further investigation. In the early 1980s, Japan focused on improving concrete durability due to a lack of skilled workers, which compromised construction quality (Okamura & Ouchi, 2003). Okamura & Ouchi (2003) also noted that using self-compacting concrete (SCC) could achieve durable structures regardless of construction quality. Self-consolidating high-performance concrete (SCHPC) is a type of concrete that flows easily into formwork without the need for vibration or compaction (Safiuddin et al., 2005). Xie et al. (2002) found that SCC with cementitious materials offers good workability, high mechanical properties, and increased durability. However, more research is needed on SCHPC incorporating POFA.

Thus, this study explores the potential of MicPOFA and NaPOFA as partial replacements for cement in Self-Compacting High-Performance Concrete (SCHPC). This initiative aligns

with Malaysia's commitment to Sustainable Development Goals 9 (Industry, Innovation, and Infrastructure) and 11 (Sustainable Cities and Communities) by promoting environmentally friendly construction materials, reducing the carbon footprint, and facilitating the development of more durable and sustainable concrete.

LITERATURE REVIEW

The industrial and agricultural sectors generate significant amounts of waste, including Palm Oil Fuel Ash (POFA), which can be environmentally hazardous if not properly managed. POFA is often disposed of indiscriminately outside factories, leading to pollution and posing health risks to nearby communities. Therefore, managing and disposing of POFA safely is crucial to prevent environmental degradation and protect public health. Sustainable waste management practices, which focus on maximizing recycling and reuse, are essential to address improper disposal and its associated issues. Using POFA as a cement replacement solves the problem of landfills. This practice lowers the cost of building materials, addresses environmental concerns, and improves waste management. Additionally, it conserves energy and prevents pollution, making it a cost-effective and environmentally beneficial alternative (Evi, 2017). Utilizing waste in place of cement can also be more economical, reducing cement content while enhancing concrete properties, such as strength and permeability. Incorporating POFA into concrete promotes eco-friendly practices and innovation in the construction industry. By partially replacing cement in Self-Consolidating High-Performance Concrete (SCHPC), POFA can improve the mechanical properties of concrete, making it suitable for high-rise buildings, tunnels, and long-span bridges.

The fracture energy of concrete is crucial for its resistance to crack formation and propagation. POFA, a byproduct of the palm oil industry, has pozzolanic properties, making it a promising partial replacement for cement. Understanding POFA's impact on fracture energy is key to optimizing concrete mix designs and enhancing the performance and sustainability of concrete structures. This study investigates the application of fracture mechanics to analyse crack behaviour in concrete, focusing on the role of POFA in Self-Consolidating High-Performance Concrete (SCHPC). It evaluates the performance of concrete by replacing part of the cement with MicPOFA and NaPOFA. Using the modified Griffith-Irwin theory, the study examines fracture energy in SCHPC, providing a practical calculation method. The research aims to elucidate the fracture behaviour of SCHPC with MicPOFA and NaPOFA, enhancing predictability through mathematical optimization using Design Experts on reinforced concrete beams.

This study explores repurposing palm oil industry waste as a sustainable cement replacement to mitigate environmental impact. Using POFA in concrete supports eco-friendly practices and stimulates construction industry innovation. Additionally, POFA can reduce cement costs and optimize concrete production. MicPOFA and NaPOFA, as partial replacements in SCHPC, can enhance the properties of SCHPC to meet the demands of complex high-rise structures. This research aligns with Sustainable Development Goal (SDG) 9, which focuses on resilient infrastructure, sustainable industrialization, and innovation. By investigating alternative cementitious materials like MicPOFA and NaPOFA, the study aims to promote environmentally friendly construction practices and address SDG 11 (Sustainable Cities and Communities) by developing durable and sustainable concrete solutions for urban environments in Malaysia.

METHODOLOGY

Materials Preparation

The specimens used in this research were 100 mm x 100 mm x 500 mm prisms. The materials included Ordinary Portland Cement (OPC), coarse aggregates, fine aggregates, Glenium, and Palm Oil Fuel Ash (POFA). POFA, serving as a cement replacement, was sourced from the United Palm Oil SDN. BHD. factory in Sungai Kecil, Nibong Tebal, Pulau Pinang, Malaysia. The OPC was procured from Tasek Sdn. Bhd. Coarse aggregates were selected to pass through a 10 mm sieve, while river sand passing through a 4 mm sieve was used as the fine aggregate. The concrete mixing process adhered to BS EN 1008:2002 standards, utilizing potable tap water. To produce MicPOFA, raw POFA was oven-dried for 24 hours and then sieved through a 212 µm sieve. Subsequently, NaPOFA was produced by grinding the MicPOFA using a high-energy ball milling machine with 10 mm zirconium balls. MasterGlenium ACE 8538, obtained from BASF (Malaysia) Sdn. Bhd. was incorporated as a partial admixture. The addition of Glenium aimed to enhance the mechanical properties of the Self-Compacting High-Performance Concrete (SCHPC), working synergistically with NaPOFA within the concrete mix. This combination of high-quality materials and advanced processing techniques was designed to optimize the performance characteristics of SCHPC, ensuring its suitability for demanding structural applications.

Samples Preparation

This research focused on using MicPOFA and NaPOFA as a cement substitute in SCHPC. Three different concrete mixes were formulated: one without POFA (Control) (SCHPC), SCHPC with 1% NaPOFA cement replacement (SCHPCNP1) and SCHPC with 1% MicPOFA cement replacement (SCHPCMP1). The concrete mixing process began by blending cement and POFA in the mixing apparatus. Potable tap water and the specified admixture were added, and the mixture was blended until a uniform cement paste was formed. The fine aggregate was gradually incorporated, followed by the addition of the coarse aggregate. The mixture was allowed to blend thoroughly before being poured into moulds. The concrete cubes were then cured for 28 days and 365 curing days.

Table 1. Concrete Mix Design

Mixes	Cement (kg/m ³)	POFA (kg/m ³)	Water (kg/m ³)	Coarse Aggregate (kg/m ³)	Fine Aggregate (kg/m ³)	Superplasticizer (kg/m ³)
SCHPC	1000	0	200	800	433	16
SCHPCMP1	990	10	200	800	433	16
SCHPCNP1	990	10	200	800	433	16

The mix proportions used in this study were based on a slightly modified version of the concrete design mix study by (Norhasri et al., 2017), as there was no direct or conventional design for the SCHPC mix. This design mix was chosen for comparison because it produces high-strength concrete using regular coarse and fine aggregates, which are more affordable and readily available materials in Malaysia. The specific design mix utilized in the study is detailed in Table 1 for reference. The selection of 1% replacement was guided by preliminary strength optimisation trials and informed by previous findings from Norhasri et al. (2017), who reported that low-level nano- and micro-additives (<2%) maximise pozzolanic activity

while avoiding adverse effects on workability and early-age strength. Additionally, the aim was to study the particle size effect, holding the dosage constant for comparative analysis.

Test Method and Procedure

Flexural Test

Nine (9) reinforced concrete beam specimens were prepared and tested, comprising three beams for each concrete mix: SCHPC (control), SCHPCMP1 (containing 1% MicPOFA), and SCHPCNP1 (containing 1% NaPOFA). Each beam measured 100 mm × 100 mm × 500 mm and was tested in flexure following BS EN 12390-5:2019. Flexural tests were conducted at two curing intervals, 28 and 365 days, to evaluate both early-age and long-term structural performance. Each mix type was tested with three replicate beam specimens per age group mixes (n = 3). The collected load-deflection data were further utilised to compute fracture energy parameters and support structural modelling analyses, including crack propagation behaviour and ductility assessment, using Irwin’s modification method. Figure 1 shows the reinforcement bar layout used in all the flexural beams. For detailed information, Table 2 references the work by (Rao et al., 2017), providing specifics on the section properties and reinforcement of each beam mix. The flexural tests were conducted according to BS EN 12390-5:2019 standards. The data obtained from these tests were then used to determine the fracture energy using the Irwin modification method.

Table 2. Specimen Description

Dimensions of The Beam	Reinforced Concrete Beam
Steel area	100 mm x 100 mm x 500 mm
Cover	10MM Ø (4 bars)
Stirrup size	25 mm
Stirrup spacing	50 mm x 50 mm
Specifications	150 mm

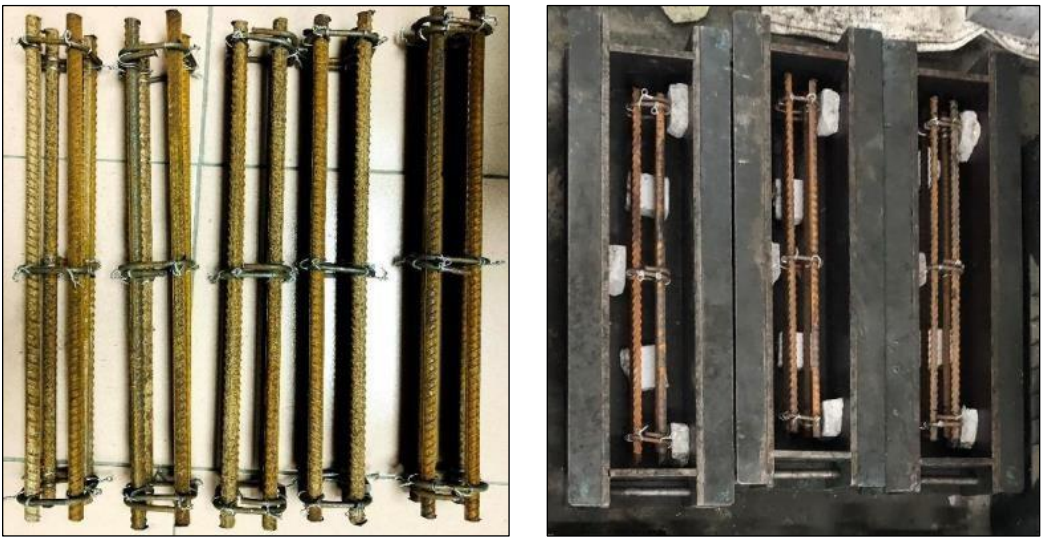


Figure 1. Setup for Reinforcement Beam

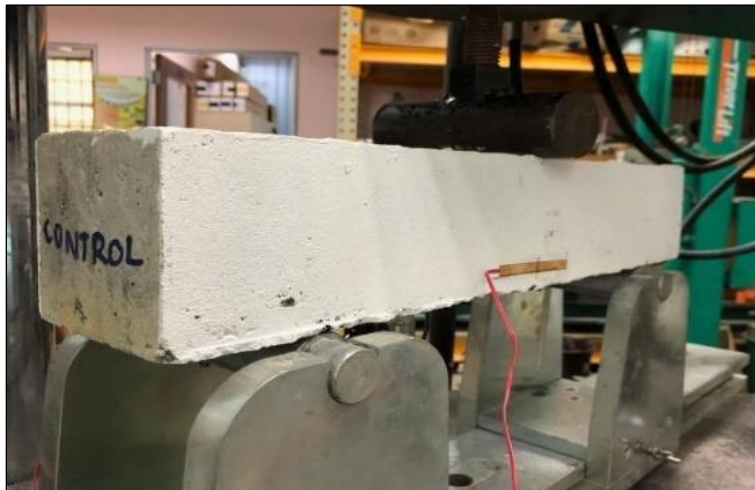


Figure 2. Flexural Beam Test Setup

Fracture Energy Analyses of MicPOFA and NaPOFA Structural Beams Using Irwin's Modification Method

In the concluding phase of the experimental procedure, fracture energy analyses were performed on MicPOFA and NaPOFA structural beams using Irwin's modification method. The fracture energy, G , quantifies the energy the beam specimen releases under loading. A load versus displacement curve was employed to determine the compliance, C , of the specimens at varying crack lengths. A graphical analysis was then conducted to plot C against the crack length, a . This plot was differentiated using an appropriate curve-fitting method to obtain the derivative, dC/da , with respect to crack length, a . Using this derivative data, the fracture energy values, G , were calculated as a function of crack length, a . Subsequently, a linear mathematical model was developed using Design Expert software, which utilized the collected data to predict fracture analysis outcomes for SCHPC mixes. This involved a comprehensive modelling analysis of the beam structures, leveraging the advanced capabilities of Design Expert software in conjunction with Response Surface Methodology (RSM).

The results of this modelling analysis extended beyond mere data interpretation, establishing precise mathematical equations that serve as practical guidelines for predicting the performance of larger-scale beam structures. These equations integrate insights from the experimental data and computational simulations to optimize the design and construction of reinforced concrete beams in real-world applications. By combining empirical data with advanced computational modelling techniques, this approach enhances our understanding of the principles governing beam behaviour, enabling practitioners to make informed decisions when designing and implementing structural systems. The resulting mathematical equations provide a systematic framework for predicting and optimizing the performance of larger-scale beam structures in diverse engineering contexts, thereby driving innovation and efficiency in civil engineering practices.

Design Expert Analysis of Self-Consolidating High-Performance Concrete (SCHPC)

Self-consolidating high-performance concrete (SCHPC) is an advanced material known for its exceptional flowability and consolidation properties. Designing SCHPC mixes requires careful optimization to meet specific project needs, and researchers have recently used advanced statistical techniques like Design of Experiments (DOE) and response surface methodology (RSM) for thorough analyses of SCHPC formulations. The Design Expert software plays a crucial role in predicting models and quantifying the contribution of palm oil fuel ash (POFA) in concrete, allowing for predictive models. This enables engineers to optimize mix designs and achieve desired properties such as workability, strength, and durability. By systematically assessing the impact of different sizes of POFA, researchers can maximize POFA utilization, reduce material usage, and lower construction costs, leading to sustainable and high-performance concrete solutions.

RESULTS AND ANALYSIS

Flexural Strength

The flexural test evaluated a 100mm x 100mm x 500mm reinforced concrete beam, incorporating 1% MicPOFA and NaPOFA as cement replacement, in comparison to the control SCHPC beam. Figures 3 and 4 demonstrate the Load-Deflection curves derived from three sets of concrete mixes, SCHPC, SCHPCMP1 and SCHPCNP1, at 28 and 365 days.

Figures 3 and 4 depict the load-deflection characteristics of various concrete mixtures both with and without optimal proportions of MicPOFA and NaPOFA replacing cement, examined at day 28 and day 365 through a three-point bending test. At day 28, the ultimate load (F_{max}) of SCHPC mixes with optimal MicPOFA (SCHPCMP1) showed a decrease compared to the control SCHPC, recording 48.65 kN. Conversely, SCHPC mixes with optimal NaPOFA (SCHPCNP1) exhibited higher results than the control SCHPC, marked by a 1.8% increase, reaching 51.87 kN. However, by day 365, both SCHPCMP1 and SCHPCNP1 displayed notable improvements in F_{max} , recording 82.31 kN and 82.80 kN, respectively, with increments of 31.17% and 31.96% compared to the control SCHPC. On day 28, the control SCHPC showed a rapid increase in load with minimal midspan deflection growth. Figure 2 illustrates that the control SCHPC reached a maximum mid-span deflection of 1.43 mm at F_{max} of 50.47 kN, indicating brittle behaviour. In contrast, SCHPCMP1 and SCHPCNP1 exhibited a more gradual increase in load accompanied by midspan deflection. Their maximum mid-span deflections were 1.9 mm and 2.57 mm at F_{max} of 48.65 kN and 51.38 kN, respectively, suggesting enhanced ductility compared to the control.

The data suggests that SCHPC incorporating POFA exhibits less brittleness and greater ductility than conventional SCHPC. Nano POFA, in particular, exhibited enhanced early-age performance, attributed to its ultra-fine particle size distribution and elevated pozzolanic reactivity, which contributed to accelerated secondary hydration and matrix densification. By day 365, the SCHPCNP1 mix achieved the highest recorded ultimate flexural load and exhibited marked ductile behaviour under bending stress. These outcomes signify a marked improvement in structural integrity, fracture resistance, and long-term serviceability when compared to the control and SCHPCMP1. The enhanced load-carrying capacities of SCHPCMP1 and SCHPCNP1 can be attributed to improvements in material properties,

resulting in more durable concrete. Additionally, nano-sized POFA reacts with cement hydration products over time, producing secondary C-S-H gels that enhance microstructure and bonding strength, resulting in stronger and more durable concrete.

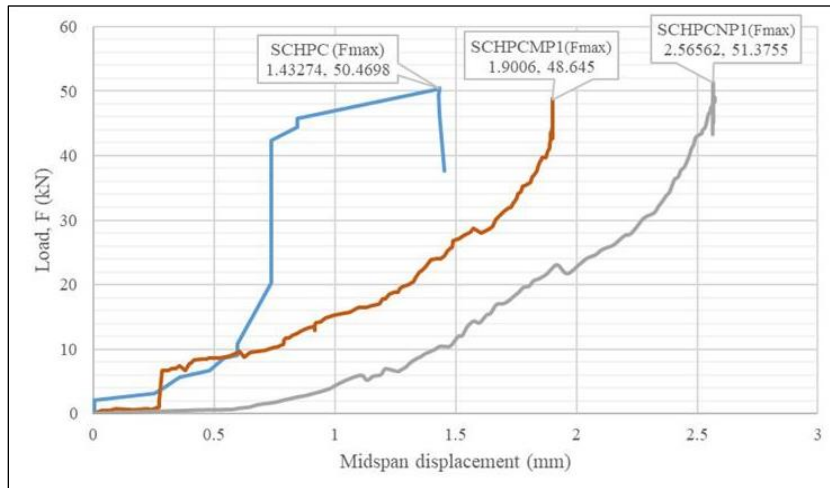


Figure 3. Load-Deflection Curve of Three (3) Series of SCHPC Mixes Without and With Optimum Percentages of MicPOFA and NaPOFA as Partial Replacement to Cement at Day 28

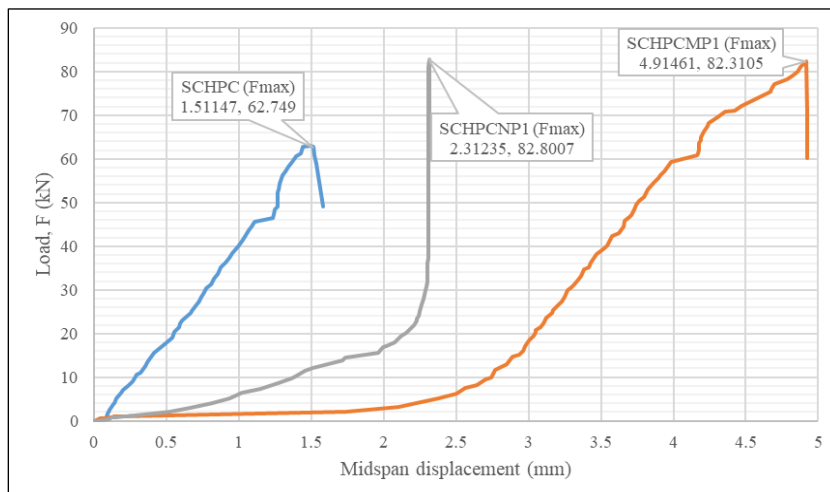


Figure 4. Load-Deflection Curve of Three (3) Series of SCHPC Mixes Without and With Optimum Percentages of MicPOFA and NaPOFA as Partial Replacement to Cement at Day 365

According to Karim et al. (2014) palm oil fuel ash (POFA) shows significant potential as a partial cement substitute in concrete due to its pozzolanic properties, attributed to its substantial silicon dioxide content. This silicon dioxide reacts with calcium hydroxide ($\text{Ca}(\text{OH})_2$) generated during the hydration process, resulting in the formation of calcium silicate hydrate (C-S-H) gel. This reaction reduces the amount of $\text{Ca}(\text{OH})_2$, thereby enhancing the durability and strength of the concrete. Additionally, the fineness of POFA improves the mechanical properties of concrete through the reaction of SiO_2 with $\text{Ca}(\text{OH})_2$, leading to the formation of additional C-S-H. Hamada et al. (2018) corroborate this, noting that the pozzolanic behaviour of nano POFA particles produces secondary C-S-H gels through reactions with free lime, further supporting the enhancement of concrete properties.

Fracture Energy

The Fracture Energy, denoted as G , is a crucial factor in comprehending the response of beam specimens to loading conditions, quantifying the energy released during fracture or failure. This study aimed to characterize the fracture energy of beam specimens constructed from various formulations of SCHPC, including SCHPCMP1 and SCHPCNP1. Table 3 displays the fracture energy values obtained at the ultimate load of SCHPC, SCHPCMP1, and SCHPCNP1 specimens, determined through the application of Irwin’s modification. A comparison of these values offers valuable insights into the fracture behaviour and mechanical performance of SCHPC, SCHPCMP1, and SCHPCNP1.

Table 3. Fracture Energy at Ultimate Load of SCHPC, SCHPCMP1, and SCHPCNP1 at Day 28

Concrete Mixes	Ultimate Load, (Fmax) kN	Midspan Displacement, (d) mm	Crack Length, (a) mm	$C = d/F_{max}$	dC/da	Fracture Energy, kN/mm	Pre-Crack Width, mm
SCHPC	50.470	1.43274	82.588	0.028	132.09	1067	0.389
SCHPCMP1	48.645	1.9006	77.878	0.039	154.34	1277	0.290
SCHPCNP1	51.376	2.56562	61.136	0.050	269.90	2909	0.140

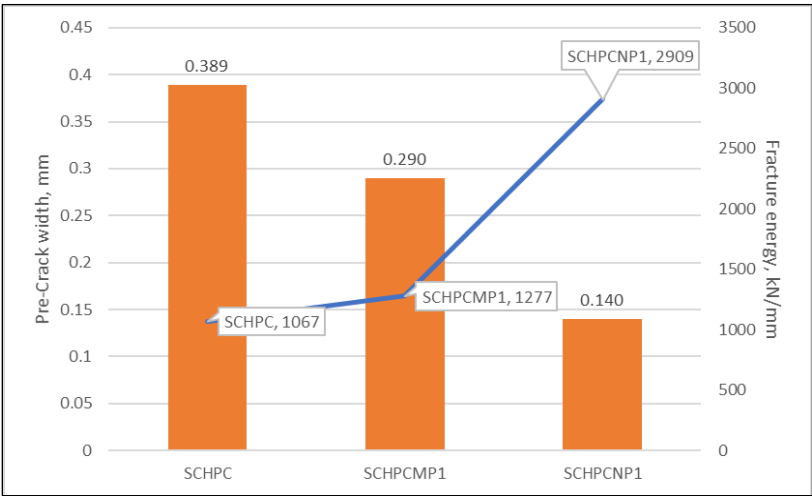


Figure 5. Relationship Between Pre-Crack Width and Fracture Energy of SCHPC, SCHPCMP1, and SCHPCNP1 at Day 28

The analysis of fracture energy trends provides significant insights into the mechanical properties of the concrete samples. Fracture energy, a key indicator of a material's toughness and resistance to crack propagation, measures a material's ability to absorb energy before failure. Figure 5 illustrates the relationship between pre-crack width and fracture energy for SCHPC, SCHPCMP1, and SCHPCNP1. Among the tested samples, SCHPC showed the lowest fracture energy at 1067 kN/mm², indicating its brittleness and limited energy absorption capacity, resulting in lower crack propagation resistance. This is evident from the larger crack width of 0.389 mm observed in SCHPC. In contrast, SCHPCNP1 exhibited the highest fracture energy of 2909 kN/mm², correlating with a significantly smaller crack width of 0.140 mm. SCHPCMP1 had an intermediate fracture energy value of 1277 kN/mm², resulting in a smaller crack width of 0.290 mm compared to SCHPC.

In conclusion, at 365 days, the SCHPCNP1 mix demonstrated the highest fracture toughness and resistance to crack propagation, as evidenced by its peak fracture energy capacity and reduced crack width, indicating improved energy absorption and post-cracking performance. The inverse relationship between fracture energy and crack width highlights the importance of fracture energy in determining concrete performance. Higher fracture energy, as seen in SCHPCNP1, leads to better crack resistance and increased durability, making such mixes ideal for applications requiring enhanced structural integrity and long-term durability.

Table 4. Fracture Energy at Ultimate Load of SCHPC, SCHPCMP1, and SCHPCNP1 at Day 365

Concrete Mixes	Ultimate Load, (Fmax) kN	Midspan Displacement, (d) mm	Crack Length, (a) mm	C = d/Fmax	dC/da	Fracture Energy, kN/mm	Pre-Crack Width, mm
SCHPC	50.470	1.43274	82.588	0.028	132.09	1067	0.389
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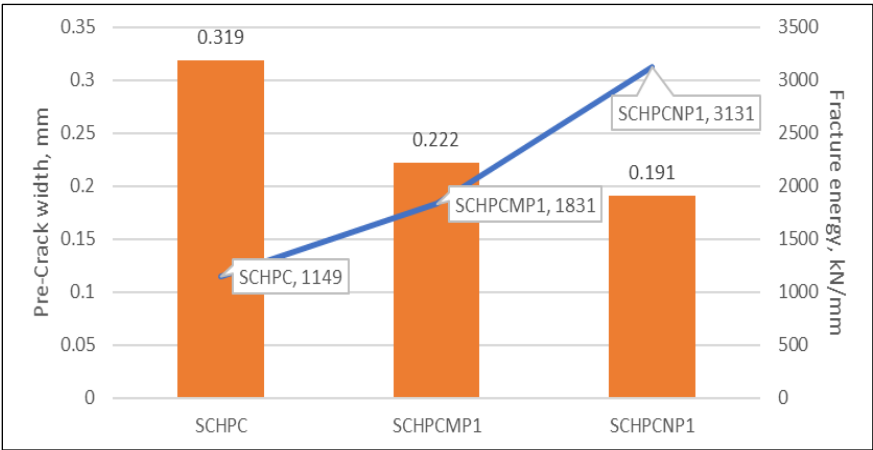


Figure 6. Relationship Between Pre-Crack Width and Fracture Energy of SCHPC, SCHPCMP1, and SCHPCNP1 at Day 365

Figure 6 illustrates the relationship between pre-crack width and fracture energy for SCHPC, SCHPCMP1, and SCHPCNP1 at day 365. SCHPC has the lowest fracture energy value of 1149 kN/mm², indicating a relatively low ability to absorb energy before failure, thus making it less tough compared to the other mixes. The observed crack width for SCHPC is 0.319 mm, which, despite being higher than the other two mixes, is still relatively small. SCHPCMP1 significantly improves fracture energy compared to SCHPC, with a value of 1831 kN/mm². This higher fracture energy suggests that SCHPCMP1 has greater toughness and can absorb more energy before failure, enhancing its resistance to crack propagation. The crack width for SCHPCMP1 is 0.222 mm, smaller than that of SCHPC, contributing to its better crack resistance.

SCHPCNP1 validates the highest fracture energy value of 3131 kN/mm², indicating it is the toughest among the three mixes with the highest energy absorption before failure. The SCHPCNP1 mix recorded the smallest crack width at 0.191 mm, indicating enhanced microcrack control and effective resistance to crack propagation under flexural loading. The observed trend from day 28 to day 365, as SCHPC, SCHPCMP1 and SCHPCNP1 exhibited increased fracture energy and reduced crack widths, suggests progressive improvement in

fracture toughness and post-cracking behaviour due to continued hydration and matrix refinement over time. This trend highlights optimising the concrete's internal structure as it cures, leading to enhanced mechanical performance and long-term durability.

Model Adequacy Verification and Interaction Verification Between Factors

The relationship between compressive strength, ultimate load, and fracture energy was analysed using Design Expert 11.0.5. The 3D response surface Figure 7 facilitated the evaluation of these parameters under different mix compositions and curing ages, providing insights into the mechanical behaviour and structural performance of the concrete specimens.

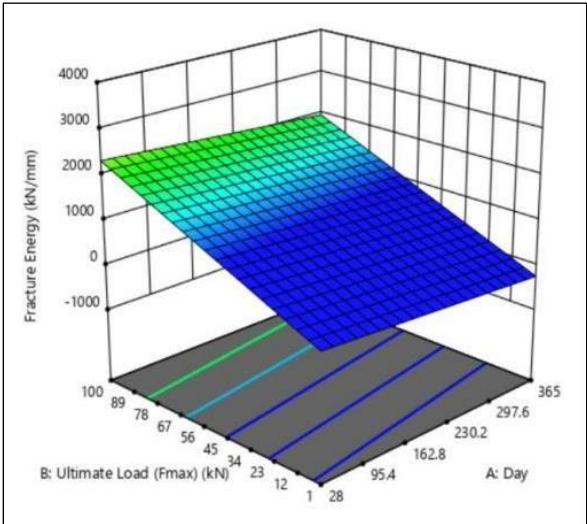


Figure 7. 3D Representation of The Response Surface of The Flexural Strength of SCHPC, SCHPCMP1, and SCHPCNP1

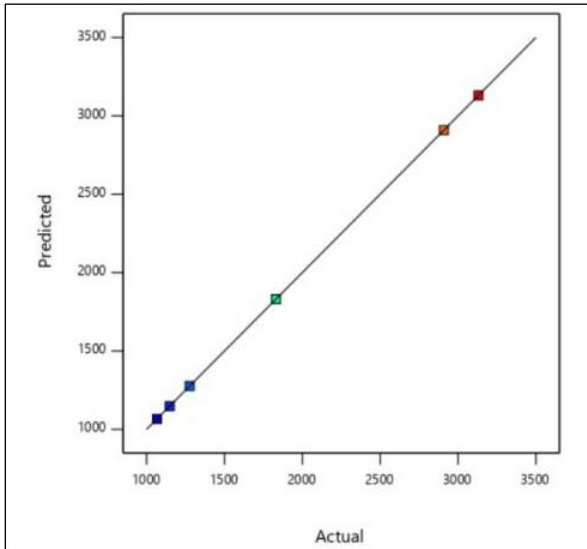


Figure 8. Predicted vs. Actual Value of SCHPC, SCHPCMP1, and SCHPCNP1 Fracture Energy

Figure 8 illustrates the distribution of fracture energy values across various mix compositions, revealing the inherent variability of this parameter. Despite the apparent dispersion, a clear linear correlation between the actual and predicted values was observed, highlighting the reliability of the predictive model. The alignment of data points along the trend line affirms the model's accuracy in forecasting fracture energy outcomes. Overall, the use of Design Expert 11.0.5 enabled a comprehensive evaluation of the interrelationship between compressive strength, ultimate load, and fracture energy, enhancing the understanding of performance characteristics and predictive behaviour for SCHPC, SCHPCMP1, and SCHPCNP1 mixes.

Numerical Optimization of The Best SCHPC Mix

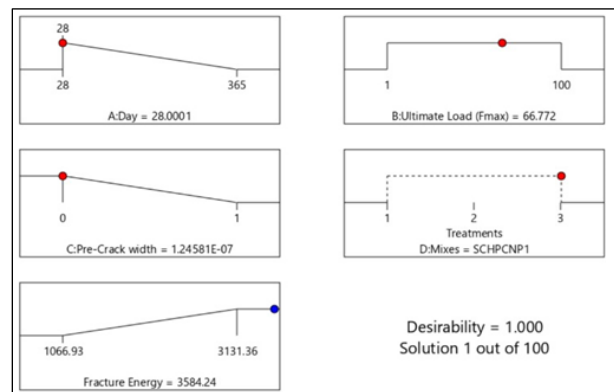


Figure 9. Best Mix Comparison Between Control and Optimum POFA Replacement on Maximum Strength at 28 Days

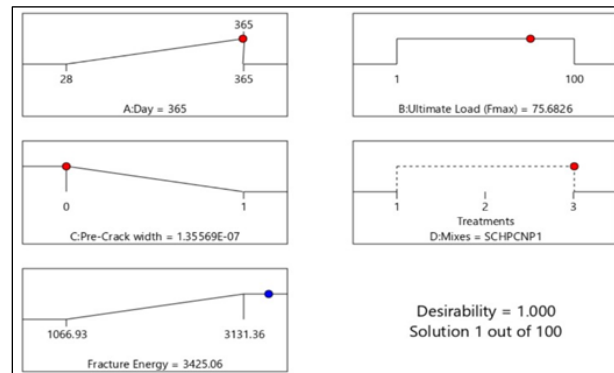


Figure 10. Best Mix Comparison Between Control and Optimum POFA Replacement on Maximum Strength at 365 Days

Numerical optimization was conducted on SCHPC, SCHPCMP1, and SCHPCNP1 mixes to identify optimal parameters influencing their fracture energy. Key factors considered were the day of the flexural test, Ultimate Load, and Pre-Crack Width. The study aimed to determine the best mix among the control SCHPC, Micro-based SCHPC, and Nano-based SCHPC by minimizing pre-crack width and maximizing fracture energy. Results presented in Figures 9 and 10 for testing ages 28 and 365 days aimed to enhance SCHPC performance by carefully controlling input parameters. This provided insights for selecting suitable mix compositions for specific engineering applications, considering both short-term and long-

term performance. Using Response Surface Methodology (RSM), the study highlighted SCHPCNP1 exhibited outstanding performance in both flexural capacity and fracture energy, achieving peak load values of 66.77 kN at 28 days and 75.68 kN at 365 days, along with corresponding fracture energy values of 3584.24 kN/mm and 3425.06 kN/mm, respectively. These results highlight the structural efficiency of nano-POFA incorporation, providing experimental validation for mix design optimisation and contributing to advancements in high-performance concrete technology and modern structural engineering applications.

Discussion of Limitations

While the findings offer valuable insights into the mechanical performance and fracture behaviour of SCHPC incorporating MicPOFA and NaPOFA, several limitations must be acknowledged. Firstly, the experimental scope was confined to small-scale laboratory specimens, and extrapolation to full-scale structural elements warrants further validation. Besides, the long-term durability performance, particularly under aggressive environmental exposures such as carbonation, chloride ingress, or freeze-thaw cycles, remains unaddressed beyond the 365-day curing period. Future investigations should incorporate extended durability assessments under service-like conditions to support practical implementation.

CONCLUSION

Over the past five years, there has been substantial growth in research on palm oil fuel ash (POFA), particularly regarding its utilization in specific concrete types like high-strength concrete (HSC). A recent study by Hamada et al. (2023), titled "Impact of Palm Oil Fuel Ash on High Strength and Ultra-High-Performance Concrete: An In-depth Review," examined the effects of POFA on HSC and ultra-high-performance concrete (UHPC) in both fresh and hardened states. Despite the considerable research in this domain, there is a noticeable gap in comprehensive investigations concerning the incorporation of various particle sizes of POFA in specialized concrete mixes. This study aimed to fill these gaps by focusing on the flexural test outcomes utilized to analyse fracture energy using Irwin's modification method. This approach provided a thorough understanding of the behaviour and strength characteristics of concrete structures. Subsequently, a Design Expert was employed to examine the beam structures and serve as a reliable guideline for predicting their practical application. This extensive analysis offered valuable insights into the behaviour and performance of the concrete beams. In conclusion, SCHPCNP1 emerges as a standout performer, demonstrating its effectiveness in improving concrete performance, particularly in terms of exceptional flow and mechanical properties. Nevertheless, SCHPCMP1 also shows significant improvement compared to the control SCHPC. The utilization of POFA has proven to enhance concrete properties, driving innovation in green concrete technology and holding immense promise for the construction industry by offering sustainable solutions for high-rise buildings, bridges, and infrastructure projects. Furthermore, these innovative concrete mixes have broader applications beyond new construction projects and can effectively contribute to the repair of deteriorated concrete structures, providing high-strength structural repairs and prolonging the service life of existing infrastructure. In summary, the findings of this study underscore the significant potential of SCHPCNP1 and SCHPCMP1 in revolutionizing concrete technology and advancing sustainability in the construction sector through the utilization of POFA, paving the way for environmentally friendly construction practices and sustainable infrastructure development.

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AUTHOR CONTRIBUTION

The authors affirmed their equal involvement in every aspect of this study. All authors thoroughly reviewed and endorsed the final version of this work.

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EXPLORING BAMBOO FIBER TEXTILE-REINFORCED MORTAR (BTRM) FOR SUSTAINABLE STRUCTURAL STRENGTHENING: PULL-OUT AND FLEXURAL STRENGTH INVESTIGATION

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Abstract

Textile Reinforced Mortar (TRM) represents a cutting-edge advancement in cementitious composites, offering versatility in civil infrastructure enhancement and structural rehabilitation. Comprising high-performance textile reinforcement and a cement-aggregate matrix, TRM provides lightweight construction, durability, and design flexibility. This study investigates the pull-out and flexural strength of Bamboo Fiber Textile-Reinforced Mortar (BTRM) as a sustainable alternative. The research explores the impact of bamboo textile mesh sizes (M1-M5) on bond characteristics and flexural behaviour. Pull-out tests reveal superior performance for smaller mesh sizes, emphasizing the interplay between mesh characteristics and material performance. Flexural tests demonstrate enhanced strength in BTRM, attributing it to the tensile strength of bamboo fibres, textile structure benefits, and optimized mesh sizes. The study delves into failure modes, showcasing a shift from brittle to ductile behaviour in BTRM, with bamboo textiles controlling crack widths, enhancing post-crack behaviour, and improving structural safety. This research contributes valuable insights for designing bamboo textile-reinforced structures, emphasizing sustainability and performance optimization.

Keywords: *Textile reinforced mortar (TRM); Bamboo fibre textile-reinforced mortar (BTRM); Sustainable construction; Mesh size optimization; Bond characteristics.*

INTRODUCTION

Textile Reinforced Mortar (TRM) stands as a cutting-edge advancement in the domain of cementitious composites, serving as a versatile solution to enhance civil infrastructure and reinforce deteriorated structures. With a myriad of advantageous properties, TRM offers lightweight construction, durability, design flexibility, and ease of installation, establishing itself as a compelling choice in the innovative applications of civil engineering, particularly in the realms of precast elements and structural rehabilitation. The fundamental composition of TRM involves the integration of high-performance textile reinforcement, composed of continuous multi-filament yarns such as polypropylene, glass, basalt or polyamides, into a matrix comprising cement as a binding agent and well-distributed, small-size aggregates. This combination not only results in a robust material but also enables adaptability to diverse structural requirements. The choice between planar (2D) or spatial (3D) textile reinforcement depends on the specific load application (Murcia, Çomak, Soliman & Reda Taha, 2022; Wu, Pan & Yan, 2023), underscoring the flexibility and customization potential of TRM.

The spectrum of potential applications for TRM is vast, encompassing architectural facades, sandwich wall panels, load-bearing shell structures, and storage units such as tanks and silos (Murcia et al., 2022). Furthermore, TRC has demonstrated its efficacy in strengthening existing reinforced concrete structures, showcasing its versatility in retrofitting applications. Studies indicate that TRM could serve as a viable alternative to traditional Fiber-Reinforced Polymer (FRP) composites for flexural and shear retrofitting, offering similar capacity enhancements while surpassing in durability (Kong, Mesticou, Michel, Si Larbi & Junes, 2017; Murcia et al., 2022). Presently, a substantial body of research has delved into examining the effectiveness of TRM in bolstering structural strength. Investigations focused on flexural strengthening of reinforced concrete (RC) elements, such as beams (Du, Shao, Chu, Zhou & Su, 2021; Giese, Giese, Dutra & Da Silva Filho, 2021; Guo et al., 2022; Koutas & Papakonstantinou, 2021; Song et al., 2023) and slabs (Dong, Deng, Dai & Song, 2021; Zhang, Wang, Lu & Guo, 2022), consistently reveal that when TRM is employed as a strengthening material, it significantly enhances flexural capacity while concurrently reducing deflection and crack widths in the structure. Widely acknowledged is the fact that incorporating additional layers of TRM in the strengthening of beams or slabs results in a notable increase in ductility and bearing capacity (Zhang et al., 2022).

TRM has also been successfully utilized in retrofitting masonry structures, proving effective in enhancing the in-plane behaviour of masonry walls (Furtado, Rodrigues, Arêde, Melo & Varum, 2021; Meriggi, Caggegi, Gabor & de Felice, 2022). This application results in increased strength and displacement capacity, accompanied by a certain level of ductility before failure. Notably, TRM addresses the common occurrence of wide cracks in unreinforced walls, ensuring more uniformly distributed shear stresses, smaller cracks, and a spread over the surface of the wall (Del Zoppo, Di Ludovico & Prota, 2019). Consequently, innovative TRM composites stand out as one of the most effective techniques for preventing failure and ensuring seismic protection in earthquake-prone areas, applicable to both structural and non-structural construction elements. The effectiveness of TRM in strengthening RC structures or enhancing the in-plane capacity of masonry depends on several factors, encompassing the geometrical and mechanical properties of the textile, the strength and stiffness of the matrix, and the retrofitting layout. Despite its unique structural performance, recent research has identified challenges related to the failure behaviour of TRM structural elements, specifically concerning the properties and geometrical structure of the yarns constituting the textile and the mesh size of the textile itself.

The geometrical characteristics of textiles, including yarn nature and arrangement, play a crucial role in predicting the performance of reinforced cement composites (Peled & Bentur, 2000). The study underscores that textile geometry can positively influence bonding and enable strain hardening in low modulus yarn textiles (Beßling, Manko & Orlowsky, 2022). However, variations in textile geometry may reduce efficiency, diminishing the strengthening effect of the yarns (Peled & Bentur, 2000). Murcia et al. (2022) reported the potential for premature debonding between textile yarns and the cement matrix at low strains. To address this, previous studies (Donnini, Corinaldesi & Nanni, 2016) suggest using organic coats to enhance the bond between fibres and mortar. Issues of early debonding are associated with improper impregnation of fibre textiles by the cementitious matrix, as microscopic images reveal varying degrees of impregnation within fibre filaments (Murcia et al., 2022). The high viscosity of cement slurry limits penetration into narrow spaces in textile yarn, leading to potential debonding under high loading rates (Häußler-Combe & Hartig, 2007; Murcia et al.,

2022). This can impact load-carrying capacity, ductility, and potentially alter the failure mode of the TRM structure.

In traditional TRM applications, textiles typically consist of warp and weft fibre bundles. The failure of TRM composites often results from debonding failures in the stressed warp fibre bundles, exacerbated by slippage between the weft and warp fibre bundles during the cracking process (Zhang et al., 2022). This limits the reinforcing effect of the textile on concrete materials to a certain extent. When it comes to strengthening structures with TRM, various types of textile materials are commonly utilized, including steel (Raji, Mostofinejad, & Eftekhar, 2022) and synthetic fibres such as glass (Furtado et al., 2021) and carbon (Li et al., 2024). However, the high embodied energy of steel and synthetic fibres, along with recycling challenges, presents obstacles to achieving global sustainability goals. In response, there is a growing interest in composites reinforced with natural fibres (green- or bio-composites), which have recently captured the attention of researchers as potential candidates for strengthening applications. Natural fibres offer excellent environmental credentials, being renewable, biodegradable, and recyclable. Nonetheless, concerns about the environmental durability of natural fibres under prolonged exposure to moisture, temperature variations, and UV radiation remain largely unaddressed. Future work should include long-term durability studies of natural textile composites in various environmental conditions. Despite the recognized potential of natural fibres as valid reinforcement materials for TRM, their reliability for strengthening structural concrete or masonry remains limited due to a lack of dedicated attention to experimental lab studies on natural TRM. Particularly, research on the tensile or flexural behaviour of natural TRM in enhancing RC structures has been lacking. In the current development of TRM, only a few studies (Ferrara, Pepe, Martinelli & Tolêdo Filho, 2021; Fidelis et al., 2016; Sadrolodabae, Claramunt, Ardanuy & de la Fuente, 2021; Trochoutsou, Di Benedetti, Pilakoutas & Guadagnini, 2021) have investigated the performance of natural TRM.

This study aims to investigate the pull-out and flexural strength of Bamboo Fiber Textile-Reinforced Mortar (BTRM). Bamboo, being a plant-based natural fibre, stands out as a low-cost renewable material abundant in many countries, including Malaysia. Despite previous research (Althoey et al., 2022; Kumarasamy, Shyamala, Gebreyowhanse & Kumarasamy, 2020) demonstrating the suitability of short bamboo fibres as reinforcement in strengthening cementitious composites, studies on the behaviour of BTRM composites are still limited. To address this gap, the following research questions are posed: 1. How does the mesh size of bamboo textile affect the bond performance between the textile and mortar matrix in pull-out tests? 2. What is the influence of bamboo textile mesh size on the flexural performance of reinforced concrete slabs? This research endeavours to assess the effectiveness and efficiency of bamboo textile by evaluating its performance in the mortar composite through a comprehensive study of bond behaviour (pull-out test) and overall flexural strength properties. The primary focus for the pull-out and flexural tests is placed on the geometrical mesh size of the bamboo textile to comprehend the intricate interaction between the matrix and reinforcement in BTRM.

EXPERIMENTAL PROGRAM

Material Description

Mortar

The mortar matrices utilized in this study were specifically designed to produce specimens for both pull-out and flexural strength tests. The constituents of the mortar mixture included binders (Ordinary Portland Cement and silica fume), fine river sand, water, and a superplasticizer. The chemical composition of the commercial Portland cement and silica fume can be found in Table 1, while Table 2 displays the grading of the fine aggregate used in this study. The mortar mix design for this investigation adhered to a ratio of 1:2.67:0.32 (binder: sand: water-to-binder ratio). In this mix, silica fume (10% by weight of cement) was incorporated as an additional mineral admixture to replace cement content and enhance the strength of the mortar binder. To ensure proper workability, a polycarboxylic ether-based superplasticizer (SP) was introduced during composite fabrication. The flow of mortar mixes was maintained within the range of 27%, ensuring adequate workability for proper compaction during the moulding of specimens. Table 3 illustrates the composition of materials for the mortar mixture.

The experimental study revealed that the average compressive strength of the mortar mix design was approximately 40 MPa. This value was obtained from three mortar cubes tested at 28 days in accordance with the BS EN 12390-3 standard, specifically chosen for this experiment.

Table 1. Typical Chemical Compositions of OPC and Silica Fume

Material	Composition (%)									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	SO ₂	P ₂ O ₅	TiO ₂	Others
OPC	16.00	3.60	2.90	72.00	1.50	0.34	3.10	0.06	0.17	0.34
Silica Fume	90.00	1.20	2.00	1.00	0.60	0.80	0.50	0.05	0.09	4.80

Table 2. Sieve Analysis of Aggregates

Aggregate	Aggregate Passing (%) According to Sieve Size (mm)								
	0.15	0.3	0.6	1.18	2.36	5	10	14	20
Sand	5	17	44	63	91	100	100	100	100

Table 3. Mix Designs of Mortar

Cement (kg/m ³)	Water (kg/m ³)	Sand (kg/m ³)	Silica Fume (kg/m ³)	SP (1% from mass of cement)	Average Compressive strength (MPa)
470	168	1380	47	0.47g	40.0

Table 4. The Properties of Bamboo Yarn Fiber

Properties	Average Maximum Load (N)	Average Tensile Strength (MPa)	Average Tensile Modulus (MPa)	Average Tensile Modulus (GPa)	Average Elongation at Break (%)
Bamboo Fibre	37.089	47.22	49862.51	49.86	33.76

Textile Reinforcement

The test parameters of this study were designed to explore the influence of geometric mesh size in lateral bamboo textile on bond and flexural behaviour when applied to strengthen mortar. In this investigation, the bamboo textile prototype was meticulously crafted through manual knitting using bamboo yarn derived from bamboo plant pulp. The properties of the bamboo yarn fibres utilized in the textiles are outlined in Table 4. The study employed five variations of bamboo textiles, each featuring distinct knitting patterns and mesh sizes in both warp and weft directions (10 x 10mm (M1), 10 x 20mm (M2), 10 x 40mm (M3), 20 x 20mm (M4), and 20 x 40mm (M5)), as textile reinforcement for enhancing mortar specimens, as depicted in Figure 1.

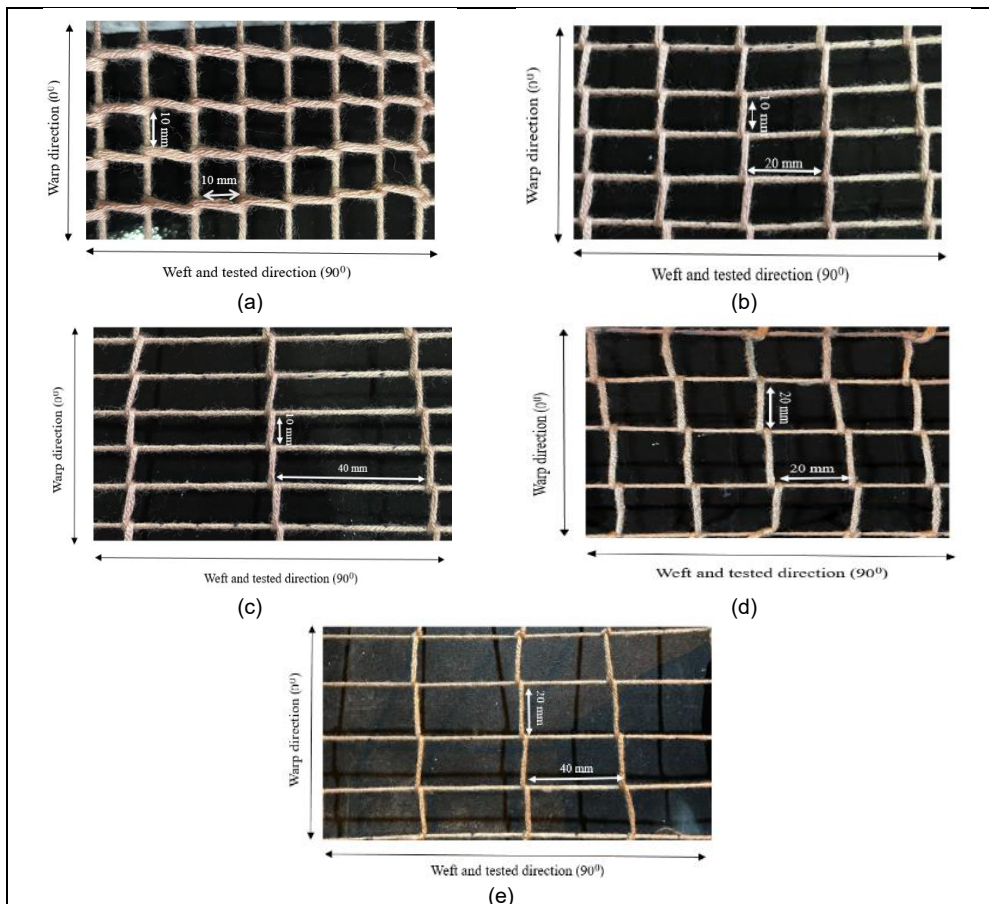


Figure 1. Bamboo Textile Mesh (a) 10x10 mm (b) 10x20 mm (c) 10x40 mm (d) 20x20 mm (e) 20x40 mm

The rationale for selecting these five specific mesh sizes lies in the need to systematically evaluate the effect of both small and large openings, and the influence of mesh aspect ratios (square vs rectangular) on composite performance. Smaller meshes (e.g., M1) are hypothesised to provide greater interfacial bonding due to a higher surface area of contact between textile and mortar. Meanwhile, larger meshes (e.g., M3 and M5) are expected to exhibit reduced mechanical interlock but offer better mortar penetration and less fibre crowding. Additionally, by comparing square meshes (M1 and M4) to rectangular meshes

(M2, M3, M5), the study investigates how directional stiffness and anchorage differ with mesh anisotropy. This mesh range was also constrained by the hand-weaving capabilities of the bamboo yarn and the need to maintain textile consistency across specimens.

Specimen Preparation

In this investigation, the pull-out test setup and specimen configuration were meticulously crafted, drawing inspiration from the double-sided doubly symmetrical test conducted by Butler et al. (2010). The presented experimental work utilized pullout specimens, each fortified with a single layer of bamboo mesh featuring distinct geometrical patterns fashioned in the shape of a bone prism. The specimens exhibited variable thicknesses, with a consistent 10 mm thickness at the ends and a reduced thickness of 5 mm in the proximity of the notch. Furthermore, the samples maintained a uniform width of 50 mm. Five distinct types of specimens were created, with each one reinforced by a single layer of bamboo textile featuring a specific geometric mesh size. Before pouring the mortar matrix, meticulous care was taken to position the textile reinforcement over the mould, ensuring optimal impregnation of the matrix. Following a day of fabrication, the specimens were demoulded and immersed in water at 20°C for a curing period of 28 days. Subsequently, they were removed from water curing and transferred to a controlled laboratory environment with conditions set at 20°C and 65% relative humidity, one day prior to testing. To enhance stability during testing, steel plates were securely affixed to the ends of the specimens and positioned between the clamping jaws of the testing machine.

Meanwhile, specimens for the flexural strength test were crafted using mortar plates with dimensions of 500 mm x 100 mm x 40 mm, with three specimens produced for each sample. A total of 6 series of mortar specimens were meticulously prepared. Within these series, five specimens were embedded with varying mesh sizes of bamboo textile (M1-M5) to reinforce the mortar plate, while one served as a non-embedded control sample (M0). These plate specimens were meticulously prepared and cast in special steel moulds. In order to create the specimens, mortar was applied in 6-7 mm-thick layers using a smooth metal trowel on a dampened concrete surface. The textile was then embedded into the mortar through hand pressure after the first mortar layer was applied. A layer of textile, kept from all four sides, was laid on the fresh concrete and rolled to ensure proper wetting. During casting, the fabric edges were secured by the mould, creating a slightly taut yet not pre-stressed fabric, potentially reducing the initial waviness, increasing peak load, and minimizing slip.

The subsequent mortar layer was applied to completely cover the textile, and a brief vibration (approximately 10s) was applied to the composite during specimen preparation to enhance compaction and penetration of the cement matrix between the textile openings. The specimens were left in the moulds for 24 hours, after which they were removed and cured in a water bath at 20 ± 2 °C for a duration of 28 days.

Experimental Setup and Instrumentation

The specimens for both the pullout and flexural strength tests were prepared and tested after a curing period of 28 days. The diagram of the specimen and the setup for the pullout tests are depicted in Figures 2 and 3, respectively. A universal servo-hydraulic machine operated under a deformation control regime was employed for this test. The strain rate was

consistently maintained at 0.05 mm/min for the textile-reinforced concrete (TRC) specimens throughout the entire test, encompassing both pre-cracking and post-cracking states until specimen failure occurred. Strain measurements were carried out using a linear variable displacement transducer (LVDT) securely fixed to the specimen and oriented in the loading direction. Additionally, the applied load and displacement of the crosshead of the testing machine were recorded to facilitate comprehensive data analysis.

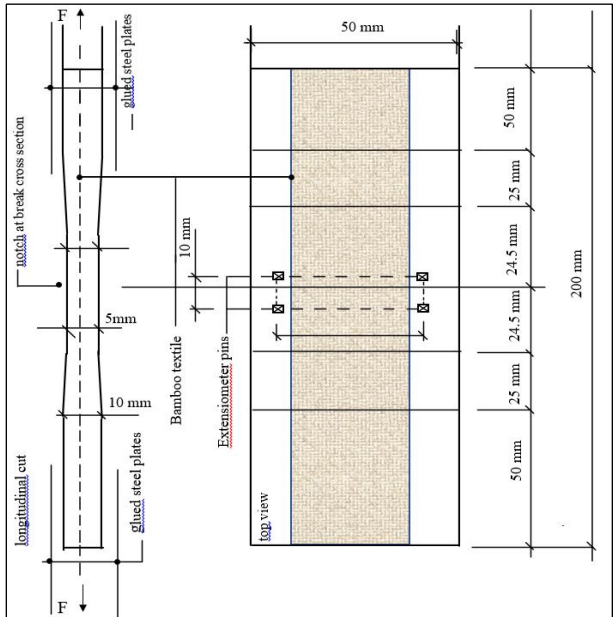


Figure 2. A Schematic Diagram for The Pull-Out Test Setup



Figure 3. Set-Up for The Pull-Out Test

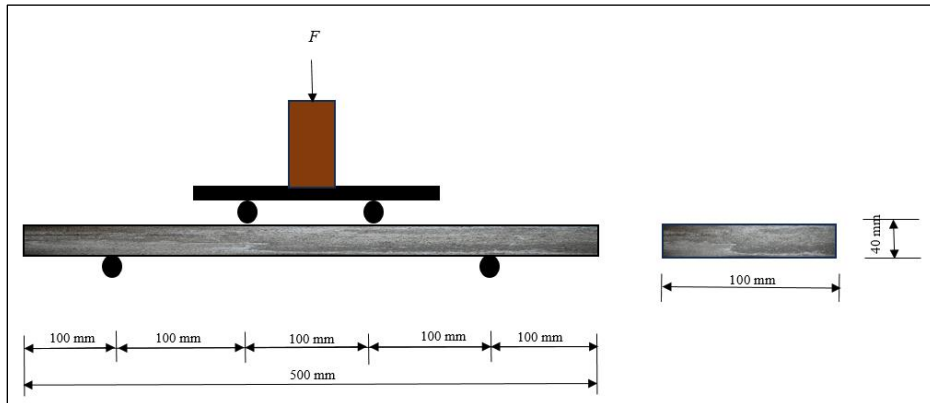


Figure 4. A Schematic Diagram for The Flexural Testing Setup

For investigating the flexural behaviour of the specimens, a four-point bending test was conducted using the TORSEE Universal Testing Machine at a crosshead rate of 1 mm/min. As illustrated in Figure 4, the support span was set at 300 mm, and the arrangement for the beams is presented in Figure 5. During the flexural test, the maximum stress was expected to occur below the point of loading on the beam specimen where the bending is most significant. Gradual and uniform loading was applied to the beam specimen until failure occurred at its ultimate strength. The flexural strength of concrete can be calculated using the following standard equation:

$$f_{cf} = \frac{FI}{d_1 \times d_2} \quad (1)$$

where,

- f_{cf} is the flexural strength (MPa)
- F is the maximum load (N)
- d_1, d_2 are the lateral dimensions of the specimen, in mm
- I is the distance between the supporting rollers (mm)



Figure 5. Set-Up for The Flexural Strength Test

EXPERIMENTAL RESULTS AND ANALYSIS

Pull-Out Test

The average pull-out force versus crack opening curves for all specimens are presented in Figure 6. The findings from the pull-out tests conducted on BTRM offer crucial insights into the bond characteristics between the developed matrix and the bamboo textile, focusing specifically on five different geometrical mesh sizes of bamboo textile. Notably, the results reveal that the knitting size has a substantial impact on the pull-out performance of BTRM. The weaving size M4 (20x20mm) demonstrated the highest maximum force (62.5), suggesting superior bond strength between the bamboo textile and mortar. This result implies that a smaller and more closely spaced mesh may contribute to a stronger bond. Similarly, M5 (20x40mm) exhibited a high maximum force (51.6) and displacement (5.92mm), indicating robust bond performance. Conversely, M3 (10x40mm) displayed the lowest maximum force (20.3), suggesting a weaker bond. The findings underline the importance of selecting an appropriate weaving size to optimize bond strength in BTRM.

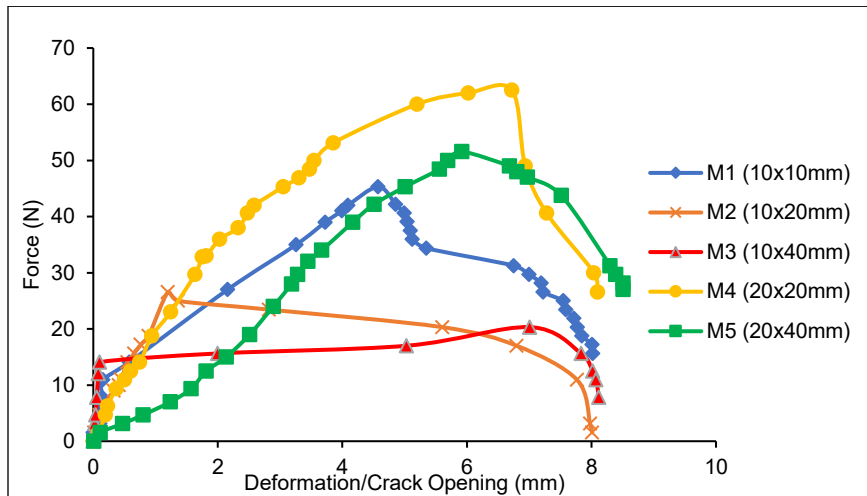


Figure 6. Force Versus Crack Opening Curves

Furthermore, M2 (10x20mm) showed a relatively lower maximum force (26.6) and displacement (1.2mm), suggesting that this weaving size may not provide as strong a bond as others. Overall, the results provide valuable information for engineers and researchers to tailor the design of bamboo textile-reinforced mortar structures based on specific application requirements, with mesh sizes such as M4 and M5 proving favourable for applications where high bond strength is crucial. However, considerations for real-world conditions, environmental factors, and long-term durability remain essential, indicating potential avenues for further research to explore additional influencing parameters on bond characteristics. The findings from the pull-out tests on BTRM highlight the significance of mesh size in influencing bond characteristics between the developed matrix and bamboo textile. The superior performance of M4 (20x20mm) can be attributed to its smaller mesh size, suggesting that a more closely spaced mesh enhances the interlocking and engagement between bamboo fibres and the mortar matrix. This proximity likely results in a more efficient load transfer mechanism, contributing to the higher maximum force observed. The positive outcomes of M5 (20x40mm) may be attributed to a balance between mesh size and spacing, facilitating an

effective distribution of forces and allowing for a robust bond. Conversely, the lower performance of M3 (10x40mm) could be attributed to a combination of larger mesh size and possibly wider spacing, leading to reduced interlocking and load transfer efficiency. The suboptimal performance of M2 (10x20mm) may be associated with a compromise between mesh size and spacing that did not promote an ideal bond strength. Overall, these findings underscore the importance of carefully selecting mesh sizes in BTRM to achieve optimal bonding, emphasizing the intricate interplay between mesh characteristics and resulting material performance.

Flexural Strength Test

The flexural strength results depicted in Figure 7 showcase the performance of various specimens, shedding light on the influence of different bamboo textile mesh sizes on flexural behaviour. The study scrutinized five distinct geometrical mesh sizes (M1 to M5: 10x10mm, 10x20mm, 10x40mm, 20x20mm, and 20x40mm, respectively) alongside an unreinforced control sample (M0). The flexural stress loads were recorded for each specimen, with the control sample (M0) exhibiting a stress load of 6.6 MPa. Notably, all reinforced specimens (M1 to M5) displayed higher flexural stress loads than the control, signifying the positive impact of bamboo textile reinforcement on mortar flexural performance. Specifically, M4 (20x20mm) demonstrated the highest flexural stress load at 7.45 MPa, closely trailed by M5 (20x40mm) at 7.43 MPa. These findings suggest that smaller mesh sizes (as seen in M4) or a balanced combination of size and spacing (as observed in M5) contribute to flexural strength.

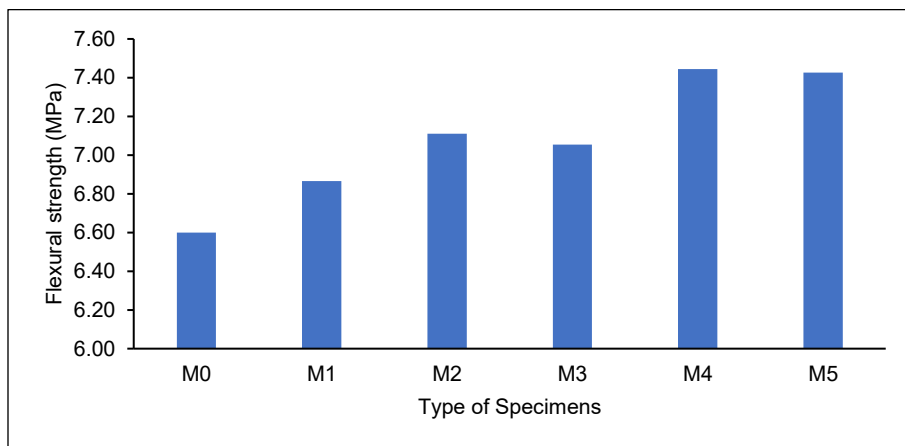


Figure 7. Flexural Strength of All Specimens

The enhanced flexural strength observed in BTRM specimens compared to the control (M0) can be attributed to multiple interconnected factors. Firstly, the inherent tensile strength and flexibility of bamboo textiles act as robust reinforcement, countering bending forces and bolstering the composite's ability to withstand flexural loads. The woven structure of the bamboo textile facilitates a more uniform distribution of stresses within the mortar matrix during flexural loading, preventing localized cracking and promoting consistent load-bearing capacity.

Mechanical interlock, achieved through the knitting of bamboo textile, enhances bonding between yarns and mortar, facilitating an efficient transfer of stresses. The choice of bamboo textile mesh sizes (M1 to M5) allows controlled variation, with specific sizes (e.g., M4 and M5) contributing optimally to overall flexural strength. The synergy between bamboo fibres' tensile strength and the mortar matrix's compressive strength results in a composite material with superior mechanical properties, particularly in flexural loading conditions.

The increased ductility provided by bamboo textiles allows the BTRM composite to deform more before failure, contributing to the observed higher flexural strength. In summary, the improved flexural strength in bamboo textile-reinforced mortar signifies the successful integration of bamboo reinforcement, underscoring the importance of considering weaving characteristics for optimal performance in structural applications.

Analysis of Failure Modes

The surface crack patterns and failure modes of mortar plates subjected to flexural loads are illustrated in Figure 8. Overall, all specimens display similar crack patterns, characterized by the initiation of a single crack during the application of bending load. This crack progressively extends towards the upper portion of the specimen as the load intensifies, ultimately culminating in failure. Noteworthy is the observation that in plain mortar plates (M0), ultimate failure coincides with the formation of the first visible crack during experimentation, indicating a sudden, brittle failure without any discernible warning. The sudden brittle failure and significant drop in flexural strength within the pure flexural zone of the M0 specimen, devoid of textile reinforcement, exemplify a classic behaviour typical of unreinforced mortar or concrete. This behaviour is commonly associated with the inherent brittleness of cementitious materials, which tend to exhibit limited flexural strength. In the absence of reinforcement, the material becomes susceptible to abrupt and catastrophic failure, often marked by the rapid propagation of cracks throughout the specimen.

A distinctive behaviour emerges in BTRM specimens, revealing a remarkable transformation in bending load capacity following the onset of initial cracks, attributed to the presence of the textile reinforcement. In these instances, mortar specimens infused with bamboo textile exhibit a notable strain-hardening response, shifting the failure mode from brittle to ductile. The primary crack initiates at the bottom and ascends. Upon reaching the textile layer, its progression halts, extending upwards while generating fine microcracks around the main fracture. As the intermediate textile adjusts within the mortar matrix, the crack swiftly extends from the middle layer until ultimate failure. The observed enhancement in flexural strength in bamboo textile-reinforced mortar specimens, as previously elucidated, implies that the textile reinforcement effectively mitigates the brittle behaviour witnessed in unreinforced specimens. This reinforcement likely contributes to a more controlled and ductile failure mode, enabling the material to deform and absorb energy before reaching its ultimate limit. The absence of sudden and catastrophic failure in reinforced specimens, evidenced by the necessity to cut the specimen into pieces, underscores the positive impact of textile reinforcement on the overall structural performance of the material. An intriguing insight from this study is that the uncut textile continues to effectively restrain the crack, preventing specimens from undergoing complete breakdown.

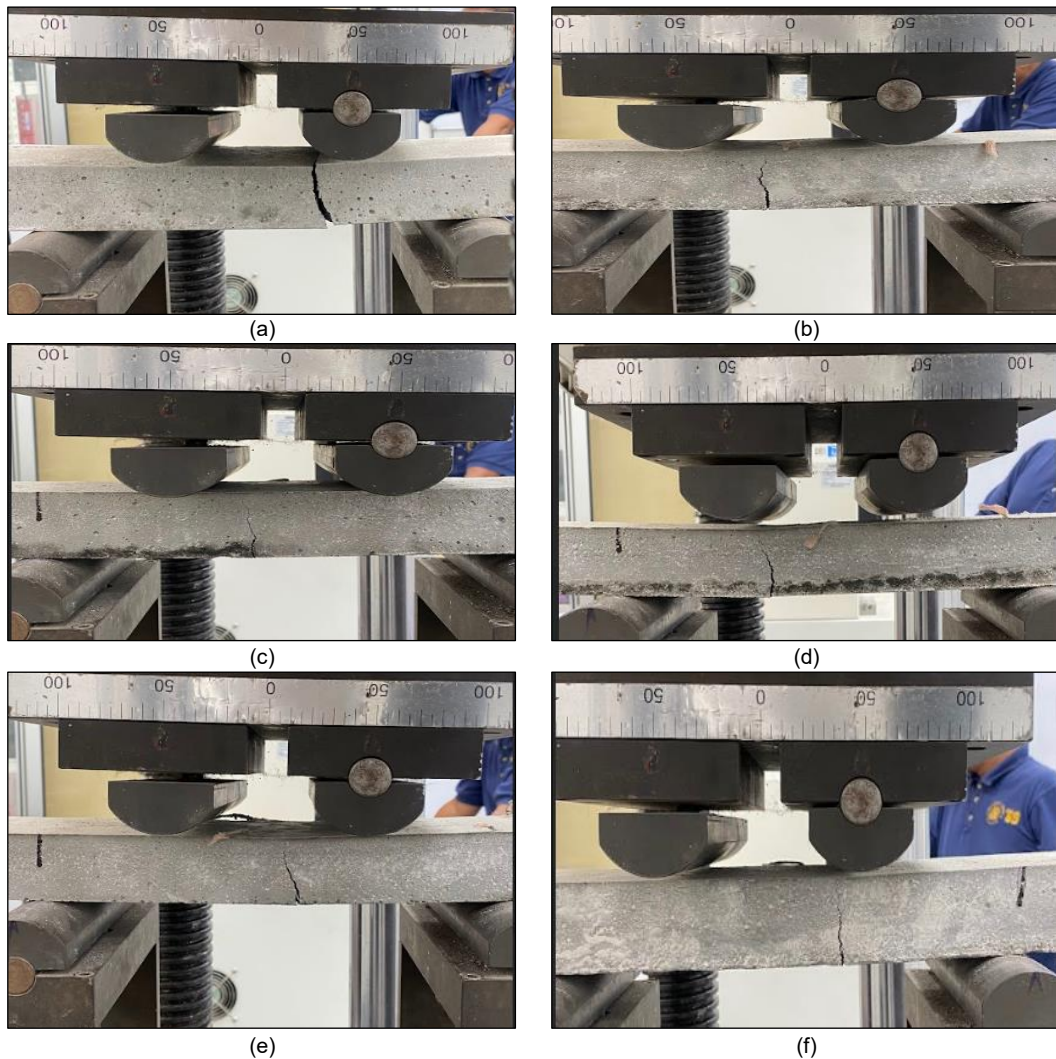


Figure 8. Flexural Failure of Mortar Plates (a) M0 (b) M1 (c) M2 (d) M3 (e) M4 (f) M5

Meanwhile, findings from this research also demonstrate distinctive responses in crack spacing for the M0 specimen compared to others, where M0 exhibits significantly wider crack widths than mortar specimens reinforced with bamboo textile. This suggests that the embedded bamboo textile exerts control over crack widths, acting as effective crack arrestors and enhancing the post-crack behaviour of the slab. This reinforcement contributes to maintaining load-carrying capacity and reducing the likelihood of spalling and fragmentation during failure events, ultimately improving the safety of the structure.

CONCLUSION

In summary, the pull-out test results on BTRM reveal that mesh size plays a pivotal role in influencing bond characteristics between the mortar matrix and the bamboo textile. Mesh types M4 (20×20 mm) and M5 (20×40 mm) demonstrated superior bond strength, whereas configurations such as M2 (10×20 mm) and M3 (10×40 mm) exhibited weaker performance. These findings highlight the importance of selecting optimal mesh geometries to enhance

interfacial behaviour and stress transfer within BTRM systems. Nonetheless, there are trade-offs to consider. While tighter and more closely spaced meshes improve bonding, they may adversely affect mortar workability, complicate textile impregnation, and increase material or production costs. These practical limitations must be weighed when adapting BTRM for large-scale or field applications.

Flexural tests further underscore the effectiveness of bamboo textiles in enhancing the ductility, crack control, and load-bearing capacity of mortar. Reinforced specimens exhibited strain-hardening behaviour and delayed failure, in contrast to the brittle fracture observed in plain mortar (M0). The integration of bamboo textiles resulted in narrower cracks and improved post-crack performance, pointing to their potential in strengthening semi-structural elements.

Despite these positive outcomes, it is important to acknowledge that the study was conducted under controlled laboratory conditions. Variables such as environmental exposure, moisture ingress, biological degradation, and freeze-thaw cycles were not addressed. As such, future research should investigate the long-term durability and field performance of BTRM under diverse environmental conditions to support its broader adoption. In conclusion, BTRM demonstrates significant promise as a sustainable and mechanically efficient alternative to conventional textile-reinforced mortars. With further validation in real-world scenarios and appropriate optimisation, BTRM has the potential to replace traditional TRMs in low-cost, eco-friendly reinforcement applications—particularly in regions prioritising renewable materials and sustainable construction solutions.

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OPTIMIZING CONSTRUCTION COST MANAGEMENT IN MALAYSIAN RAIL DEVELOPMENTS: REVIEW OF MULTIPLE ROLES WITHIN A PROJECT TEAM

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Abstract

Rail projects in Malaysia, spanning from 1956 to 2025, have been a focal point of national goals and strategies outlined by the government. However, numerous challenges have emerged, notably concerning escalating costs, misalignment within project teams, and a persistent pattern of project delays. It has become increasingly apparent that the rail industry lacks academic research addressing critical issues in cost management that have led to cost overrun. This paper aims to address this gap by examining the current data available from research publications related to construction cost management in Malaysian rail developments. A systematic review of 23 journal publications spanning from 2018 to 2023 has been conducted, focusing specifically on research pertaining to rail cost management. The review analysis revealed the inadequate implementation of project cost management practices within the rail construction industry, along with unclear involvement of project team throughout the pre-construction and construction phases. The review also identified several key areas for future research and highlights four critical components of cost management (planning, estimating, cost budgeting, cost control) that have been consistently underutilized in rail projects, serving as key indicators of cost overruns. The research outcome can provide valuable insights for project managers and quantity surveyors, equipping them with the formulation of effective strategic plans and mitigating the risk of cost overrun in Malaysian rail projects.

Keywords: *Construction Cost Management; Construction Project Management; Rail Projects; Quantity Surveyor; Project Team*

INTRODUCTION

The growth of the rail industry has had a positive impact on the country's economy, primarily because people heavily rely on road transportation. Malaysia continuously pursued initiatives that encouraged the development of its rail industry, starting with the First Malaya Plan (1956–1960) in 1956 and continuing with the Malaysia National Land Public Transport Master Plan (NLPTMP) in 2014 (Chen et al., 2018) the National Transport Policy 2019–2030, the Malaysian Rail Supporting Industry Roadmap 2030, the Mid-Term Review of the Eleventh Malaysia Plan for 2016–2020, and the 10th Malaysia Plan (10MP) for 2011–2015. In light of Malaysia's considerable efforts to develop its rail network, it is imperative for ensuring productive rail investment, in contrast to projects globally that experience massive cost overruns (Ismail et al., 2021). Moreover, Malaysia has experienced a persistent problem with cost overruns for the previous thirty years.

A number of studies with an emphasis on the cost control of rail projects have also been carried out (Hemanta Doloi, 2012). According to previous research, errors in three areas—cost, time, and quality—are the main causes of financial loss and project delays globally. Rail construction projects are typically expensive, large-scale, and have a dismal track record of being completed on schedule (Andrić et al., 2019). According to Kassa et al. (2020), imprecise

cost estimates and projections have exposed the contractor's cost-estimating methodology. Therefore, it is recommended that the entire project cost management process should be carefully examined (Idan & Dheyab, 2019).

The specific stakeholder and project team role in rail project development has not received sufficient discussion in the large body of research on rail project cost management. Considering the employment of a quantity surveyor and cost manager for rail project cost management, there is a dearth of information in the literature (Omotayo et al., 2022). Concerning this research, the project team plays a variety of responsibilities in the cost management procedures of rail projects, and their participation is crucial for both efficient cost management and ensuring that all parties comply. Based on the reviewed literature, the research discusses the following aspects:

- i. The primary challenges influencing how well railway cost management practice in rail industry.
- ii. The current practices in Asia and Malaysia in ensuring effective participation of project team role in rail project.
- iii. The noticeable gaps in research.

The goal of this study is to conduct a Systematic Literature Review (SLR) of publications over the previous ten years that discuss the significant contributions made by different academicians and project team to the Malaysia rail project's cost management.

LITERATURE REVIEW

Distribution of Article

With reference to Figure 1, the distribution of article records shows that studies of how poorly cost management was implemented resulted in cost overruns in urban rail projects that started in 2003 and have been continuously occurring since 2004 till the present, 2023. It is noteworthy, nevertheless, that prior to 2011, there was little research conducted on this subject; in 2012, only five studies were published. However, research on it remained continuous and significant. It's interesting to see that no articles were published in 2005, 2009, 2010, 2014, or 2015. However, after 2016, there was a sharp rise in publications.

Furthermore, it's worth highlighting that the 23 publications in the second period (2016–2023) were roughly on par with the 12 articles published in the first period (2003–2015). This implies that this rise in research activities could be attributed to the respective countries' desire to expand its rail system. The sudden rise in publication starting from 2016 reveals an upward trend of research in the field of cost overruns in urban rail projects. In contemporary project management, advancement is anticipated to yield knowledge-based economic growth (Matahir et al., 2022). Additionally, technical risks associated with railway construction projects should be thoroughly understood to be managed effectively, particularly those involving cost impact (Hutchinson & Zhang, 2020).

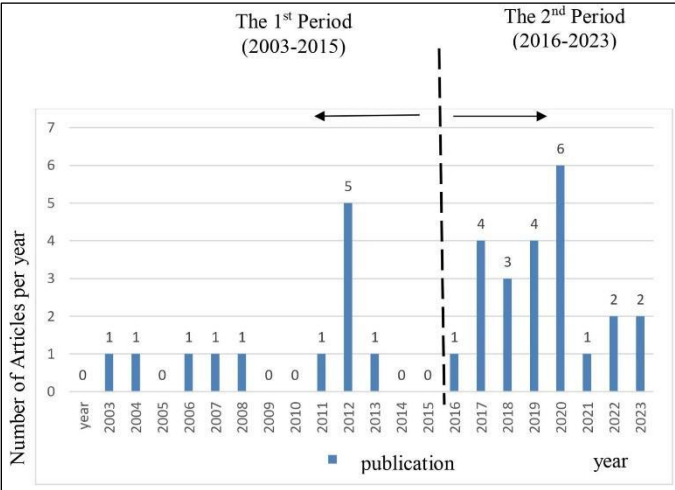


Figure 1. Articles Related to Rail Cost Overrun (2016 to 2023)

Top Journals in Discussing Cost Management in Rail Project

A total of twenty-three journals has published articles related to the research topic. Journal of Transport Reviews were the most active, with publications results Quartile Q1 and the highest impact factor record with 11.3. The majority of articles published today appear in the first and second quartiles (Q1 and Q2), where the number of publications has substantially grown (Fire & Guestrin, 2019). Following Journal of Transportation Research Part A: Policy and Practice and Journal of Construction Engineering and Management – ASCE with 6.4 and 5.213 impacts factor. While Research in Transportation Economics results in Q1 with 3.8 impact factor. Continuously, the following journals, Journal of Infrastructure System records Quartile 2 with 3.462 impact factor. The journal's impact factor (IF) is the most prominent index that the WOS and Scopus databases rely on to rank journals (Aghaei Chadegani et al., 2013).

Table 1. Top Journals That Published Relevant Articles

Source	TP	TC	Impact Factor	Cite	Source
Journal of Transport Reviews	143	92	11.3	20.5	Q1
Journal of Transportation Research Part A: Policy and Practice	1119	13861	6.4	12.4	Q1
Journal of Construction Engineering and Management – ASCE	793	6353	5.213	8.0	Q1
Research in Transportation Economics	340	2235	3.8	6.6	Q1
Journal of Infrastructure System	251	1405	3.462	5.6	Q2

Table 1 shows that the academic subject of cost overrun in rail projects had been discussed well and critically in top tier journals based on their impact and quality. The high Impact Factor and CiteScore for the journals reveal that there are many ongoing research and debate on the subject matter with multiple trending or emerging issue in the discipline. The elevated Impact Factor and CiteScore of these journals indicate not only the academic importance of the topic but also reflect a vibrant and active research community engaged in ongoing debates. This suggests that cost overrun in rail projects remains a pressing and complex issue, with multiple emerging themes and interdisciplinary interest driving evolution of the field.

Countries Under Investigation

Most of the studies were conducted within a single geographic setting, with only one study conducting a comparative analysis between countries. The geographical areas covered in this review is shown in Figure 2.

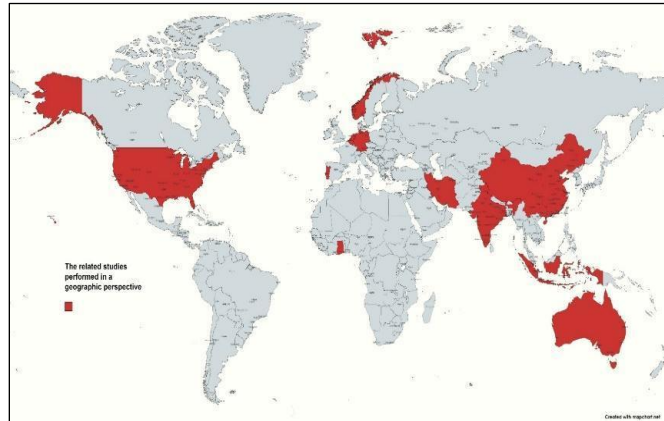


Figure 2. Countries with Literature Associated in The Review

Figure 2 shows a geographical overview of where the study's data or literature came from, indicating an international scope but with some countries contributing more than others. As shown, the study samples were distributed across various countries, with the highest number in the United Kingdom ($n = 6$; 22%), followed by India ($n = 4$; 15%), China ($n = 3$; 11%), the USA ($n = 2$; 7%), and the remaining are Australia, Netherlands, Germany, Norway, Belgium, Africa, Ghana, Portugal, Iran, Hong Kong, Indonesia, and Malaysia with 1 literature (4%) for each nation. These countries might be leading in this research area due to policy relevance, funding, or socio-economic factors.

Thematic Analysis

Summaries of 26 publications' titles and abstracts, which contain important terms, serve as the basis for building the visualization of topical research. In the process of creating theme research, this stage is extremely significant. First, 750 important terms are determined. The research topic covered in the article divides the terminology into four primary components, which are A1: Planning, A2: Cost Estimation A3: Cost Budgeting, and A4: Cost Control. The four major components, as shown in Table 2, stand for the keywords that appear most frequently in the articles.

According to Table 2, the major problem in project management is finding a balance between project costs, deadlines, and quality (Samuel Ogbeibu et al., 2018). According to the Andric et al. (2019) paper, cost overruns are more common in Asia than cost underruns, and they are more likely to occur in railway projects than in road system projects. The biggest issue that Asian countries are dealing with is A1: Planning. For example, in India, delays are thought to be responsible for 40% of overall cost overruns. The same issues with construction delays, numerous design modifications, shifting the scope of work, and longer project durations because of general poor planning during the rail construction phase are present in China, Hong Kong, and Indonesia.

Table 2. Literature Theme Analysis

Item	Country	Sector & Period	Authors	Poor Cost Managements
1	China	Road (74) & rail (21) 1984-2008	Ansar et al. (2016)	A1: Planning costs are systematically biased towards underestimation i. The schedule is met but traded off with quality
2	Hong Kong	Mega transport projects 1985-2015	Huo et al. (2018)	A1: Planning delays in construction, frequent design changes, A2: Cost Estimation inaccurate quantity take-off, fluctuations in the prices of materials i. Rail projects are more prone to cost escalation compared to fixed-link and road projects
3	India	Metro Rail 1984-2019	Kumar et al. (2019)	A1: Planning i. 40% of total cost overrun is assumed to be contributed by delay
4	Indonesia	Railway Signalling Project 1980's	Rustandi et al. (2022)	i. Project Management Practices carried out by LRS have followed the SOPs set by the company A1: Planning changes in the scope of work, an increase in the duration of the work; weak planning A2: Cost Estimation an increase in material prices.
5	Malaysia	Rail 1995-2026	Yusoff et al. (2021) Zhang et al. (2020)	A3: Cost Budgeting i. ECRL is important to CCCC for it is currently the largest (in terms of contract value) railway project in Southeast Asia ii. MRT3 to go execute financial assessment and financial control measures across several routes

A2: Cost Estimation is where the second component exists. Compared to fixed-link and road projects, rail projects in Hong Kong are more likely to experience cost inflation. Unlike in China, where costs are consistently skewed toward underestimating, the timeline is fulfilled at the expense of quality. Inaccurate quantity taken and variations in material prices were also reported as issues.

For A3: Cost Budgeting: Price despite government changes, budgeting has a positive impact on Malaysian rail projects, which regularly manage their budget. The ability of the Malaysian government to implement well-known initiatives like the ECRL and MRT projects shows how dedicated it is to be addressing socioeconomic needs (EPU, 2021). Abdul Rahman Dahlan, a former minister of the EPU, emphasized that the ECRL is expected to have a major multiplier effect and spillover effects that will strengthen the economies along the new trade routes (Habidin et al., 2021). Furthermore, the exceptional accomplishment of Delhi Metro Rail Corporation's Phases I and II, which were finished on time and under budget, is credited to the exceptional management of the former managing director, Sreedharan, who gained the nickname "Metro Man" (Sharma & Newman, 2017).

Ismail et al. (2021) argue that maintaining high-cost performance is the key success criterion for megaprojects, which leads them to call for an evolution away from solely relying on contractor accomplishments (Fentahun Kassa, 2020). Shah & Naghi Ganji's (2019) identification of project success criteria highlight the crucial relationship between project success and its effect on cost and time, giving construction projects a more intricate dynamic

(Aljohani, 2017). There are a number of reasons why cost overrun issues occur, including inexperienced contractors, frequent design modifications, and erroneous quantity take-off (Atapattu et al., 2023) which finally led to the lack of appointment a quantity surveyor in the project team.

The lack of thorough discussion of cost control practices in cost management is evident from the generally subpar application of cost management on rail projects worldwide. Involving the essential parties might contribute to closing any gaps in the overall cost management implementation. An in-depth study to develop a framework for integrating stakeholders in cost budgeting and managing rail the project's costs, particularly in light of Malaysia's rail industry.

RESEARCH METHODOLOGY

The research gathered data by selecting academic articles from relevant journal articles. The database used to retrieve the articles are Scopus, Web of Science and Emerald Insights. Appropriate keywords were used to search for the articles, which are “construction cost management”, “Malaysia rail industry”, “roles of parties”, and “rail projects”. The screening process is illustrated below.

Table 3. Screening Process

Process	Description	Articles Retrieved
1. Initial Keywords Search	Retrieving articles using selected keywords from three academic databases	152
2. Removal of Duplicates	Identifying and removing duplicate entries across databases	115
3. Title Screening	Excluding irrelevant articles based on title content	65
4. Abstract Screening	Reviewing abstracts to assess alignment with research scope	40
5. Full-Text Review	Examining articles for relevance to the topic	23

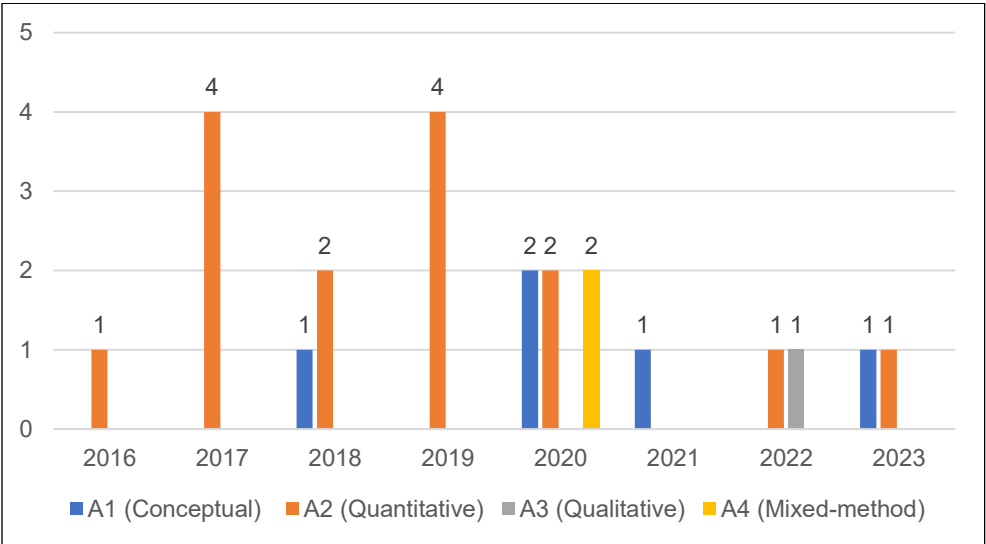


Figure 3. Distinction of Research Methodology in The Literature Reviewed

Ultimately, 23 articles were gathered for literature data analysis. The selected articles have used various techniques of research methodology. The quantitative analysis methodology accounts for 15 cases (65.21%). This is followed by the utilization of conceptual methodology with 5 cases (21.74%), mixed methods make up the third most common approach with used in 2 cases (8.695%) and, the qualitative methodology, represented only 1 case (4.347%), as illustrated in Figure 3.

RESULTS AND DISCUSSION

This study adopts a Systematic Literature Review (SLR) approach to address questions pertaining to cost management in railway projects. In this section, the literature reviewed were discussed based on four research focus.

The Primary Challenges Influencing How Well Railway Cost Management Functions

A thorough examination of 23 articles has identified three overarching categories that encapsulate the primary challenges hindering the effectiveness of cost management in rail projects. Theme has defined three categories, which include:

Theme 1 - Cost Overruns in Global Railway Projects

This theme highlights the prevalence of cost overruns in railway projects across multiple countries, indicating a persistent global issue. The analysis reveals that countries such as Ethiopia, Germany, India, Indonesia, and Malaysia have all experienced significant budget overruns in their rail initiatives (Steininger et al., 2021). Melaku Belay et al. (2021) stated that these overruns are often due to:

- a) Inadequate cost estimation during the planning phase
- b) Unforeseen technical complications during construction
- c) Regulatory delays and changes in project scope
- d) Inflation, material cost increases, and currency fluctuations

The literature emphasizes that despite the differences in economic or political systems, these cost overruns share similar root causes, suggesting a need for universal improvements in forecasting methods, risk management, and cost control mechanisms.

Theme 2 - Poor Implementation of Cost Management Practices and Project Characteristics

This theme focuses on internal project challenges related to the execution of cost management strategies. Poor implementation is often attributed to:

- a) Lack of standardized cost control procedures
- b) Inconsistent use of project management tools and software
- c) Weak integration of cost, time, and quality objectives
- d) Deficient monitoring and reporting mechanisms

Additionally, certain project characteristics—such as complexity, long project durations, and the involvement of multiple agencies—further complicate cost management (Belay et al., 2021). Articles stress the importance of adopting best practices in cost planning, budgeting, and change control throughout the project lifecycle.

Theme 3 - Stakeholder Involvement and Project Team Dynamics

Effective stakeholder engagement and cohesive project teams are essential for cost management success. This theme explores how insufficient collaboration and unclear stakeholder roles can lead to miscommunication, delays, and increased costs. According to Ismail et al. (2023), the key issues include:

- a) Limited early involvement of stakeholders in planning
- b) Misalignment of goals among clients, contractors, and consultants
- c) Lack of accountability and ownership within project teams

Research underscores that strong stakeholder relationships are vital for minimizing conflicts and ensuring smoother decision-making. For instance, Zhang et al. (2020) argue that improving relationships among project participants enhances value creation and project success. Moreover, Andrić et al. (2019) suggest that clear, user-friendly project documentation is essential for aligning expectations and enhancing cost visibility and control.

The Current Practices in Asia and Malaysia in Ensuring Effective Participation of Project Team Role in Rail Project

The outcomes of the analysis ignited a comprehensive qualitative discussion aimed at addressing this subject. The discussion was guided by the co-occurrence network of terms and focused on summarizing the key themes that emerged from the study. More importantly, the research themes that had been explored involved the participation of key stakeholders and project team in the rail industry. There are contractors, government, consultants, suppliers, and project managers. Research on the poor execution of cost management and the involvement of key players in rail projects globally, in Asia, and in Malaysia is shown in Table 4.

The participants of stakeholders and project team are mainly discussed and effected in the performance in rail worldwide project. Considerations for builders and adaptability to various situations during pre-construction and construction phases should be integrated into the early design stage and decision-making processes (Akinradewo et al., 2022). Wu & Jia's (2018) research identifies ineffective public participation as a cause of schedule and cost overruns. For instance, Addis Ababa–Djibouti Railway, the Railway Construction Project in Ethiopia, the political and business interest and psychological bias of project parties and stakeholders are hidden factors which are highly affects project time overruns beyond the initial planned. Additionally, impacted; on the parties of a project and the socio-economy of the country with the total cost overrun USD4 billion (8.83%) from counting years 2011–2018.

Table 4. Research on The Poor Execution of Cost Management and The Involvement of Key Players in Rail Projects Globally, in Asia, and in Malaysia

Country	Project Name, Duration & Cost Overrun <i>Theme 1</i>	Poor Implementation of Cost Management <i>Theme 2</i>	Stakeholder Participants/ Project Team <i>Theme 3</i>	Authors
Ethiopia	Railway Construction Project 2011-2018 Addis Ababa–Djibouti Railway USD4 billion (8.83%)	Findings: design changes, right-of-way risk, construction errors, incomplete contract details, poor site management, and, lack of coordination, the incomplete study to project approval, poor project management and coordination, the right of way acquisition issue, inaccurate forecasting, project stakeholder's overconfidence bias and self-interest of project stakeholders, and inefficiency capacities of contractors.	1.The political and business interest and psychological bias of project parties and stakeholders are hidden factors. 2. Three categorized questions from project delay factors incorporated: technical, over-confidence bias, and self-interest of project stakeholders.	Gashaw et al., (2022) Fentahun Kassa (2020)
German	Railway Launched on 18 April 1994 Stuttgart 21 Railway EUR 8.2 billion (2.228% higher than expected in 1995) The estimated delay is six years	Factors; the project scope changed, the fundamental cost calculation considerations (i.e. price increases and inflation), the project partners underestimated	The combination of economical and political causes proves to be useful for explaining systematic errors which exist in the long run	Steininger et al.(2021) Cantarelli et al. (2010) Flyvbjerg, 2009
India	Metro Rail 1984-2019 Amrit Bharat train-set 40% of total cost overrun is assumed to be contributed by delay		Phase I and II of Delhi Metro Rail Corporation's construction, completed on schedule and within budget, is attributed to the exemplary leadership of the former managing director, Sreedharan, earning him the moniker "Metro Man"	Kumar et al. (2019) Sharma et al. (2017)
Indonesia	Railway Signalling Project 1980's The Whoosh (Jakarta–Bandung high-speed railway)	Project Management Practices carried out by LRS have followed the SOPs set by the company	5 factors that were stated explicitly or implicitly by the informants as the causes of project cost overruns: changes in the scope of work; an increase in the duration of the work; weak planning; and an increase in material prices.	Rustandi et al., (2022)
Malaysia	Rail 1995-2026 KTM Komuter, Kuala Lumpur Monorail, East Coast Railway Line (ECRL), MRT 1: Sungai Buloh- Kajang Line The Gemas-Johor Bahru Electrified Double-Tracking Project, costing RM 9.43 billion	i.ECRL is important to CCCC for it is currently the largest (in terms of contract value) railway project in Southeast Asia ii.MRT projects to meeting socioeconomic demands (EPU, 2021)	i.Former EPU Minister, Abdul Rahman Dahlan, stressed the ECRL is poised to generate significant economic multiplier and spillover effects that will boost the economies along the new trade routes ii.The MRT1 and MRT2 projects, along with the planned Circle Line, aim to enhance rail transit in the Klang Valley, generating significant returns on investment (Yusoff et al., 2021).	Yusoff et al. (2021) Ismail et al. (2021) EPU, 2021 Zhang et al. (2020)

According to Zhao et al. (2019), political and economic factors can be combined to explain systematic errors that endure over time. The informants highlighted the following elements as causes of project cost overruns in Indonesia, Malaysia, and Hong Kong, either directly or indirectly: adjustments to the scope of work, changes in the length of the project that cause delays in construction, inadequate planning, inexperienced contractors, fluctuating material prices, and frequent design modifications (Rustandi et al., 2022). For example, the German railroad Stuttgart 21 Railway is experiencing a running cost overrun of EUR 8.2 billion, which is 2.228% more than anticipated in 1995. The projected delay is six years. An in-depth discussion will be given on the market's volatility and another aspect affecting decision-making (Zhao et al., 2019).

The Noticeable Gaps in Research

This study employs regional time zone analytics in conjunction with a review of frequently cited literature to identify existing gaps in the research. The identified gaps are as follows:

1. Regional and Economic Bias in Existing Literature

One of the most glaring deficiencies in current railway cost management research is its regional and developmental skew. A significant proportion of empirical studies and case analyses are concentrated in developing countries, such as Ethiopia (Gashaw et al., 2022), India (Kumar et al., 2019), and Indonesia (Rustandi et al., 2022), while developed nations—despite having high-profile and often controversial projects like Germany's Stuttgart 21 (Steininger et al., 2021)—are comparatively underrepresented in scholarly databases. This imbalance creates a two-fold problem: (1) the perceived generalizability of findings is skewed toward low- and middle-income economies with different governance, procurement systems, and resource capacities; and (2) there is limited comparative analysis of how cost management practices succeed or fail across different economic, institutional, and technological contexts.

Moreover, developed countries often have more mature systems for integrating digital solutions and BIM (Building Information Modelling) into cost forecasting, yet their experiences are underexamined as potential benchmarks for adaptation in the Global South. This lack of comparative research constrains the development of universally adaptable models for rail project cost control.

2. Deficiencies in Cost Management Documentation and Transparency

A recurring but insufficiently addressed theme in the literature is the lack of standardized documentation and transparent reporting mechanisms throughout the rail project lifecycle. Documentation practices—especially those tied to procurement, change orders, and stakeholder communications—remain fragmented and inconsistent across projects and jurisdictions. Wu & Jia (2018) emphasize that insufficient public participation and documentation inconsistencies are root causes of cost and schedule overruns. Furthermore, inadequate record-keeping impairs institutional memory, weakens auditability, and leads to repeating the same mistakes across projects and generations of project managers.

In the Malaysian context, the failure to maintain accessible, timely, and detailed records during projects like the ECRL or MRT projects restricts the ability to assess long-term economic benefits versus costs and undermines public trust. This is compounded by the opaque communication among stakeholders and inconsistent involvement of cost managers throughout the project's evolution.

3. Absence of a Unified Framework for Professional Involvement in Cost Management

Perhaps the most urgent and under-researched gap is the lack of a standardized, practical framework defining the role and timing of cost management professionals-especially cost managers and quantity surveyors-in rail project teams. There is limited empirical investigation into when these professionals should be involved, how their responsibilities evolve across phases (planning, design, construction, commissioning), and what competencies are critical for effective delivery.

The early exclusion or marginal involvement of cost professionals has been repeatedly linked to flawed initial cost forecasts, unrealistic budgeting, and poor stakeholder communication (Belay et al., 2021; Akinradewo et al., 2022). Yet, academic literature fails to articulate a robust model for integrating these roles within the wider multidisciplinary teams in rail infrastructure projects. This gap also extends to client requirement gathering—a critical phase that often lacks methodological clarity. Research has yet to consolidate best practices for eliciting, validating, and translating client needs into cost-effective project specifications, particularly in complex mega-project environments.

4. Recommendations To Fix Cost Management Issues

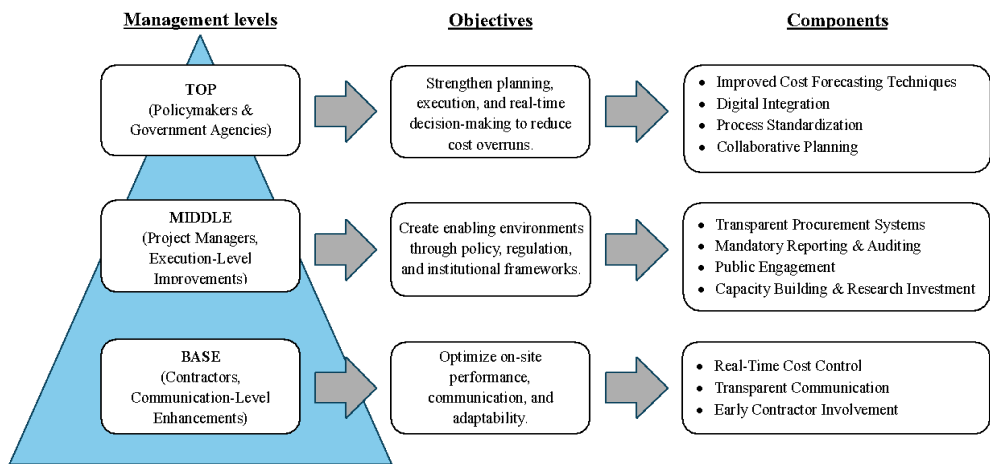


Figure 4. Preliminary Framework

Ultimately, this research identifies a key gap which is to develop a unified cost management framework. Malaysia should emulate the UK's RIBA Plan of Work and NEC Contracts, or India's Metro Rail policies which offer potential blueprints for defining roles of cost professionals, mapping their involvement across project stages and setting expectations for reporting, approvals, and decision-making. Malaysia can customize these to local contexts through pilot programs or public-private collaborations. Drawing on successful international models, the research came up with a preliminary framework that consists of a three-tiered

action plan-operational (project managers), governance (policymakers), and execution (contractors). The parties involved can significantly address the cost management issues and these strategies not only enhance efficiency and transparency but also build the foundation for sustainable rail infrastructure growth. The preliminary framework is shown in Figure 4.

For Project Managers: Operational & Execution-Level Improvements

One of the primary concerns at the project management level is inaccurate cost estimation and forecasting. To combat this, project managers should adopt Reference Class Forecasting (RCF), a method that uses historical data from comparable projects to improve the realism of cost predictions. This technique, notably used in the UK's Crossrail project, helps mitigate optimism bias and strategic misrepresentation (Flyvbjerg, 2007; Love et al., 2015). Furthermore, integrating risk-adjusted models that account for uncertainty is essential to improving forecast accuracy, especially in projects with long timelines and complex interfaces.

The use of digital tools such as Building Information Modelling (BIM) and integrated cost-tracking platforms should be standardised across the project lifecycle. The success of Japan's Shinkansen rail projects illustrates the role of digital integration in enhancing cost visibility and decision-making. BIM not only supports real-time collaboration but also reduces rework and enhances predictive control (Succar & Kassem, 2015; Zhao, 2017). Standardization of processes, including budgeting, reporting, and monitoring, is another crucial strategy. The Delhi Metro, for example, adhered strictly to Standard Operating Procedures (SOPs), facilitating timely completion and budget adherence. Standardization helps reduce scope creep and cost drift by ensuring consistent methodologies and expectations across project teams (Rahman et al., 2013).

Additionally, early team involvement is critical. Bringing in quantity surveyors, cost engineers, and other key personnel during the planning phase—rather than after design finalization—fosters a culture of collaborative planning. Tools such as Integrated Project Delivery (IPD) models promote early and equitable involvement of all stakeholders, helping to align design decisions with budget constraints and construction feasibility (Kent & Becerik-Gerber, 2010).

i. For Policymakers & Government Agencies: Strategic & Governance-Level Reforms

At the policy level, there is a pressing need to enhance transparency and accountability through improved procurement systems. Open tendering processes and the use of digital procurement platforms, as practiced by the UK's National Infrastructure Commission, can reduce corruption and provide traceable, auditable pathways for public spending (Mahmoud et al., 2022).

Equally important is the establishment of mandatory cost reporting and auditing frameworks. Countries like Malaysia could institutionalize these requirements through regulatory bodies such as the Public Works Department (JKR) or the Economic Planning Unit (EPU). National cost management standards should include protocols for change order handling, documentation practices, and audit trails. Such frameworks are essential to institutional learning and long-term capacity building (Osei-Kyei & Chan, 2018).

Public engagement and stakeholder inclusion should also be formalized. Structured participation in early planning stages—through stakeholder forums, town halls, and community surveys—can reduce resistance and last-minute scope alterations. Germany and Japan often incorporate local public councils into transport infrastructure planning, which has led to fewer disruptions and improved social license to operate (Cheng et al., 2020).

Finally, investment in research and training is critical. Government support for universities and technical institutes to develop specialized programs in cost engineering, digital construction technologies (e.g., AI, BIM), and stakeholder communication can strengthen the overall professional ecosystem. The integration of academic knowledge into industry practice can help bridge theory-practice gaps and foster innovation (Li et al., 2021).

ii. For Contractors: Execution & Communication-Level Enhancements

Contractors play a pivotal role in real-time cost control and stakeholder communication. Adopting real-time cost monitoring tools that track labour, material, and equipment usage allows for proactive adjustments. The Japanese concept of Kaizen—or continuous improvement—has been instrumental in maintaining operational discipline and responsiveness on construction sites, promoting iterative improvements in productivity and efficiency (Imai, 2012).

Moreover, transparent communication with clients and consultants is vital for trust and coordination. The use of dashboard-style reporting tools and shared data platforms, such as those employed by Singapore's Land Transport Authority, enables all stakeholders to access up-to-date progress and cost data. This aligns expectations and facilitates timely decision-making (Chong et al., 2021).

Contractors should also be integrated into the early design stages of projects to ensure buildability and cost alignment. The Design-Build (DB) project delivery model exemplifies this approach, promoting early collaboration between designers and builders to reduce conflicts and change orders. Evidence from projects in India and the UK suggests that DB models outperform traditional procurement methods in terms of cost and time efficiency (El Wardani et al., 2006).

CONCLUSION

Through a thorough review of the literature, this study is aimed at helping the project team to participate constructively in the management of the cost of the rail project. It provides a concise overview of previous publications related to current cost management practices in worldwide rail projects. The research addresses the relevant knowledge gaps which calls for a recalibrated research agenda that embraces:

- a) Comparative studies across regions and income classifications;
- b) Development of digital tools for real-time documentation and transparency;
- c) Formalization of cost management roles in early design and strategic planning phases;
- d) Inclusive stakeholder models that integrate socio-political, environmental, and economic realities.

Future research must move beyond descriptive case studies and venture into prescriptive, policy-oriented frameworks that link practice to performance metrics. Furthermore, interdisciplinary collaboration—including urban planners, economists, data scientists, and sociologists—is essential for capturing the full spectrum of cost management influences in rail infrastructure.

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AUTHOR CONTRIBUTION

The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research reported in this study.

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IDENTIFICATION OF SIGNIFICANT BARRIERS TO A SUSTAINABLE LEAN CONSTRUCTION IMPLEMENTATION IN CONSTRUCTION PROJECT

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Abstract

In Malaysia, the construction industry contributes significantly to the country's economic growth. The implementation of sustainable methods, such as lean construction management, can result in significant benefits to the construction industry. Sustainable lean construction is a well-known approach to minimize environmental impacts throughout the project lifecycle. This includes reducing resource consumption, minimizing waste generation, and implementing eco-friendly construction practices such as using sustainable materials, energy-efficient design, and renewable energy technologies. While lean construction has great advantages, its adoption in Malaysia faces so many challenges. Therefore, the objective of this paper is to identify significant issues to a sustainable lean construction implementation through extensive literature review. An online questionnaire survey has been conducted on 22 experienced construction professionals. A quantitative approach which incorporated the use of frequency analysis and mean analysis were used to analyse the data. The results have succeeded in identifying the barriers in few aspects such as management, financial, social and governmental too. Many respondents have highlighted resistance to change by top management as the key obstacles. Furthermore, this paper also suggests ways to increase the implementation of sustainable lean practices in improving project efficiency, reducing costs, and enhancing project outcomes.

Keywords: *Lean Construction; Lean Practices; Barriers; Cost Saving; Strategies*

INTRODUCTION

In Malaysia, the construction sector plays a significant role in the expansion of the economy. The construction industry's gross output in 2021 was RM170.8 billion, a 1.4% decline from the previous year. The intermediate input, valued at RM112.8 billion, decreased by 0.3% in tandem with the reduction in gross production. Nevertheless, the building sector is still worth billions of dollars. (Department of Statistics Malaysia, 2022). Apart from that, MIDF Research has forecast that the second quarter of 2023 will see moderate growth in the construction and services sectors, accompanied by a slightly weaker index of industrial products. This trend is expected to lead to more moderate growth in the overall economy over the same period. Malaysia's construction activity continued to grow in the second quarter of 2023, according to MIDF Research, which noted that this was the fifth consecutive expansion since the second quarter of 2022. The industry stated that the value of work completed increased by 8.1% annually, totalling to RM32.4 billion. (Department of Statistics Malaysia, 2022). According to the survey, a revival of government-led projects and the ongoing growth of private sector output could propel the construction industry's growth in the upcoming months. The trend shows that there is still a sizable market requirement for new construction, which has led to a rise in building projects and new developments in Malaysia. With the high demand, it also will increase the usage of various types of materials and varying methods or

techniques will be applied to complete the construction projects. Hence, the contractors or developers must deliver the completed project efficiently and effectively to increase the performance of the organization in the right way.

With increasing demand comes intensified use of materials, labour, and energy—raising significant concerns over environmental impact, resource depletion, and construction waste. Addressing these challenges requires a shift beyond conventional project delivery methods. Without the integration of lean and sustainable practices, construction projects in Malaysia continue to suffer from avoidable delays, escalating costs, excessive material waste, and increasing environmental degradation. Sustainable lean construction emerges as a promising solution that integrates the principles of traditional lean construction with environmental stewardship and social responsibility and extends its scope to include energy efficiency, sustainable material selection, carbon footprint reduction, and overall environmental impact minimization throughout the project lifecycle. This holistic approach not only improves productivity and operational efficiency but also supports long-term sustainability in the construction sector. However, implementing sustainable lean construction is not without challenges. Success requires a deep understanding of both lean principles and sustainability practices, as well as a willingness from all project stakeholders—especially contractors and top management—to adopt new methods and mindsets. Past studies have revealed that one of the primary barriers is the lack of awareness and exposure to lean construction concepts, alongside persistent on-site challenges that hinder smooth execution (Chong & Nordin, 2017).

This paper aims to identify key barriers to implementing sustainable lean construction practices within Malaysia's construction industry, with a particular focus on the Klang Valley region. The Klang Valley was selected due to its status as the most densely developed and economically active construction hub in Malaysia. The region's high construction activity, complexity, and diverse stakeholder involvement make it an ideal setting for examining both the challenges and opportunities associated with adopting sustainable lean construction practices. In addition, this paper also seeks to propose practical solutions and strategic recommendations to overcome these barriers.

LITERATURE REVIEW

Lean is an idea in increasing and maximising the value and productivity while reducing and minimizing waste production. It also removes the unwanted materials and other waste through a less production, reducing times, semiautonomous machines, collaboration of provider and other techniques (Wan Muhammad et al., 2013). Lean production or lean manufacturing was developed by Toyota in Japan in the 1950's, where it is established by Taiichi Ono and friends. Outside the automotive industry, lean production has been widely applied including the maintenance sector and construction sector. The central idea of lean manufacturing is relentlessly to eliminate waste from the manufacturing process (Vorne, 2011). In delivering the goods of lean in the construction industry, the principles of lean thinking must be considered to ensure the functionality and smoothness of lean construction.

According to some experts, there are five (5) lean principles that can be utilized as a framework and will be employed in the organizational structure to execute lean. Value, Value Stream, Flow, Pull, and Perfection are some of the fundamental lean thinking concepts that form the basis of lean building. These principles are not only instrumental in improving

productivity but are also highly applicable to sustainable construction practices. Value refers to identifying what the client truly needs and eliminating anything that does not contribute to this objective; in sustainable construction, value extends beyond cost and schedule to include environmental performance, such as energy efficiency and use of green materials. Value Stream involves mapping all activities required to deliver the project and eliminating non-value-adding steps, which, in a sustainable context, also means assessing and minimizing the environmental impact of each stage. Flow emphasizes uninterrupted progress of construction processes, which helps reduce delays and energy consumption—especially when using prefabrication or just-in-time delivery to reduce site waste. Pull systems ensure that tasks are performed only when required, avoiding overproduction and excess material use, which supports sustainability by minimizing unnecessary resource consumption. Finally, Perfection advocates for continuous improvement, where each project becomes a learning opportunity to further reduce waste, enhance efficiency, and improve environmental outcomes. When applied collectively, these principles support the development of lean construction systems that are both productive and environmentally responsible (Womack and Jones, 1996).

Furthermore, there are several tools and techniques that can be implemented in the construction industry to improve the performance and productivity of the construction process until the completion, saves time and costs with adding value, and reduce the waste and non-added value from the construction. The tools and techniques can be applied from the design phase, which is the pre-construction phase, then during the construction phase, and also in post-construction phase. The tools and techniques developed must match the lean principles such as Last Planner System (LPS), Five S's (5S), Value Stream Mapping (VSM), Visual Management, Just-In-Time (JIT), Kanban System/Board, Concurrent Engineering and Total Quality Management (TQM).

While traditional lean construction focuses primarily on improving efficiency by minimizing waste and maximizing value, recent research emphasizes that integrating sustainability elevates these principles by addressing environmental, social, and long-term economic impacts. Sustainable lean construction goes beyond the original goals of productivity by embedding eco-efficiency into every phase of a project—from planning and design to execution and maintenance. This integration involves not only eliminating physical waste but also reducing carbon emissions, conserving natural resources, and promoting responsible construction practices. For instance, the use of sustainable materials such as recycled aggregates, bamboo, and low-VOC finishes aligns with lean objectives by minimizing overuse while significantly lowering environmental impact (Tam et al., 2007; Kibert, 2016). Furthermore, energy-efficient strategies—including passive solar design, high-performance HVAC systems, and energy modelling via Building Information Modelling (BIM)—help reduce long-term energy consumption, going beyond lean's immediate cost focus to embrace lifecycle efficiency and climate responsibility (Azhar et al., 2011; Wong & Zhou, 2015). Waste reduction remains a shared priority, with lean tools like Just-In-Time (JIT), 5S, and Value Stream Mapping (VSM) being adapted to not only improve operational flow but also minimize environmental harm caused by excessive construction debris (Formoso et al., 2002; Abdul-Rahman et al., 2012). Additionally, tools such as Environmental Impact Assessments (EIA) and Life Cycle Assessments (LCA) have been recognized for their role in identifying inefficiencies and environmental risks early in the project lifecycle, allowing for more sustainable planning and decision-making (Ding, 2008; Zainul Abidin, 2010). Ultimately, the literature reveals that sustainable lean construction represents a more

holistic and forward-thinking evolution of lean practices—one that balances productivity with environmental stewardship and long-term industry resilience.

Numerous studies also have emphasized the synergy between lean construction and sustainability, particularly in the areas of material efficiency, energy performance, and environmental impact assessment. Sustainable material selection, such as using recycled aggregates, low-VOC products, and renewable resources, aligns with lean principles by reducing waste and lifecycle costs (Ahn et al., 2010). Lean practices also enhance energy efficiency by promoting just-in-time delivery, modular construction, and improved workflow coordination, thereby lowering fuel consumption and onsite energy use (Aziz & Hafez, 2013). Research by Osmani et al. (2008) found that lean techniques like value stream mapping and pull planning significantly reduce construction waste, often by over 30%, contributing to both cost and environmental benefits. Moreover, integrating environmental impact assessments within lean project planning enables stakeholders to measure and manage carbon footprints, resource consumption, and pollution outputs more effectively (Kibert, 2016). These findings support the view that sustainable lean construction not only improves project performance but also advances environmental responsibility in the construction industry.

Barriers of Sustainable Lean Construction Implementation

Despite the proven benefits of sustainable lean construction—such as improved efficiency, reduced waste, and enhanced environmental performance—its implementation in Malaysia remains limited. Various interrelated challenges continue to obstruct widespread adoption, particularly in high-density and complex regions like the Klang Valley. These barriers are not solely technical in nature but often stem from organizational, financial, social, and regulatory shortcomings. Understanding these barriers is crucial for formulating effective strategies to enhance the uptake of sustainable lean practices in the construction sector. The following sections explore these challenges;

Management Aspect

One of the biggest obstacles to implementing lean construction is the use of traditional management principles rather than productivity and quality management concepts. This is due to the fact that top management plays a crucial role in an organization and is responsible for all operational, planning, scheduling, and controlling tasks. Because top management makes decisions and is averse to change, organizations always adhere to traditional management. It is also found that poor project definition, inadequate resources and delay in material delivery were found to be some of the constraints to management for the successful implementation of lean construction (Bashir et al., 2015). Besides that, the lack of attentive and commitment from the top management are also one of significant issues in implementing the sustainable lean construction practice in the Malaysian construction industry.

Social Aspect

The construction industry involves a wide range of professionals, including engineers, architects, contractors, subcontractors, and labourers. In Malaysia, this workforce is often multicultural and multilingual, with a high presence of foreign workers. While such diversity can bring valuable skills and perspectives, it also introduces significant social challenges that

directly hinder the adoption of sustainable lean construction practices. One of the main issues is miscommunication, often caused by language differences and varying communication styles. According to Tejas Vidhat and Ashwini Salunkhe (2018), a multicultural workforce and inconsistent language use can create misunderstandings and disrupt collaboration on-site. Miscommunication can lead to serious project setbacks, such as incorrect material usage, construction errors, and delays due to rework-all of which contradict lean principles of reducing waste and enhancing efficiency. Furthermore, lack of cooperation and trust between subcontractors and other stakeholders can limit the sharing of information and reduce engagement in collaborative problem-solving, which is essential for lean implementation (Salunkhe & Vidhat, 2018). In many cases, workers and supervisors lack sufficient training or understanding of lean and sustainability practices, making it difficult to shift from traditional methods to more integrated and efficient workflows. Without clear communication, mutual respect, and a shared understanding of lean goals, the implementation of sustainable lean practices remains fragmented and ineffective. Addressing these social barriers requires targeted training, inclusive leadership, and a strong emphasis on building a unified project culture that supports open communication and collaboration.

Financial Aspect

Researchers found that successful implementation of lean construction requires strong financial in order to provide the required tools and equipment, in order to pay the professional wages, incentives and reward systems such as providing training and development programmes for the workforces, and cost for the employing a lean specialist in order to provide the guidance to the employers and employee regarding the implementation of the lean construction (Saad & Fox, 2013). Financial issue is the common issue that will be faced by most organizations who intend to implement lean construction. Other researchers also found that some of the financial challenges include inflation, and the implementation cost of lean construction is expensive (Bashir et al., 2015). This is because implementation of lean construction requires various types of technologies and high cost to pay for the wages of the workers where the person who will integrate with the lean construction must be skilled workers to enable them to handle all the technologies and specialized machineries required for the lean construction to work.

Lack of Training

As the lean construction is new in the construction industry, proper training for both employers and employees must be provided to familiarize them on how the lean construction works, and how to handle the tools and equipment that will be used in the lean implementation. A proper training also will give them an acknowledgement regarding the lean concept. In many organizations, proper training is rarely provided because of financial issues. Large number of workforces need to attend the proper training and the cost for the training is expensive because they must attend the training multiple times. Other than that the obstacle that disrupt the success of lean construction is the fact that training is only centred on the lean tools that can improve productivity and performance, but with minimal focus on the lean concepts and principles. (Kim & Park, 2006).

Understanding and Awareness

According to Bashir et al. (2015), several researchers found that the illiteracy or low level of knowledge among workers, lack of awareness, insufficient training and lack of information sharing to be the common challenges. This is because, the lean construction is the adaptation of lean manufacturing concept. Therefore, there will be various of principles that will provide different understanding to the employers and employees. The differences in the lean construction must be fully understood in order to use the concept fully (Abdullah et al., 2009). He also stated that to clearly understand the concept, the parties involved must have full understanding about manufacturing concept beforehand. The lack of understanding will result in low quality projects and inability to improve the productivity of the projects.

Governmental Aspect

The role of the government is pivotal in promoting sustainable lean construction, yet in Malaysia, several policy-related shortcomings continue to impede its effective implementation. While frameworks such as the Construction Industry Transformation Programme (CITP) 2016–2020 aimed to improve environmental sustainability and productivity in construction, there has been limited continuation and expansion of these initiatives post-2020 (CIDB, 2016). The absence of a dedicated policy that integrates lean principles with sustainability objectives leaves a critical gap in national construction reform efforts. One key barrier is the voluntary nature of green certifications, such as the Green Building Index (GBI). While GBI encourages environmentally friendly designs, it does not mandate lean practices like waste minimization, value stream mapping, or pull-based workflows (Green Building Index, 2023). Consequently, many developers, especially SMEs, are reluctant to adopt these practices without legal or financial incentives. Other issues include bureaucratic delays in project approvals, which undermine lean principles of efficient planning and scheduling. Additionally, fluctuations in raw material prices, partly due to a lack of long-term national procurement strategies, make it difficult for firms to plan sustainably. Asri and Nawi (2015) noted that government bureaucracy, inconsistent policies, limited infrastructure, and lack of social policies were all critical barriers, further compounded by limited availability of sustainable materials and a lack of government-backed supply chain support.

Duration of Lean Implementation in The Construction Process

Lean construction has been introduced to the contractors in Malaysia, and it is considered as recent in this industry (Chong & Nordin, 2017). Therefore, the understanding regarding the concept and flow of the lean in construction obviously will require a long time by all parties involved in the construction. If the organization persistent to implement lean construction, it will affect the construction process such as late completion and late delivery of the project. This is because the lack of understanding of the persons involved would make it difficult for them to handle the task required in the project with the new ways of construction.

Procurement and Contracts

Saad and Fox (2013) observed that many construction companies continue to adopt a hybrid approach, combining traditional methods with lean techniques. However, the

persistent reliance on conventional practices-such as traditional lump-sum contracting and Critical Path Planning (CPP)-often limits the effectiveness of lean construction. In particular, procurement methods that separate design and construction phases, such as those that appoint external consultants for design work without ongoing collaboration, hinder the lean objective of integration and continuous communication across project stages. In the context of Malaysian construction, traditional Design-Bid-Build (DBB) contracts remain the dominant form of project delivery. This method often leads to fragmented responsibilities, delays, and rework due to poor coordination between designers and contractors. To address these limitations, the Malaysian construction industry is gradually exploring alternative contracting approaches such as Design and Build (D&B) and Public-Private Partnerships (PPP). These models are more aligned with lean principles as they encourage early contractor involvement, better integration of project teams, and shared accountability. For example, the Industrialised Building System (IBS) promoted by the Construction Industry Development Board (CIDB) Malaysia supports lean practices by integrating prefabrication, reducing waste, and encouraging better coordination across stakeholders. While adoption is still limited, these integrated methods present promising opportunities to improve project efficiency, reduce waste, and support sustainable lean implementation in Malaysia (CIDB, 2020; Hamzah et al., 2019).

Strategies to Improve Sustainable Lean Implementation in Construction

Through various barriers that have been justified, an approach to the opportunities must be taken in the way to improve and enhance the lean construction implementation among the contractors in the construction industry. The basis for the implementation of lean in construction has been grouped into five categories which are:

Leadership

Leader has the great influences in an organisation in terms of motivating the other employees in the organisation to achieve the goals and visions that can lead to the success of the construction projects and the organisation itself. In adapting the leadership, the top management level in the organization must be committed to learn and understand the aim of lean and to change their own behaviour accordingly (Pekuri et al., 2012).

Competence

The person involved in lean construction must have a thorough awareness of the principles and how lean construction operates as a whole in construction projects. Top management must offer employees with training to ensure their competency in managing and adopting the lean construction idea, as there are numerous levels of roles in an organization that limit their exposure because they only focus on their own jobs and responsibilities.

Motivation

Construction organisation in general were thought to need a little bit of 'an outside domination' from the clients and lean consultants to change their thinking and way of works (Pekuri et al., 2012). This is because, without the motivation, existing employers and employees would have no idea on how the lean construction works. Besides, with the outside

domination, they will also gain an understanding and will make a continuous improvement to achieve successful implementation of lean construction. From the understanding gained by the motivation, the duration for the employers and other new learner to adapt the lean concept in the construction project can be reduce as they already know how the lean will operate and function in the construction.

Trust

To successfully implement the lean construction, trust must be established between the temporary parties involved in the construction project. This is because, with the trust, it will lead to the willingness in cooperating between all parties which is essential for developing construction works in a better way where they believe that the other party collaborating in the project team will give the best to achieve the target of construction.

People

Lean implementation needs people who are willing to work with new ideas and to get out of their silos, which essentially often means having social skills to work in more collaborative situations (Pekuri et al., 2012). Without the willingness and spirit to work with the lean concept, it will slow down the flow of the construction project due to the lack of understanding and unwillingness to adapt to a new working environment.

RESEARCH METHODOLOGY

This paper achieves the objectives from the extensive literature review and the use of online questionnaires. Two categories of data were utilized: primary and secondary. Primary data was collected directly from online questionnaires, while secondary data was gathered from existing resources, including research texts, documents, papers, and media accessible through library references. The online questionnaire was distributed to various construction professionals in the Klang Valley area, with 22 respondents directly involved in sustainable lean construction projects. In this study, frequency analysis and mean analysis were selected to evaluate the data collected through the questionnaire survey, which targeted experienced construction professionals in the Klang Valley. These methods were chosen due to their effectiveness in identifying common trends, summarizing quantitative responses, and highlighting the relative importance of various barriers to implementing sustainable lean construction practices. Apart from that, the questionnaire used in this study was designed into three main sections:

Section A – Respondent Demographics

This section gathered background information such as respondents' job roles, years of experience in the construction industry, and types of projects they were involved in. These questions helped to contextualize the responses and ensure a diverse range of professional perspectives.

Section B – Awareness and Understanding of Sustainable Lean Construction

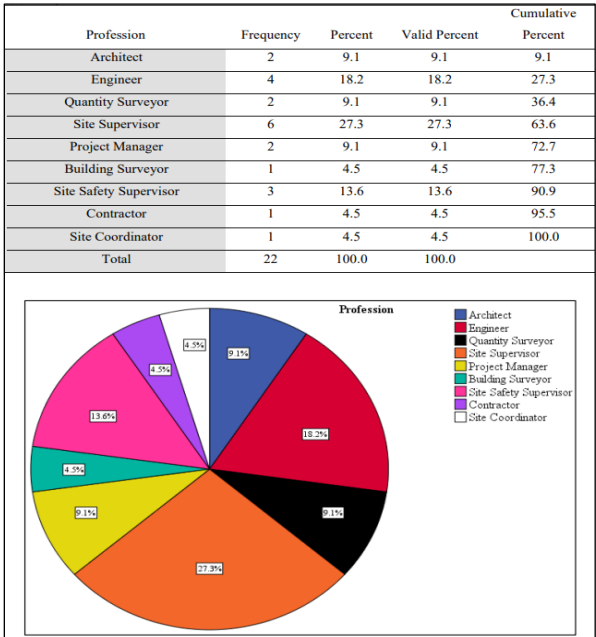
This part assessed the respondents’ familiarity with lean principles and sustainability concepts, their previous experience with lean practices, and their perceptions of its benefits. It included multiple-choice and Likert scale questions to gauge levels of awareness and involvement.

Section C – Barriers to Implementation

This core section was designed to identify specific barriers across four key aspects: management, financial, social, and governmental. Respondents were asked to rate various potential obstacles (e.g., “lack of top management support,” “poor communication,” “insufficient government policies”) on a 5-point Likert scale ranging from Strongly Disagree (1) to Strongly Agree (5). These questions were formulated based on insights from previous literature and refined to suit the local construction context.

The structure ensured that the questionnaire captured both the breadth and depth of challenges faced by practitioners, enabling a comprehensive analysis of the most critical barriers to sustainable lean implementation.

Somehow there are few limitations faced while conducting this study. Firstly, the sample size was relatively small, comprising only 22 respondents, which may limit the generalizability of the findings across the broader Malaysian construction industry. Secondly, the study focused exclusively on the Klang Valley region, which, although highly active and representative of major construction activity, may not fully reflect the conditions and challenges present in other regions of Malaysia, especially in rural or less developed areas. Additionally, the reliance on self-reported data through questionnaires may introduce subjective bias, as responses are based on individual perceptions and experiences.



RESULTS AND DISCUSSION

Respondents' Demographic

In reference to Figure 1 above, it was discovered that there were nine types of profession of respondents which are Architect, Engineer, Quantity Surveyor, Site Supervisor, Project Manager, Building Surveyor, Site Safety Supervisor, Contractor, and Site Coordinator. The total number of respondents who completed this questionnaire survey is 22 who were previously involved in Sustainable Construction Project.

Barriers in Implementing the Sustainable Lean Construction

Table 1. Analysis of Barriers in Implementing the Sustainable Lean Construction

Barriers	Freq_1	Freq_2	Freq_3	Freq_4	Freq_5	Total	Average Index Score	Rank	Rating
Organization stick to the conventional management because top management as a decision maker in the organization.	1	0	4	11	6	87	3.95	1	Agree
Require a long time to understand the concept and flow of lean by the person involved in construction.	1	1	4	9	7	86	3.91	2	Agree
Inadequate knowledge among workers. Various principles give different understanding.	1	0	6	10	5	84	3.82	2	Agree
Governmental policies and attitudes toward construction industry. Lack of social amenities, material unavailability and fluctuation commodities price.	1	0	7	10	4	82	3.73	4	Agree
Financial issue due to the inflation and high implementation cost of lean construction	1	1	5	11	4	82	3.73	4	Agree
Lack of training provided because of the financial issues. Due to cost for the training is expensive.	1	1	6	10	4	81	3.68	5	Agree
Organization use combination techniques in procurement that will discourage the aim of collaboration and integration among parties.	1	1	6	11	3	80	3.64	6	Agree
All parties from different fields did not works together and cooperate to achieve success. Various language applied mislead the information and create miscommunication.	1	3	10	4	4	73	3.32	7	Neutral

From the results in Table 1, it clearly shows that the critical barrier faced by the respondents are organizations continue to rely on conventional management methods, largely due to top management, as decision-makers, favouring familiar approaches with an average index score of 3.95. This is primarily because management is used to the traditional approaches that have been around for many years. Switching to new methods for managing construction projects can be tough for them, as it means they would have to adapt many established processes.

The second most significant barrier in sustainable lean construction is that it requires a substantial amount of time for those involved in construction to fully understand its concepts and processes, with an average score of 3.91. Additionally, inadequate knowledge among workers, due to varied interpretations of lean principles, received an average score of 3.82. This suggests that management holds considerable influence over lean construction's successful implementation. By introducing lean practices and providing comprehensive information on lean construction, organizations can help workers better understand these concepts and reduce the time needed for them to adapt to new construction management norms. Successful lean construction relies on a workforce that is knowledgeable and skilled in these practices, as emphasized by Mohamed Saad Bajjou and Anas Chafi (2018).

However, there were some respondents who were neutral with the statement that all parties from different fields did not work together and cooperate to achieve success where various language applied mislead the information and create miscommunication with 3.32 average index. This may be observed in the construction team, when many parties from different backgrounds come together to form a single team with the same goals to accomplish a project. Misinformation and miscommunication are common in construction companies that engaged foreign workers; thus, they will have difficulties understanding the language used by the employers.

The analysis in Table 2 below highlights that the most impactful strategy to improve lean construction practices is for top management to actively support employees through training. This training helps ensure that everyone is comfortable with and skilled in using lean principles, with an average score of 4.23 showing its importance. Furthermore, top management needs to be dedicated to learning and embracing the purpose of lean practices themselves, with a notable score of 4.18. It also essential that those directly involved in construction projects fully understand and are committed to applying lean concepts across the organization, with a score of 4.14. This shows that top management plays a crucial role in promoting lean construction throughout the company. By providing the right information, knowledge, and training, they help employees become confident and capable in lean methods. This finding aligns a study by Mohamed Saad Bajjou & Anas Chafi (2018), who emphasized the need for management to raise awareness across the workforce to ensure lean practices are implemented successfully.

Table 2. Strategies to Improve Sustainable Lean Implementation in Construction

Suggestions	Freq_1	Freq_2	Freq_3	Freq_4	Freq_5	Total	Average Index Score	Rank	Rating
Top management must provide the training to the employees. To ensure they are competence in handling and adapting lean concept.	0	0	3	11	8	93	4.23	1	Agree
In adapting the leadership, the upper management level in the organization must committed to learning and understanding the aim of lean.	0	0	4	10	8	92	4.18	2	Agree
The person involved in construction must have great understanding and dedicated to promote lean in organization and its project.	1	0	3	9	9	91	4.14	3	Agree
Government policies and legislation. Initiate official website to facilitate lean construction concept. To acknowledge organization on how to implement lean.	0	1	3	12	6	89	4.05	4	Agree
Trust will create a willingness in cooperation between all parties. Good communication and collaboration will enhance possibility successful of implementation.	1	0	3	12	6	88	4	5	Agree
Outside domination can be a motivation for workers to gain understanding and make an improvement to reduce time to adapt the concept in organization.	1	0	4	12	5	86	3.91	6	Agree
Use partnership as a procurement method. Can create a collaboration and good relationship within the parties.	1	0	10	7	4	79	3.59	7	Agree
Organization try the 'low hanging fruit' method as an initiative to implement lean. Inventory changes can be made after gain profit.	1	2	8	7	4	77	3.5	8	Agree

CONCLUSION

The implementation of sustainable lean construction promises significant improvements in efficiency, waste reduction, and overall project performance. However, there are obstacles in the way of completely reaping these advantages, and they need to be carefully resolved. This paper has identified several key obstacles that impede the effective adoption of sustainable lean construction practice including management aspect, financial aspect, social aspect and governmental aspect. The most critical barriers are the resistance to change by the top management and inadequate knowledge among workers. As a conclusion, while the barriers to lean construction are substantial, they are not impossible to overcome. Addressing these challenges through strategic planning, committed leadership, and willingness to embrace change, the construction industry is essential for advancing the adoption of sustainable lean construction practices across Malaysia. Future research could expand the geographic scope, increase the sample size, and incorporate qualitative methods such as interviews or case studies to gain deeper insights into the implementation of sustainable lean construction. Additionally, future research could compare the implementation of sustainable lean construction practices between countries with similar construction contexts. Such comparative studies would offer valuable insights into how local culture, regulatory environments, and market dynamics influence the success of lean initiatives. Furthermore, researchers could evaluate the effectiveness of digital technologies (e.g., BIM, IoT, project management software) in facilitating lean-sustainable integration or explore the long-term benefits of lean construction on environmental performance and project outcomes through longitudinal studies.

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BUILDING INNOVATION: LEVERAGING ORGANIZATIONAL DEVELOPMENT FOR BIM ADOPTION IN CONSTRUCTION

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Abstract

The adoption of Building Information Modelling holds significant potential for enhancing the efficiency and competitiveness of organizations within the construction industry. Despite the acknowledged benefits of BIM, its full potential remains largely untapped. This study addresses the gap in research concerning organizational and human factors influencing BIM implementation by focusing on organizational development for optimal BIM implementation within construction organisations in Malaysia. The objectives were to: identify key features of Organization Development; examine current BIM implementation practices; and propose an OD approach tailored for BIM implementation. Key findings indicate that managing human capital presents the most significant challenge within organisations. The research also revealed that aligning organizational culture and values with individuals is a key feature of Organization Development that facilitates BIM implementation. In-depth interviews were conducted with six large organisations in Malaysia, and data analysis was conducted using thematic analysis. The findings reveal three organisation development approaches conducive to BIM implementation: aligning organizational culture and values with individuals; developing organizational strategies to enhance BIM utilization; and fostering organisational innovation. This study contributes to a deeper understanding among researchers and practitioners regarding the practical actions and potential outcomes associated with integrating BIM into construction operations, emphasizing organizational aspects.

Keywords: *BIM Implementation; Construction Organisation; Human Factors; Innovation; Organisation Development*

INTRODUCTION

Organisational Development (OD) is a discipline grounded in the behavioural sciences that focuses on facilitating growth, innovation, and adaptability within organisations. It aims to enhance both individual competencies and organisational effectiveness, helping firms respond proactively to change and improve overall performance (Waddell et al., 2019). As industries continue to experience rapid digital transformation, OD becomes increasingly vital in supporting organizations through complex transitions.

One of the most significant digital shifts in the construction industry is the adoption of Building Information Modelling (BIM). BIM is an advanced digital methodology that enables the integration of project design and data management throughout a building's lifecycle. It is widely recognized as a transformative tool for addressing inefficiencies in construction, including fragmentation, cost overruns, schedule delays, and collaboration challenges (Al-Ashmori et al., 2019). However, the successful implementation of BIM extends beyond technological adoption; it requires a fundamental transformation of organizational processes, structures, and mindsets.

Research indicates that implementing BIM often disrupts established workflows and necessitates significant organisational change. According to Abbasnejad (2020), construction firms must adopt new technologies and delivery methods, marking a departure from traditional practices. This transition demands strategic planning and cultural shifts, which many organizations are unprepared for. In developing countries like Malaysia, BIM is primarily used for low-level functions such as visualization and clash detection, with limited application during the construction phase (Chan et al., 2019b). This fragmented implementation reflects a broader issue of low BIM maturity, as highlighted in Malaysia's Construction Industry Transformation Plan (CITP) 2016–2020.

The problem is not solely technological—it is organisational. BIM implementation involves complex changes in areas such as organizational structure, policies, training, software and hardware acquisition, and project delivery approaches (Sacks et al., 2016). However, many firms are still operating within their comfort zones and lack the strategic frameworks needed to manage these changes effectively (Juan et al., 2017; Al-Ashmori et al., 2019). OD provides a potential solution, offering a structured approach to manage change and build organizational capacity for BIM integration.

Despite the growing interest in BIM, the majority of existing research focuses on its technical aspects and project-level outcomes, often overlooking the human and organisational dimensions of its implementation (Haron et al., 2015; Mohammad et al., 2018). Firms frequently emphasize short-term goals such as time, cost, and quality, neglecting the long-term organisational readiness needed for sustainable BIM adoption. Given BIM's socio-technical complexity—where technology interacts closely with people and processes—it is crucial to explore the role of OD in shaping successful implementation strategies.

Furthermore, BIM should be recognized not just as a technological innovation, but as an organisational one (Succar & Kassem, 2015). Organisational innovation involves internal changes in response to environmental shifts, often requiring adjustments in culture, values, infrastructure, and workflows (Damanpour, 1991). Successful BIM adoption, therefore, depends on effective change management and the ability to overcome internal resistance (Abbasnejad et al., 2016). As Ziyee and Shengyue (2021) emphasize, realizing the full potential of BIM requires organisations to undergo significant internal transformation.

In Malaysia, construction firms face considerable challenges in adopting BIM effectively. Although the technology is available, implementation remains superficial and fragmented, primarily due to the absence of strategic organisational change management. The central problem lies in the lack of organisational readiness, leadership support, and cultural adaptability required for meaningful BIM integration. There is currently a gap in understanding how Organisational Development can be leveraged to support BIM adoption, especially within the unique context of Malaysia's construction sector. This study seeks to fill this critical gap by investigating the role of OD in facilitating successful BIM implementation in Malaysian construction organizations. By linking organizational theory with practical BIM adoption. The outcome is expected to contribute to the development of an OD-based framework that construction organisations can use to navigate change, overcome implementation barriers, and elevate BIM maturity across the industry. Therefore, the objectives of this paper are;

1. To identify key features of organisational development relevant to BIM implementation.
2. To examine the current practices of BIM implementation in Malaysian construction organisations.
3. To recommend an OD approach tailored for BIM implementation in Malaysian construction organisations.

LITERATURE REVIEW

Organisational Development

Organisational Development (OD) emerged in the 1950s under the guidance of industrial psychologists (Cummings & Worley, 2009), evolving over time into a comprehensive strategy for organisational transformation drawing from psychology, sociology, and systems theory. This approach systematically drives business performance (Basadur et al., 2012). Initially, OD practitioners relied on methods like T-groups and survey feedback to address organizational challenges. By the 1970s, OD interventions began yielding measurable productivity gains. In the 1980s, the field shifted towards quality management, emphasizing effectiveness measurement, interdisciplinary knowledge, and the role of power (Sanzgiri & Gottlieb, 1992). The 1990s saw a focus on team building, management style enhancement, and strategy development assistance. The 21st century ushered in new OD frontiers, including deeper collaboration with human resources, global leadership, and talent management (Sharkey, 2009).

Internally, organisational development is often spearheaded by the Human Resources (HR) department, leveraging its understanding of organisational culture, demographic shifts in the workforce, and expertise in managing employee performance (Yaeger & Sorensen, 2009). Conversely, organizations may enlist external OD practitioners to guide them through the OD process.

BIM Implementation

Between 2016 and 2019, BIM adoption in Malaysia saw a notable increase from 17% to 49%, while the United Kingdom experienced a rise from 54% to 69% during the same period (BIM Report, 2019). However, despite this growth, Malaysia still lagged behind other developed nations in BIM implementation (CIDB, 2018). Initially, in 2013, Zahrizan et al. found BIM implementation in Malaysia to be at Level 0 to Level 1, which then progressed to Level 1 to Level 2 the following year (Enegbuma et al., 2014). Though plans were in place to achieve Level 2 by 2019 (Amiruddin, 2018), it was only realized in the development of the MRT Line 2 by the Mass Rapid Transportation Corporation (MRT Corp) (Azman, 2018).

Against this backdrop, major players in the Malaysian construction industry such as the Public Works Department (PWD), Sime Darby Property, Sunway Property, Gamuda Bhd., and Brunsfield Construction Sdn. Bhd. have significantly contributed to the widespread adoption of BIM. These organizations have not only established their own in-house BIM departments but have also engaged external BIM consultants to provide customized BIM services. With diverse portfolios encompassing various public and private projects, these firms offer valuable insights for effective BIM integration across the construction sector.

Numerous studies have highlighted the multifaceted factors influencing the effective implementation of BIM. Successful deployment of BIM necessitates a clear understanding of implementation mechanisms, assessing the organization's readiness for change, and devising optimal strategies to foster innovation and attain key BIM advantages (Al Ahbabi & Alshawi, 2015; Kulatunga et al., 2011). Shehzad et al. (2020) identified a comprehensive list of seventy-four influencing factors categorized into individual, organizational, technological, and environmental domains. Individual factors pertain to professionals' intentions, attitudes, motivation, and self-efficacy in technology adoption. Organisational factors involve inter-organisational processes, practices, and policies influencing BIM adoption. Technological factors encompass BIM tool-related considerations impacting technology utilization, while environmental factors encompass external factors such as economic demands, policies, and contractual frameworks.

BIM has emerged as a pivotal tool in mitigating uncertainties and enhancing the efficiency of the construction process. Consequently, construction organizations have realized myriad benefits from BIM implementation, spanning short-term and long-term gains in investment, project enhancement, and business operations (Musa, 2018). These benefits include but are not limited to improved collaboration and communication, model-based cost estimation, pre-construction project visualization, enhanced coordination and clash detection, optimized scheduling and sequencing, positive return on investment (ROI), and overall superior project outcomes (Samimpay & Saghatforoush, 2020).

Table 1. Significance of OD in Organisation for BIM Implementation

No.	Functions of OD	Organisation Development Source	BIM Implementation Source
1.	Continuous Improvement OD represents a proactive stance that embraces both internal and external change, harnessing it as a catalyst for renewal. Through the OD process, organizations engage in a continuous cycle of improvement, where strategies are meticulously planned, implemented, evaluated, refined, and monitored. This iterative approach is particularly crucial for ensuring the sustainability of BIM implementation efforts.	Mulili & Wong, 2011	Semaan <i>et al.</i> , 2021;
2.	Increase Communication Collaborative working approaches are imperative for effectively executing BIM-related tasks and activities. OD activities facilitate increased communication, feedback exchange, and interaction within the organization, fostering a culture of collaboration essential for successful BIM implementation.	Ulbrich <i>et al.</i> , 2011	Du <i>et al.</i> , 2020;
3	Employee Development The necessity for employee development arises from the continual shifts in industry and market dynamics. OD plays a pivotal role in identifying the essential training and development needs, encompassing adjustments to traditional roles and responsibilities to accommodate digital innovation, among other requirements.	Gatarik, 2019	Yusuf <i>et al.</i> , 2022
4.	Product and Service Innovation Effective training programs yield numerous benefits for individuals, equipping them with the skills and knowledge needed to navigate new innovations and enhance service delivery.	ODN, 2023; Anning-Dorson <i>et al.</i> , 2017	Khudhair <i>et al.</i> , 2021
5.	Increase Business Success OD impacts the bottom line in multiple ways, including heightened innovation, productivity, efficiency, and ultimately, increased profits.	Madhani, 2018	Madanayake <i>et al.</i> , 2021

Significance of Organisation Development in Organisation for BIM Implementation

In today's volatile, uncertain, complex, and ambiguous (VUCA) business landscape, profitability, productivity, morale, and Work-Life Balance (WLB) stand as significant concerns for most firms, directly influencing organizational sustainability (Smither et al., 2016). Organizational Development (OD) recognizes the interplay between the organization and its employees, placing emphasis on the human element and the rich data within the employee-organization dynamic. By employing OD strategies, organizations can cultivate heightened employee commitment and adaptability, thereby fostering an environment conducive to successful BIM implementation. Table 1 shows the significance of OD in organisation for BIM Implementation.

From an organizational development standpoint, comprehending and identifying the elements pertaining to both people and the organization greatly enhance the firm's efficiency in successfully implementing BIM (Oraee et al., 2017; Kumar et al., 2022).

METHODOLOGY

This research study adopts a qualitative approach, utilizing in-depth interviews as the primary data collection method. The focus is on understanding human social behaviour and organisational cultures in the context of organisational development (OD) and Building Information Modelling (BIM) implementation. The aim is to develop conceptual frameworks that deepen our understanding of the social phenomena, emphasizing the meanings derived from individuals' experiences, perceptions, and behaviours within these organizational settings.

Participants

The study engaged six construction organisations, including clients/developers, consultants, and contractors from both public and private sectors (three firms from each). These organisations have actively implemented BIM in their projects. Participants were selected through purposive sampling, based on their relevance and involvement with BIM implementation, determined through desk-based research. As suggested by Farrell (2011), the number of interviewees was selected based on the research context and objectives, ensuring robust insights without overburdening the analysis. Purposeful sampling, in line with Shaheen et al. (2019), emphasized selecting information-rich participants who could provide deep insights into the phenomena under study. However, the small sampling size may limit the generalisability of findings to all construction organizations that already engaged with BIM and may exclude perspectives from firms that still in the early stages of BIM adoption.

Instrumentation

The interview guide, comprising nine questions divided into three sections, was developed based on a thorough review of existing literature on organisational development and BIM implementation. The questions were designed to capture both objective and subjective data, allowing respondents to freely express their opinions and experiences. The interviews lasted approximately 45-60 minutes, and questions were designed to allow for

open-ended responses, ensuring the collection of rich qualitative data to ensure validity, the interview questions were reviewed by experts in the fields of organisational development and BIM, and a pilot interview was conducted to refine the clarity and relevance of the questions. Feedback from the pilot interview led to minor adjustments to the wording and structure of the questions.

RESULTS AND DISCUSSION

Respondent’s Profile

The demographic profile of each respondent includes their organization, current position, years of experience, years of experience with BIM, and the sector in which they are involved. In-depth interviews were conducted with six respondents from both public and private construction organizations. Details of each respondent are presented in Table 2.

Table 2. Respondent’s Profile

Respondents	Firm	Position	Year of Experience	Year of BIM Experience	Sector
Respondent 1 (R1)	A	Assistant Vice President (AVP)	10 years	6 years	Public/ GLC
Respondent 2 (R2)	B	BIM Coordinator	7 years	6 years	Private
Respondent 3 (R3)	C	Head of BIM Unit	23 years	11 years	Public
Respondent 4 (R4)	D	BIM Manager	21 years	14 years	Public / GLC
Respondent 5 (R5)	E	Senior Architect	17 years	5 years	Private
Respondent 6 (R6)	F	Assistant Manager	6 years	5 years	Private

Among the participants, three (3) were from public firms and held the position of Head of BIM unit in their organizations. Additionally, three (3) respondents from private firms occupied senior positions assisting the Head of BIM unit. The majority of the participants had extensive working experience, with 66% (four respondents) having more than ten (10) years of experience. Only 33% (two respondents) reported a total working experience of more than five (5) years. Notably, respondents working for public organizations demonstrated a significant amount of expertise in their field. Furthermore, all participants had firsthand experience with BIM implementation, with a minimum of 5 years’ experience. Interestingly, data saturation occurred after the 6th respondent, aligning with the assertion that at least six interviews are necessary to reach the threshold of data saturation and develop important themes (Ahankoob et al., 2018).

Section A: Features of Organisational Development

Challenges Faced by Organisation

From the findings most respondents stated that people were the biggest challenge in their organisation. The notion that ‘people’ are an organisation's greatest asset is one that is frequently expressed, both in academic and practical contexts. People, or human capital, provide a collective bank of knowledge, skills, capacities and expertise, all of which plays a crucial role in enhancing the productivity of the firm (Leroy et al., 2018). On the other hand, external factors such as financial resources, construction business environment and the adaptability to change are the emerging themes of challenges poses by the organisation in implementing new innovation and technology especially BIM.

Activities Used in Organisation

Activities or interventions are techniques employed in OD to instigate change within an organization, contributing to its health and effectiveness. Four (4) techniques were identified by respondents of the organizations, including training and development, employee engagement, surveys and feedback, and learning through projects. All respondents affirmed that their organizations implement training and development initiatives. As highlighted by Prabhu et al. (2019), employee training positively impacts both individual and organizational performance. Effective training enhances employees' knowledge and skills, as well as their satisfaction levels, all of which are crucial for achieving organizational objectives (Guest et al., 2020). Respondents from public construction organizations emphasized that training and development initiatives promote longevity within the organization.

In contrast, private construction firms adopt a more pragmatic approach to training, prioritizing short-term goals to minimize employee turnover. Training programs are tailored to match market demands, equipping individuals with enhanced knowledge and capabilities relevant to their professions and daily tasks. Examples of such training include re-orientation, workforce preparation, initiatives to improve worker well-being, formal training programs aimed at fostering a safer workplace, and refresher courses, all of which have significantly impacted company outcomes (Alserhan & Shbail, 2020).

Strategies Used in Organisation

The interview results revealed common strategies outlined by respondents that are applied by their organizations, involving functional strategy, business strategy, and corporate strategy. These strategies delineate the environment in which the firms conduct their business operations. Firstly, findings indicated that Firm A and B utilize the functional strategy approach. As noted by Fuertes et al. (2020), functional strategy closely pertains to the firm's processes and actions, encompassing how resources are utilized and applied. Functional strategies must be well-defined and aligned with corporate and business strategies. These strategies encompass various domains such as production, marketing, human resources, technology, organizational, and financial. Among these, production strategy holds precedence and is anticipated to remain the top priority in the coming years, followed by technological and human resources strategies in order of priority.

Conversely, Respondents R1, R3, and R4 stated that their firms adopt the business strategy approach. Business strategies wield considerable influence on mitigating the risk of financial mishaps, which could have immediate economic ramifications for company owners and investors (Habib & Hasan, 2017). These strategies are devised by management with the objective of achieving successful performance in specific business domains. The primary focus of a company's business strategy lies in establishing and sustaining its competitive position over the long term. In cases where an organization operates in diverse businesses, strategic planning may involve creating strategic business units (SBUs). Each SBU represents a distinct business or a cluster of related businesses, enabling the formulation of a unified strategy. Each SBU is endowed with its own unique mission and competes in a distinct market, allowing it to develop an independent strategy from other businesses within the organization.

Additionally, Respondents R5 and R6 from Firms E and F mentioned that their organizations employ a corporate strategy. The objective of corporate strategy is to fortify a company's business portfolio to surpass competitors. For organizations operating in multiple industries, a corporate strategy, such as company diversification, becomes essential as delineated in the responses. As Fuertes et al. (2020) elucidate, corporate strategy encompasses the organization's capacity to delineate its future positioning. The methods of articulating this positioning range from straightforward motivational statements to the attainment of rigorous objectives and comprehensive business particulars, linking business indicators and variables through a methodical approach. For diversified organizations, each division develops its own strategy, defining the products or services offered, the target clientele, and other pertinent aspects.

Section B: Current Practice of BIM Implementation in Construction Organisation

BIM Structure in Construction Organisations

A growing body of international research highlights organizational structure as a critical factor influencing successful BIM implementation (Sinoh et al., 2020; Chan et al., 2019a). This study supports that conclusion by examining how various structures across participating firms shape their BIM integration strategies and effectiveness. Firms A, B, and F have adopted a **divisional structure** for BIM implementation. In these firms, BIM functions primarily as a support tool for the design team, often aligned with project requirements from the earliest stages. This approach appears to be influenced by the firms' roles as clients or developers, where strategic decisions are typically driven by project outcomes. BIM responsibilities are frequently outsourced or delegated to external stakeholders such as consultants and contractors during the design and construction phases. These findings align with Chan et al. (2019b), who observed that organizational roles and business models significantly influence BIM deployment methods.

In contrast, Firm C employs a **matrix structure**, dividing BIM responsibilities between two dedicated teams: one that focuses on policy and standards development, and another that manages project-level BIM execution. This structural design promotes open communication and cross-functional collaboration, allowing for a more integrated and strategic BIM implementation. This reflects earlier literature suggesting that matrix structures can be more adaptable to innovation and process-driven technologies like BIM (Sacks et al., 2016).

Firm D has adopted a **BIM expert unit model**. Initially organized around a general BIM team, the firm has transitioned to a more specialized expert unit, likely due to the increasing complexity of internal BIM documentation, requirements, and policies. This structure allows the expert unit to serve as a centralized knowledge hub, providing guidance and technical support to various business units interested in BIM implementation. This evolution in structure is consistent with past findings, which emphasize the importance of having centralized expertise to scale BIM capabilities across the organization (Succar & Kassem, 2015).

BIM Implementation Approaches in Construction Organisations

Two primary approaches to BIM implementation were identified across the case firms: (1) mandated implementation through organizational policies, and (2) project-based implementation tailored to specific needs and constraints.

Firms B, D, E, and F have **institutionalized BIM through mandates, policies, and legal requirements**. For example, Firms B, D, and F—acting as clients or developers—embed BIM obligations within project contracts prior to tendering. These firms also assess the BIM competencies of their consultants and contractors to ensure alignment with project goals. They have invested in Digital Transformation strategies and have established internal BIM policies, standards, and platforms to support BIM Level 2 implementation. These practices echo recommendations in previous studies that highlight the value of clear policy frameworks and top-down support in achieving BIM maturity (Sacks et al., 2016).

Firm E, operating as a contractor, mandates BIM even when it is not specified in project requirements. Its approach leverages the **Integrated Project Delivery (IPD) model**, which promotes collaboration among all stakeholders from early design to construction. This proactive use of BIM for process optimization is consistent with literature emphasizing the synergy between IPD and BIM in enhancing project delivery efficiency (AIA, 2014).

In contrast, Firms A and C employ a **flexible, project-driven approach** to BIM implementation. Their strategies depend on the project's budget, complexity, and client requirements. Firm A is in the early stages of BIM adoption, with limited in-house expertise, indicating a need for phased implementation. Firm C, while recognized as a BIM pioneer in Malaysia, continues to invest in training and technological upgrades to achieve full integration. These findings mirror past research indicating that organizational readiness and resource availability often dictate the pace and depth of BIM implementation (Gu & London, 2010; Wong et al., 2011).

BIM Integration Benefits

Analysis of the case firms revealed **four major benefits** associated with BIM integration: **on-time project delivery, improved communication and collaboration, better cost control, and enhanced risk mitigation**. These outcomes align with the positive stakeholder perceptions described by Bradley (2016), and they reflect the expected value-add of BIM throughout the project lifecycle. As firms progress in their BIM journeys, the integration of design, construction, and operations becomes more seamless. This, in turn, enhances the value of project data at each stage, leading to greater process efficiency and improved project quality (Eastman, 2011). Notably, the findings reaffirm the potential of BIM to improve cost predictability and reduce project risks—benefits widely discussed in prior literature—while also underscoring the importance of aligning these advantages with organizational readiness and structural support.

Section C: Recommendation of Organisational Development Approach for BIM Implementation in Organisation

Aligning Culture and Values of Organisation and People

According to responses from four respondents (R1, R2, R3, and R4), it's evident that people are the primary drivers of change. They emphasized that a firm's culture plays a crucial role in fostering new adaptations or behavioural changes. Therefore, organizations must recognize the significance of individuals and their impact on BIM deployment. Values serve as the invisible threads of culture (Henderson & Thompson, 2003). When businesses align their culture and values with those of their employees, it enhances employee commitment and job satisfaction (O'Reilly et al., 1991). Values-aligned organizations strive to understand the impact of values within their firm and aim to align employee values with organizational ideals (Henderson & Thompson, 2003).

Values-aligned firms are aware of how values influence behaviour, performance, and outcomes. They consciously work with values to bridge the gap between employee and organizational values. Such firms understand the significant power of values and leverage them to give purpose to employee endeavours. Values-based organizations benefit from having a clear set of values that facilitate effective change management. Additionally, respondent R4 highlighted the importance of top management support in nurturing value creation. A study by Abbasnejad et al. (2020) suggests that top management characteristics impact value creation. Value creation facilitates organizational growth, supporting the development of BIM implementation. The Value Creation Model (VCM) illustrates how systems develop by adding value to their environment, which grants them the right to exist (Schaveling & Bryan, 2017).

Developing Organisational Strategy to Enhance BIM

Respondents R2, R4, and R6 have recommended developing the organizational strategy of the firm to enhance BIM implementation. The policies implemented by these firms ensure alignment with the organization's vision and mission. Furthermore, the strategies devised by the firm will determine the future positioning of the organization. According to Siebelink et al. (2018), BIM policy is among the most critical factors in BIM deployment. Establishing a clearly defined policy at both the micro and macro adoption levels of the firm is essential for successful BIM implementation. Additionally, policies that articulate a clear vision regarding project delivery methods, quality procedures, and information consistency among construction companies are crucial for BIM implementation in construction projects (Kassem et al., 2014). This perspective is further supported by Succar (2009), who identifies policy as a crucial component of BIM operations.

Becoming an Innovative Organisation

Respondents R4 and R5 underscore the importance for firms to embrace innovation. Beyond merely implementing BIM, innovative firms are encouraged to explore the potential of other collaborative BIM technologies such as artificial intelligence (AI), blockchain (BC), data analytics (DA), cloud computing (CC), Internet of Things (IoT), laser scanning (LS), and machine learning (ML), all of which offer significant advantages to the construction sector.

A survey by McKinsey (2018) found that 84% of executives believe future success hinges on innovation. In general, organizational innovation involves either developing or adopting new ideas or behaviours within an organization. This entails focusing on knowledge-based concepts and transformative behaviours (Lam, 2006). By fostering an innovative culture, organizations can advance value-added services, particularly in the context of BIM implementation within the construction sector.

However, it's essential to recognize that internal politics and an organizational culture resistant to failure, external suggestions, or change pose significant threats to organizational innovation, as noted by Gartner (2016). Therefore, fostering an environment that encourages experimentation, embraces failure as a learning opportunity, and welcomes external input is crucial for promoting innovation within organizations. Other suggestions from the respondents, such as leadership, benchmarking, increasing specialization, defining BIM goals, commitment to education, and adopting a holistic or unified BIM approach, are also vital in fostering an innovative organization.

CONCLUSION

This study investigates the organisational development required for effective BIM implementation in construction organizations. Through qualitative in-depth interviews with experienced respondents from public and private sectors, insights were gathered across three main sections: Features of Organizational Development, Current Practices of BIM Implementation, and Recommendations for Organizational Development Approaches for BIM. The analysis reveals that managing human capital presents the most significant challenge within organisations. While people are valued as assets, their diverse knowledge, skills, and expertise pose complexities. External factors such as financial resources and adaptability to change also shape the implementation of innovations like BIM. Training and development initiatives have demonstrated positive impacts on both individual and organisational performance, enhancing skills and satisfaction. Common strategies include functional, business, and corporate strategies, tailored to organisational needs. Structural approaches to BIM implementation vary, with divisional, matrix, and expert unit structures being prevalent. BIM implementation strategies encompass mandates and consideration of project budgets and requirements. Benefits of BIM integration include improved project timelines, communication, cost control, and risk mitigation. Aligning organisational culture and values with employee perspectives drives effective change. Developing a clear organisational strategy for BIM deployment is essential, as is fostering innovation and embracing emerging collaborative technologies such as AI, blockchain, and data analytics in the construction sector. The study acknowledges limitations due to a small sample size and suggests future research to validate findings across a broader demographic using a systematic questionnaire approach.

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ASSESSMENT OF TEMPORARY HOUSING FOR CONSTRUCTION WORKERS IN MALAYSIA: ENHANCING SAFETY AND WELFARE

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Abstract

This paper examines the compliance of temporary housing provided for construction workers in Malaysia with national standards, particularly MS 2593:2015. It evaluates critical aspects such as living space, sanitation, safety, and welfare amenities. Through site observations and unstructured interviews at two construction sites in Selangor, the study identifies widespread non-compliance and captures workers' perceptions of their living environments. Findings highlight recurring deficiencies that pose health and safety risks, including overcrowding, poor ventilation, inadequate sanitation, and weak fire prevention measures. These conditions reflect deeper structural neglect and unequal treatment of migrant labourers in the built environment. Drawing from labour welfare theory and the Total Worker Health approach, the study frames worker housing as an essential component of occupational well-being and human dignity, rather than a secondary operational concern. The paper argues that enforcement mechanisms must be strengthened through regular audits, meaningful penalties, and transparent reporting. It also calls for housing designs that are modular, culturally sensitive, and integrated with safety standards from the outset. Attention to spatial justice is emphasised to ensure that worker accommodations are not hidden or marginalised but fairly situated within construction ecosystems. This study contributes to the discourse on construction governance, occupational welfare, and migrant housing reform. It offers practical insights for construction managers, designers, and policymakers aiming to enhance worker welfare, reduce risk, and promote long-term sustainability in the Malaysian construction industry.

Keywords: *Regulatory compliance; Construction industry; Migrant workers; Labour welfare; Worker accommodation*

INTRODUCTION

Context of Foreign Labour in Malaysia

Malaysia hosts nearly 2.4 million documented migrant workers, with estimates suggesting an additional 2 million undocumented migrants, making it one of the highest users of foreign labour in the Asia Pacific region (Immigration Department of Malaysia, 2023). The construction sector relies heavily on these workers to sustain its workforce (Department of Statistics Malaysia, 2023).

Substandard Housing and Health Hazards

The term 'kongsi house' refers to the temporary accommodations provided for construction workers at project sites. These accommodations are often constructed from discarded materials such as plywood and metal sheeting, resulting in living conditions that barely meet basic standards. These structures present serious risks to health and safety, particularly due to poor ventilation, sanitation, and vulnerability to fire. Exposure to fire may result in structural collapse and injury or death of the occupants of the building (Sivakumar

et al., 2018). Beyond physical inadequacies, these housing arrangements also reflect deeper social and spatial inequalities experienced by migrant workers.

Policy Interventions and Persistent Gaps

In response to growing concerns, Deputy Prime Minister Dato' Seri Dr. Ahmad Zahid Hamidi announced in 2023 that the government would mandate employers to provide at least minimum standard accommodations for foreign workers. Employers failing to comply with this directive would face restrictions on hiring new foreign workers (New Strait Times, 2017). Nevertheless, compliance remains inconsistent, and the gap between policy and practice continues to widen.

In Malaysia, temporary accommodations for construction and migrant workers remain overcrowded, unsafe, and unsanitary despite growing awareness and legal reforms. The COVID-19 pandemic exposed severe vulnerabilities in worker housing, where cramped living quarters facilitated the spread of infection and underscored long-standing neglect (Jones et al., 2024). Reports indicated that over 90% of worker accommodations were non-compliant with legal standards during the height of the pandemic (Bernama, 2022). These living arrangements, commonly known as kongsi houses, frequently consist of makeshift units constructed from metal sheets and plywood, offering minimal ventilation, privacy, or hygiene (Ng et al., 2024).

National Standards and Regulatory Framework

In response to these challenges, Malaysia introduced MS 2593:2015, a national standard for temporary construction site worker housing. This code outlines minimum requirements for space, sanitation, safety, and welfare (Department of Standards Malaysia, 2015). However, the adoption of this standard remained voluntary until legal reinforcement through the 2019 amendment of the Workers' Minimum Standards of Housing and Amenities Act 1990 (Act 446). These amendments expanded the law's applicability across all industries, including construction, and made compliance mandatory (Khor, 2021).

Despite this legal shift, compliance levels remain low. Inspections in 2021 found that nearly half of construction employers still failed to provide housing that met basic standards, with some employers citing delays or approval issues as justification (Malay Mail, 2021). The Ministry of Human Resources reported issuing RM12.4 million in compound fines from 2020 to 2022 to errant employers (Bernama, 2022). The primary causes of non-compliance include cost constraints, weak enforcement, and limited awareness of legal obligations (MalaysiaNow, 2020).

International Comparisons and Emerging Models

Scholars and policymakers increasingly recognise that poor living environments not only infringe upon workers' rights but also diminish productivity and occupational safety. International benchmarks, such as the ILO Workers' Housing Recommendation No. 115 and the Responsible Business Alliance Code—provide additional guidance for dignified accommodations (International Labour Organization [ILO], 2022). Malaysia's Act 446 and

MS 2593:2015 largely align with these principles but face challenges in on-the-ground enforcement (Nasir et al., 2023).

Efforts to pilot solutions such as Centralised Labour Quarters (CLQs) offer a way forward. These facilities are purpose-built dormitories that comply with minimum standards and separate worker housing from construction zones. When properly implemented, they have demonstrated better living conditions and reduced enforcement issues (Ng et al., 2024). Regionally, Malaysia compares favourably to Thailand but lags behind Singapore's Foreign Employee Dormitories Act, which tightly regulates large-scale dormitories and post-pandemic upgrades (ILO, 2022).

Ultimately, improving construction worker housing in Malaysia is not merely a legal compliance issue, it is integral to health, productivity, and national reputation. Continued enforcement, design innovation, and participatory governance are essential for sustaining worker welfare reforms. This study addresses these gaps by evaluating the extent of compliance with MS 2593:2015 across two construction sites, identifying common deficiencies, and examining workers' perspectives to inform future policy and design interventions.

AIM AND OBJECTIVES

The aim of the research is to assess the compliance of temporary housing facilities for construction workers in Malaysia with national standards, particularly MS 2593:2015, and identify areas for improvement in living conditions to enhance worker safety, well-being, and overall welfare. The objectives include:

1. To evaluate the compliance of current temporary housing facilities for construction workers with the MS 2593:2015 standards.
2. To examine common non-compliance issues pertaining to the temporary housing facilities for construction workers.
3. To investigate workers' perspectives from different backgrounds in order to gather insights about their welfare at the temporary housing facilities.

METHODOLOGY

This research adopts a qualitative approach to comprehensively assess the temporary housing conditions for construction workers in Malaysia. Grounded in exploratory case study methodology, the study integrates site observations and unstructured interviews to capture both environmental conditions and lived experiences. Two active construction sites in Selangor were selected as field locations. Observational data focused on space, sanitation, and safety features, while interviews gathered narratives on worker comfort, risks, and perceptions of welfare. This approach provides a robust framework for assessing the temporary housing conditions of construction workers in Malaysia. The findings aim to inform policy enforcement and promote the development of more humane and compliant housing standards.

Case Study Selection

Two construction sites in Selangor were selected for this study. These sites were chosen based on their size, type of construction activity, and accessibility for detailed examination. Site A represents a large-scale commercial development, while Site B involves a medium-scale residential project. The selection criteria reflect purposive sampling, which is appropriate for qualitative case studies seeking in-depth insight rather than statistical generalisability (Creswell & Poth, 2018). The diversity in project types allows for a comparative analysis of the temporary housing conditions across different construction contexts. Both sites remain anonymous in this study to protect the privacy and confidentiality of the companies involved and to encourage transparency and honest participation in data collection. Anonymity also minimises potential bias and promotes ethical integrity in presenting findings that may highlight non-compliance or welfare deficiencies.

Site Observations

Observations were conducted at both sites to evaluate the living conditions of the workers against the criteria outlined in MS 2593:2015. This Malaysian Standard provides comprehensive guidelines on the minimum requirements for amenities and accommodation at temporary construction sites (Department of Standards Malaysia, 2015). The use of direct observation allowed for a first-hand, non-intrusive assessment of compliance across multiple physical and environmental dimensions. Observational data were systematically recorded. This approach enhanced the reliability of the data and reduced bias typically associated with self-reported conditions. The criteria were assessed using a structured checklist encompassing the following key aspects:

Table 1. Observation Checklist Based on MS 2593:2015

Criteria	Explanation
Accommodation Size	Adequacy of sleeping areas, common areas, and overall space per worker.
Sanitisation Facilities	Availability and cleanliness of toilets, showers, and laundry facilities.
Safety Measures	Presence of fire safety equipment, emergency exits, and general safety protocols.
Ventilation and Lighting	Quality of air circulation and natural/artificial lighting within the accommodations.
Health and Welfare Amenities	Availability of medical facilities, recreational areas, and dining facilities.

Unstructured Interviews

To complement the observational data, unstructured interviews were conducted with a total of 10 construction workers across Site A and Site B. The sample included workers of Bangladeshi, Burmese, and Indonesian origin, reflecting the ethnic diversity typical in Malaysia’s construction workforce. This diversity enabled the study to explore how cultural background may influence perceptions of adequacy and welfare.

Unstructured interview was selected for their ability to elicit rich, in-depth insights on lived experiences and emotional responses, particularly relevant in qualitative exploratory research (Creswell & Poth, 2018). All interviews were conducted on-site with the informed consent of participants. The interview data were transcribed and manually coded using thematic analysis, allowing recurring ideas to be grouped into key themes aligned with the study’s objectives. This approach provided a nuanced understanding of worker perspectives, supplementing the physical assessments made through site observations.

LIMITATIONS

The limitations of this study include its restricted scope to two construction sites in Selangor, which may not reflect conditions at other sites across Malaysia, thereby limiting the generalisability of findings. The qualitative approach, relying on unstructured interviews and observations, introduces subjective elements that may vary by participant and setting, affecting consistency. Access constraints and language barriers also influenced participant availability, particularly when discussing sensitive matters such as welfare or regulatory violations. The study's focus on compliance with MS 2593:2015 does not encompass other national or local frameworks, such as Act 446 or municipal-level guidelines, which may shape housing practices differently. Furthermore, enforcement variability and employer interpretation of standards were not directly measured. Finally, as a snapshot in time, the research may not capture seasonal changes or future policy shifts that could affect the ongoing relevance of the findings.

RESULTS

Site Observations

Data collected from Site A and Site B were evaluated against MS 2593:2015, which stipulates the minimum requirements for temporary construction site workers' accommodation and amenities. Key parameters assessed include accommodation size, sanitation, safety measures, ventilation, lighting, and welfare facilities. The findings reveal systematic non-compliance at both sites, with recurring issues that compromise worker well-being and violate established standards.

Table 2. Observation of Site A

Criteria	Findings
Accommodation Size	Sleeping quarters were overcrowded, with each worker allocated significantly less than the minimum recommended floor area. Beds were closely packed, offering no personal storage or privacy.
Sanitisation Facilities	Toilets and showers were insufficient in number and poorly maintained. Communal facilities lacked privacy and cleanliness.
Safety Measures	Fire safety measures were absent. No extinguishers were installed, and building materials such as plywood increased the risk of fire.
Ventilation and Lighting	Poor ventilation led to high humidity and discomfort. Both natural and artificial lighting were inadequate for basic daily activities.
Health and Welfare Amenities	No medical facilities were available on site. Recreational and dining spaces were overcrowded and unhygienic.

Table 3. Observation of Site B

Criteria	Findings
Accommodation Size	Similar to Site A, overcrowding was prevalent. Workers shared narrow sleeping spaces with limited access to personal storage.
Sanitisation Facilities	Toilets and bathing areas were limited and not subject to regular cleaning schedules. Sanitation was compromised.
Safety Measures	Fire extinguishers were either absent or non-functional. Use of combustible materials such as plywood presented fire hazards.
Ventilation and Lighting	Air circulation was inadequate. Poor lighting conditions contributed to discomfort and risk of injury during night-time activities.
Health and Welfare Amenities	Medical support was unavailable. Recreation facilities were insufficient, and dining areas did not meet hygiene requirements.

Overall, both sites failed to meet multiple provisions under MS 2593:2015, with recurring deficiencies in space allocation, health infrastructure, and fire safety. These findings underscore systemic gaps in standard implementation at the site level.

Unstructured Interviews

Unstructured interviews were conducted with a total of 10 construction workers across Site A and Site B. The sample comprised individuals of Bangladeshi, Burmese, and Indonesian origin to reflect the ethnic and cultural diversity typical of Malaysia's construction workforce. The aim was to capture workers' lived experiences, perceptions of adequacy, and emotional responses to their temporary housing conditions. The interviews were analysed using thematic analysis, whereby responses were transcribed, manually coded, and categorised into recurring themes. Four dominant themes emerged from the analysis: perceived adequacy of space, sanitation and hygiene, safety concerns, and emotional well-being and dignity.

Perceived Adequacy of Space

The interviews were analysed using thematic analysis, whereby responses were transcribed, manually coded, and categorised into recurring themes. Four dominant themes emerged from the analysis: perceived adequacy of space, sanitation and hygiene, safety concerns, and emotional well-being and dignity.

Sanitation and Hygiene

All interviewees, regardless of nationality, expressed dissatisfaction with sanitation facilities. Complaints included unclean toilets, lack of proper bathing spaces, and irregular maintenance. Several Burmese workers emphasised the psychological discomfort of using shared facilities without privacy.

Safety Concerns

Interviewees voiced a general awareness of fire hazards but accepted these risks as part of daily life. None reported the presence of fire extinguishers, and some highlighted prior incidents of electrical faults or minor accidents.

Emotional Well-being and Dignity

Indonesian workers, in particular, raised strong concerns about overcrowding, lack of privacy, and the absence of recreational areas. They described feelings of neglect and disconnection, suggesting higher expectations of humane treatment shaped by previous employment or cultural norms. These findings underscore that technical compliance alone does not equate to perceived adequacy. Cultural background and previous experience shape how workers evaluate their living conditions. As such, worker accommodation policies must go beyond structural guidelines to also consider psychological well-being, cultural sensitivities, and participatory feedback mechanisms.

DISCUSSION

This study reveals persistent deficiencies in the implementation of minimum housing standards for construction workers, particularly in reference to MS 2593:2015. Across both case study sites, non-compliance was consistently observed in areas such as spatial allocation, sanitation, safety measures, and welfare amenities. These findings validate widespread concerns highlighted by national inspection reports and academic studies (Ng et al., 2024; Nasir et al., 2023). The overcrowded accommodation and inadequate sanitation observed reflect structural neglect that endangers worker health and safety. Despite the legal reinforcement provided by amendments to Act 446, compliance appears to be undermined by weak enforcement mechanisms, cost constraints, and limited awareness among employers (Bernama, 2022; Malay Mail, 2021). As such, the findings point not only to technical gaps but also to broader institutional shortcomings.

From a policy perspective, the data reinforce the urgency of transforming housing from a cost-driven obligation into a strategic investment in workforce productivity and industry sustainability. Compliance with MS 2593:2015 should not be seen as the ceiling but rather the baseline for dignified housing. The lack of fire safety equipment, for instance, poses serious legal and ethical concerns, given repeated fire-related incidents in such accommodations (Sivakumar et al., 2018).

The interviews further reveal divergent experiences across different nationalities, suggesting that technical compliance alone may be insufficient to ensure worker satisfaction. Cultural expectations and previous exposure to substandard housing shape individual responses, underscoring the need for more adaptable and inclusive design frameworks. Participatory approaches that include feedback from workers of various backgrounds could enhance the relevance and acceptance of housing solutions.

Regionally, Malaysia has taken steps in the right direction with Centralised Labour Quarters (CLQs), yet these remain limited in scope and geographic reach. Lessons may be drawn from Singapore's tighter regulatory framework under the Foreign Employee Dormitories Act, where post-pandemic upgrades have significantly improved baseline conditions (ILO, 2022). However, Malaysia must contextualise these models to its own economic and enforcement realities.

In summary, addressing temporary worker housing in Malaysia demands more than infrastructural upgrades. It calls for multisectoral collaboration, consistent enforcement, design innovation, and a shift in perception, from housing as a liability to housing as an asset. Future research should explore worker housing performance over time, the role of local councils in implementation, and the long-term effects of dignified living on retention and safety outcomes.

CONCLUSION

This study assessed the compliance of temporary housing facilities for construction workers in Malaysia with national standards, particularly MS 2593:2015. Through site observations and unstructured interviews at two case study locations, the research identified consistent shortcomings in spatial adequacy, sanitation, fire safety, ventilation, and welfare

amenities. These deficiencies not only breach regulatory expectations but also compromise the health, safety, and dignity of workers. The study also revealed varying levels of satisfaction and tolerance among workers based on nationality, indicating that cultural background and previous experiences shape perceptions of adequacy. This highlights the importance of incorporating participatory and culturally sensitive approaches when designing and implementing worker accommodation.

Despite the existence of regulatory frameworks such as MS 2593:2015 and Act 446, enforcement remains inconsistent. This study reinforces the call for stricter monitoring, clearer accountability mechanisms, and wider dissemination of housing compliance requirements. Employers must view worker accommodation not as a legal burden but as an investment in workforce sustainability and project efficiency. To improve conditions, the construction sector should consider adopting innovative solutions, including modular housing systems, centralised labour quarters, and feedback systems that empower workers to voice concerns. Future research could expand on these findings by exploring longitudinal impacts of housing reforms, comparing practices across regions, or assessing cost-effective upgrades. Ultimately, ensuring safe, clean, and dignified housing is essential to the welfare of construction workers and the integrity of the industry. Sustained improvements will require commitment not only from policymakers but also from developers, contractors, and society at large.

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DETERMINATION OF COMPRESSION BEHAVIOUR ON BUILT-UP COLD-FORMED STEEL WITH SIX LIPPED CHANNEL SECTIONS FILLED WITH WASHED BOTTOM ASH CONCRETE

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Abstract

Cold-formed steel (CFS) characterised by its slender profile and thin surface is produced from sheet steel using rolling, pressing and bending processes, and is sometimes referred to as a thin-walled structural material. CFS is produced in various forms, dimensions and grades based on use and demand, and is widely employed in interior wall panels, roof truss systems and storage racks. However, the CFS section is susceptible to buckling failure when subjected to self-weight or external action. Several research is completely conducted to solve the buckling failure by joining two or more individual single sections to become a built-up CFS section. Additionally, many researchers have studied filling the built-up CFS section with normal or special concrete to strengthen the section before being used as a structural component. Thus, this study formed the built-up CFS section by consuming six lipped channels and lastly filled with special concrete, which replaced sand in concrete with washed bottom ash (WBA). The main objective of this study is to determine the compression behaviour of built-up CFS with six lipped channels filled with WBA concrete. The experimental activity comprises three specimens, which are separated into built-up CFS without concrete, built-up CFS with normal concrete and built-up CFS with WBA concrete. The compression behaviour of all specimens is documented, and the failure mode of each specimen is examined. In summary, the ultimate load of built-up CFS without concrete is augmented by 33.87% when the section is filled with normal concrete and by 31.34% when filled with WBA concrete.

Keywords: Cold-formed Steel; Buckling Failure; Built-up Section; Compression Behaviour; Washed Bottom Ash Concrete

INTRODUCTION

Cold-formed steel (CFS) or known as a thin-walled structural material is manufactured at ambient temperature to provide a thin surface in many individual shapes, including channel, zee, sigma and angle, as well as different cross-sections and grades. The processes that are involved in the production of the CFS are the rolling process, pressing process and curving process, which contrast to hot-rolled steel production by shaping at high temperatures. The application in civil engineering activity and general usage includes structural components and non-structural components, wall framing systems, flooring systems, roofing systems, and furniture panels. Sang et al. (2023) have mentioned about the extensive utilisation in various domains, including structural building components, solar photovoltaic brackets, storage shelves, and portal frames, and the shape of the structure becomes more intricate and progressively progresses from a low-rise building to a multi-high-rise building. CFS has found and produced a lot of benefits, for example, sustainability, lightweight, corrosion resistance, durability, efficiency, cost-effectiveness, ease of production and installation, and high strength-to-weight ratio.

Buckling is a serious failure mode for columns, beams, frames and panels, especially when deliberating with thin surfaces and slender profiles such as CFS. In general, buckling refers to the structural component which suddenly movement to sideways or is deflected when subjected to a critical load. This critical load either in compression or bending load is less than the load which required to cause the material to fail due to yielding or breaking. CFS faces several types of buckling when a critical load is applied to it, for instance, local, distortional, global and flexural buckling as shown in Figure 1. Factors involved with the buckling failure mode are slenderness ratio, cross-section profile, material properties, end support conditions and load conditions. Researchers have used several techniques to minimise buckling failure by considering the design requirement, such as increasing thickness, utilising additional bracing, using stiffeners, employing advanced finite element examination and optimising cross-section profile.

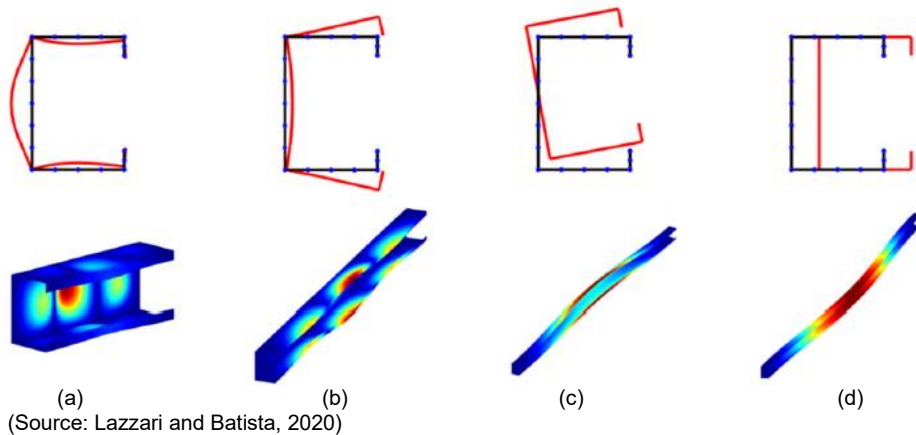
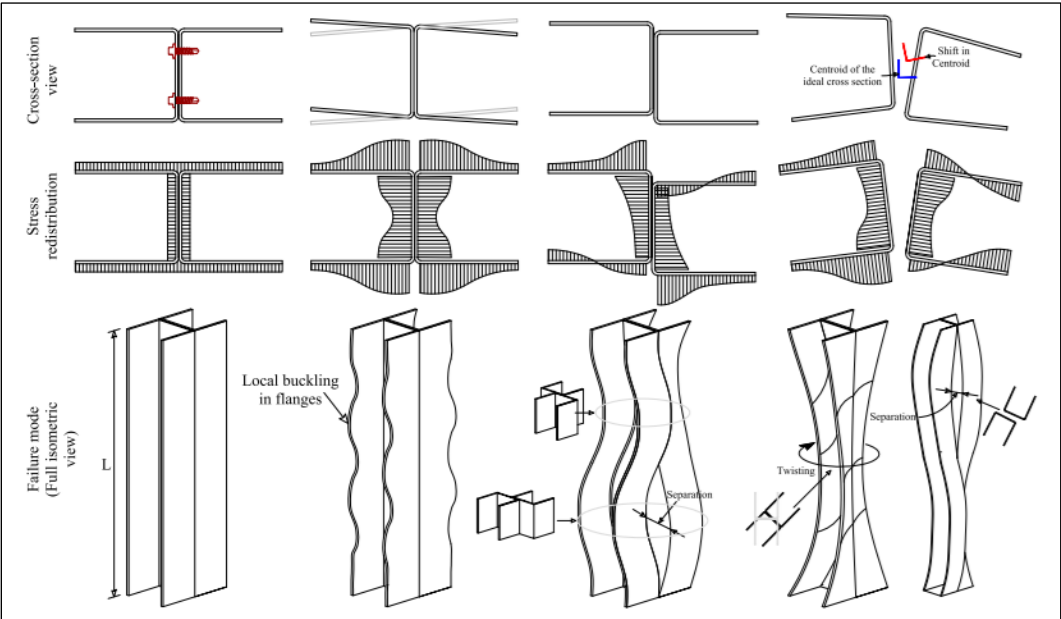


Figure 1. Failure Modes of The CFS Channel with Lipped Column, for Example, (A) Local Buckling, (B) Distortional Buckling, (C) Global Buckling and (D) Flexural Buckling

With the intention to reduce the structural integrity, a built-up CFS section is suggested to satisfy the design requirement of increasing thickness and optimising the cross-section profile, which combines two individual shapes for creating a single stable section. The fasteners or jointer are used to combine and compose the built-up CFS section such as bolts and nuts, self-drilling screws, self-tapping screws, spot welds and alternative innovative fasteners. The built-up CFS is used as a structural component due to structural performance extension based on stiffness, stability and strength, and is suitable for long spans and load-bearing capacity applications. In order to offer a high loading strength and long span distance, the built-up CFS section is commonly utilised in window and door opening frame headers, roof truss members, exterior wall chords, shear wall chords and other appropriate components (Sang et al., 2023).

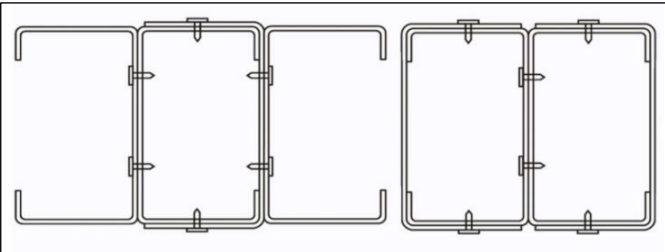
The characteristics or attributes of the built-up CFS section include an improved moment of inertia, avoidance of initial local buckling, enhanced load capacity, advanced composition advancement and customisability. The commonly built-up CFS section using individual channel sections with two identifiers is categorised as a back-to-back section and a face-to-face section. These two built-up CFS sections are regarded as popular sections as they have greater levels of torsional and flexural rigidity, thus, the strength determination and the failure mode of both sections are considered complicated (Mahar et al., 2022). Nevertheless, the

commonly built-up CFS section whether in a face-to-face configuration or back-to-back configuration, that connects two individual shapes by using fasteners is susceptible to buckling failure as shown in Figure 2.

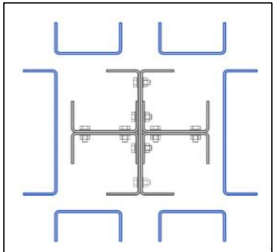


(Source: Selvaraj and Madhavan, 2022)

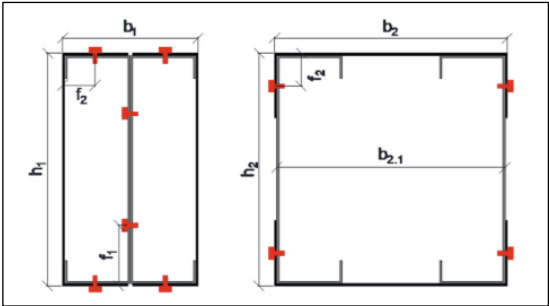
Figure 2. Failure Mode of The Built-Up CFS Section in Back-to-Back Configuration Using Self-Drilling Screws



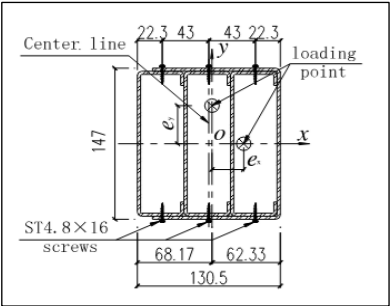
(Source: Ma et al., 2024)



(Source: Dobric et al., 2024)



(Source: Craveiro et al., 2022)



(Source: Nie et al., 2022)

Figure 3. Example of The Built-Up CFS Section Using Channel Shape

However, the built-up CFS with two individual sections is improved by adding more individual sections to make the section becoming more stable, strong and able to reduce the buckling failure. There are various previous studies which used more than two individual channel sections as shown in Figure 3 such as Ma et al. (2024) with three lipped channels and one unlipped channel; and two lipped channel and two unlipped channels, Dobric et al. (2024) with four unlipped channel of 100 mm depth and two unlipped channel of 200 mm depth, Nie et al. (2022) with one unlipped channel (147 mm × 118 mm × 1.5 mm) and three lipped channel (143 mm × 43 mm × 15 mm × 1.5 mm), and Craveiro et al. (2022) with two lipped channel (149.94 mm × 42.96 mm × 15.16 mm × 1.5 mm) and two unlipped channel (153.08 mm × 43.06 mm × 1.50 mm). From the figure, the self-drilling screw as the fasteners is used to join the individual channel with other individual channel at the web and flange element including the use of bolts and nuts. The location of self-drilling screw in production of the built-up CFS section is still under study and there is no clear information in the design codes. The built-up CFS section is formed either in a closed or open section however, the section should be in stable condition and symmetrical circumstances.

The primary issue with all of the systems based on the built-up CFS section nowadays is the improvement of the column capacities by developing the potential solution such as using elements with improved performance, an ideal configuration composition, the appropriate spacing between fasteners and to use of other materials for forming hybrid or composite section (El Hady et al., 2022). Thus, the built-up CFS section with other materials such as normal concrete, special concrete, normal mortar, special mortar or timber board is promoted in the production of structural components. The combination of built-up CFS section with concrete can be used in various structural component applications such as wall frames, floor systems, beams and columns because of stability, strength enhancement, durability enhancement, fire resistance improvement, architectural flexibility, construction efficiency, thermal insulation and acoustic insulation. The idea and concept behind a built-up CFS section filled with concrete parallels that of a concrete-filled steel tubular (CFST), whereby the empty parts or hollow portions are filled with concrete and have the ability to improve and regulate the performance of the structure when subjected to earthquake and fire exposure (Mohd Sani and Muftah, 2021). Furthermore, the normal concrete using traditional material such as sand, gravel and cement increases the production cost and environmental problems. Thus, many researchers are tried to replace the traditional material in normal concrete by using waste material from industry for promoting the special concrete to fill in built-up CFS section such as geopolymers foam concrete (Li et al., 2025), lightweight foam concrete (Wang et al., 2025), High strength concrete (Zhang et al., 2025), self-compacting lightweight concrete (Teoh et al., 2023) and rubberised concrete (Jafarifar et al., 2023). The flowchart of the summary of the literature is illustrated in Figure 4.

The investigation and analysis of replacing the traditional material in normal concrete with waste material aims to decrease structural integrity and environmental impact. Thus, bottom ash (BA) is recognised as a waste material from coal-fired electric power plants and has a coarse and porous surface, granular, and lightweight in nature is observed to assess the suitability when replacing the traditional material. BA is collected from the bottom side of the boiler or furnace, while another waste product, sometimes called fly ash is collected from the precipitator process as shown in Figure 5. Inadequate management of the BA will have negative implications on human health, such as an elevated risk of cancer and respiratory illnesses, as well as negative repercussions on the environment, such as air, water, soil and

groundwater pollution. Additionally, BA has the ability to seep dangerous chemicals into groundwater, disposing of it may be environmentally problematic, especially the landfilling method of disposal. Besides, the sand quarrying activity in the stream has produced a lot of environmental problems, including river erosion, riverbank collapse, high CO₂ emission, water pollution, and riverbeds becoming deeper, which caused flood problems and aquatic life interrupted (Mohd Sani et al., 2022). Because of this, BA is recommended for the reduce, reuse and recycle (3R) activity after being washed or treated, and is utilised as a concrete production material, structural filling material and road base material.

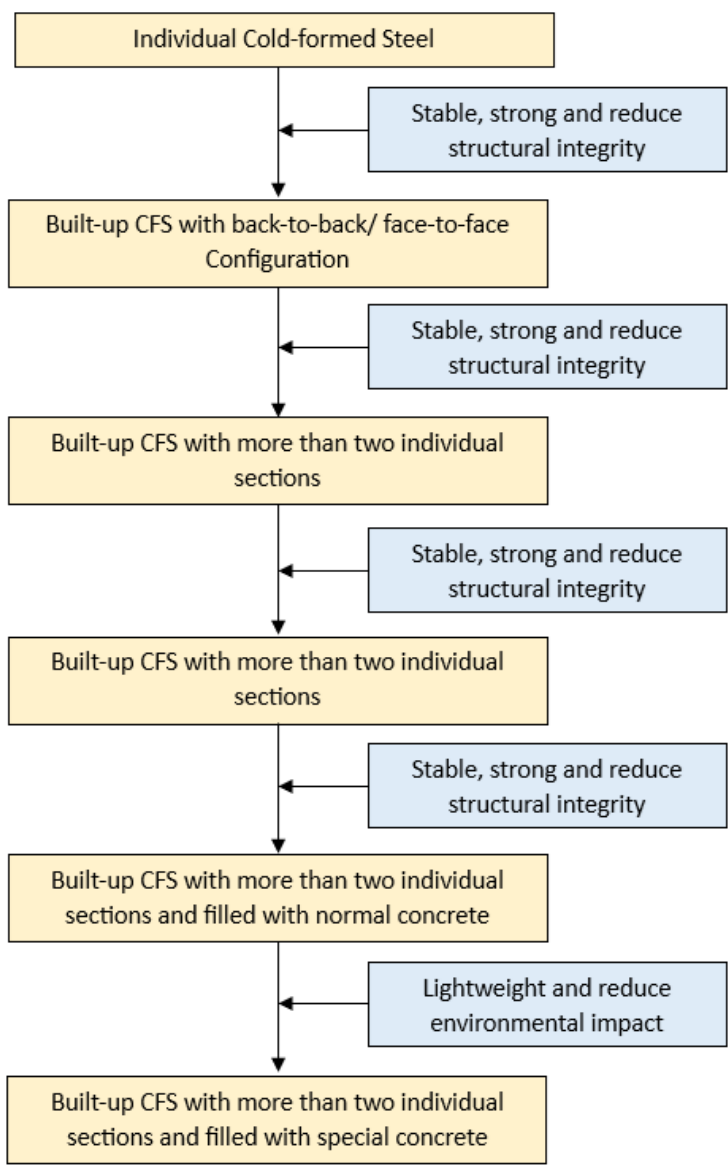
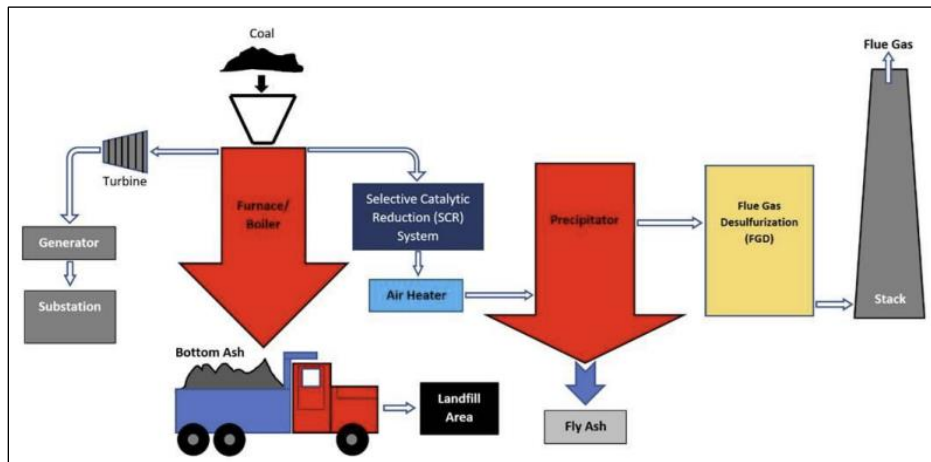


Figure 4. The Flowchart of The Summary of The Literature Review



(Source: Mohd Sani et al., 2023)

Figure 5. The Waste Product Production from Coal-Fired Electric Power Plants

BA has distinctive chemical and physical properties that affect its appropriateness for concrete applications. BA is mostly used in concrete as a replacement for sand and in some instances, as a partial replacement for cement. Many researchers have conducted studies of BA in concrete, for example, the use of 30% as sand replacement by Hongthong et al. (2025), 0-100% as sand replacement by Ashraf et al. (2025) and 0-30% as cement replacement by weight by Kiruthiga et al. (2025). The study generally concludes that BA can be effectively used as sand replacement where the balance between compression behaviour and sustainability benefits is most favourable.

As a result of the previous study, the research on the built-up CFS section remains in progress, and there is no available information on the built-up CFS section formed by the assembly of six lipped channel sections using spot welding. Research on built-up CFS sections using normal and special concrete is currently ongoing and has yielded a wealth of fresh data and insights. The main objective of the study is to ascertain and determine the compression behaviour of a built-up CFS column using six lipped channel sections filled with WBA and observe the failure mode of the column.

SPECIMEN AND EXPERIMENTAL PREPARATION

A CFS lipped channel section with dimensions of web element; 100 mm, flange element; 50 mm, lipped element; 12 mm, thickness; 1.55 mm and steel grade; G450 is preferred and favoured due to its availability in the Malaysian construction market as shown in Figure 5. The cross-sectional area and yield stress of the CFS lipped channel section are 329 mm² and 450 MPa, respectively. The mass of the single individual CFS lipped channel section is 0.65 kg for a length of 250 mm. The determination of the cross-section ratio of the CFS lipped channel section is a flange to thickness ratio is 32.26, flange to lipped ratio is 4.17, web to flange ratio is 2.00, web to thickness ratio is 64.52, web to lipped ratio is 8.33 and lipped to thickness ratio is 7.74. The given cross-section ratios are essential geometrical factors that directly control a CFS lipped channel section from local buckling, which in turn determines its structural capacity under different loading scenarios. The value of the cross-section ratio is susceptible to local buckling; however, the inclusion of the lipped element may mitigate this phenomenon.

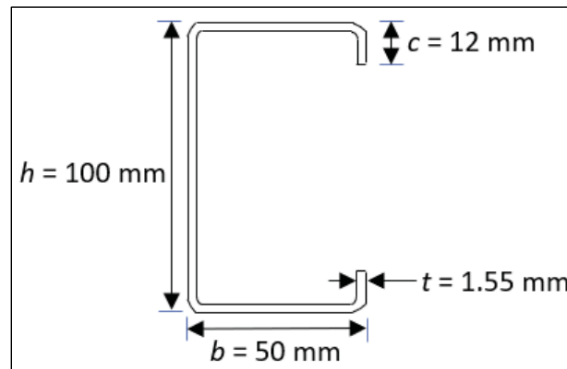


Figure 5. The Dimension of The CFS Lipped Channel Section

Six lipped channel sections are clean and combined together by utilising spot welds in side-to-side configuration at the flange element, and next, combined in face-to-face configurations at the flange and lipped element as shown in Figure 6. Thus, the depth of the built-up CFS section is 200 mm, and the width of the built-up CFS section is 103.10 mm. The overall area of the built-up CFS section without concrete is 11084 mm². The depth to width ratio of the built-up CFS section is 1.93, and the height of the built-up CFS column is 250 mm.

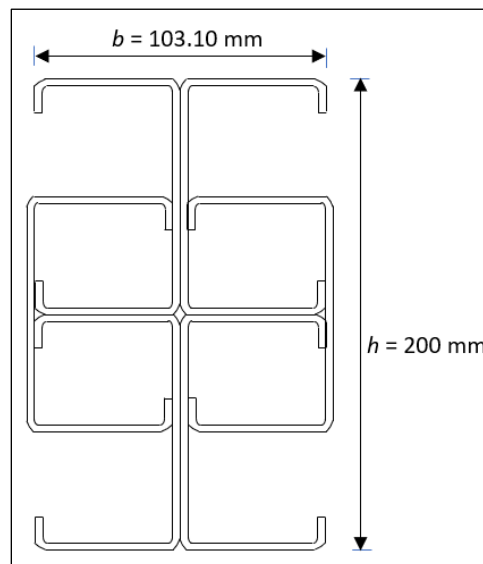


Figure 6. The Dimension of The Built-Up Section with Six Numbers of CFS Lipped Channel Sections

The study employed washed bottom ash (WBA), sand, gravel and Portland cement for the concreting process and in the trial, WBA is used in full percentages to replace sand. WBA is collected after the washed process of BA using tap water for removing impurities and minimising the amount of carbon and checked them that it is free from soil or deleterious material in the concrete. WBA is in grey as shown in Figure 7, while sand is in yellow. The WBA is shown to have a porous condition and be lighter than sand. WBA is sieved by using a sieve shaker and a sieve pan of 5 mm size, and collected, which passes through the pan. Other materials used in concreting are gravel with a 20 mm passing sieve pan, and also superplasticiser to enhance the workability and strength of the mix. The design mix concrete

of grade 30 is prepared and recorded as having a density in the concrete of 410 kg/m³ of cement, 1120 kg/m³ of gravel, 690 kg/m³ of sand and 222 kg/m³ of water. The concrete mix has a water-cement ratio of 0.54. All concrete materials, including WBA are mixed by using an electric drum mixer and filled into the empty areas of the built-up CFS section. Three specimens are included in the experimental preparation as tabulated in Table 1. Normal concrete and WBA concrete are used to fill the empty areas of the built-up CFS section.



Figure 7. WBA in Grey Colour

Table 1. The Description of All Specimens

Description of Specimen	Specimen Labels	Mass (kg)	Depth-Mass Ratio
Built-up CFS without concrete	BCFS1	7.50	26.67
Built-up CFS with normal concrete	BCFS2	8.45	23.67
Built-up CFS with WBA concrete	BCFS3	8.03	24.91

There are two parts of the experimental activity include the determination of the material properties of CFS in tensile and WBA concrete in compression, and the determination of the compression behaviour of built-up CFS columns without and with normal and WBA concrete. The experimental activity of the material properties of the CFS is conducted by cutting them into the tensile coupon test shape as follows to BS EN10002-1 standard, and utilising the universal testing machine (UTM) with 100 kN load capacity and with a pace rate of 1 mm/min. The tensile coupon test shape specimen is placed in the UTM and attached at the middle part of the specimen with an extensometer of 50 mm of gauge length. The ultimate stress and yield stress of the web element and flange element are documented. Whilst as, the experiment on the material properties of normal concrete and WBA concrete is conducted by using a 150 mm × 150 mm × 150 mm of cube mould, and an automatic compression machine (ACM) with 2000 kN of load capacity for a curing duration of 3, 7, 28 and 60 days. The compression stress for both concretes is recorded. The built-up CFS column specimen also used an ACM with 6.80 kN/sec in determining the ultimate load after being cured for 28 days. Lastly, the failure mode of all specimens is observed and classified.

RESULT AND DISCUSSION

The result of the two parts of the experiment activity is reported, analysed and discussed here, including the material properties of CFS and WBA concrete, the compression behaviour of the built-up CFS column. The failure mode of the built-up CFS column specimens, especially at the flange and web element is observed and discussed.

Material Properties of Cold-Formed Steel and Washed Bottom Ash Concrete

The result data of the material properties of the CFS lipped channel section, especially web and flange elements are presented in Table 2. In the table, the percentage difference of the properties between the web and flange elements is also displayed. The ultimate stress of the web element is recorded to have 509.71 MPa, and the ultimate stress of the flange element is recorded obtaining 524.82 MPa. The yield stress of 485.75 MPa for the web element and the yield stress of 500.39 MPa for the flange element are verified. As expected, the bending, curving and rolling process caused the yield stress and ultimate stress of the flange element to be larger than the web element. The percentage difference between the ultimate stress of the web and flange element is 2.88% and the percentage difference between the yield stress of the web and flange element is 2.93%. Next, the percentage difference between the deformation at ultimate load and yield load for web and flange elements is 3.61% and 2.47%, respectively. The value of the modulus of elasticity of the CFS section is more than 200 GPa and noted that the CFS section is formed using a pure steel material.

Table 2. The Material Properties of The Web and Flange Element of The CFS Lipped Channel Section

Properties	Elements		Percentage of Difference (%)
	Web	Flange	
Ultimate Load (N)	9,709.94	9,997.87	2.88
Deformation at Ultimate Load (mm)	6.5538	6.3170	3.61
Ultimate Stress (MPa)	509.71	524.82	2.88
Modulus of Elasticity (GPa)	235.52	209.79	10.92
Yield Load (N)	9,253.62	9,532.47	2.93
Deformation at Yield Load (mm)	1.3576	1.3241	2.47
Yield Stress (MPa)	485.75	500.39	2.93

The ductility of the steel is checked by referring to ultimate stress and yield stress and recognised as the ability to undergo significant plastic deformation before failure, and the materials with higher ductility normally can stretch further before failure. Thus, the ultimate and yield stress values must be higher and consistent with the same value to indicate better ductility. The ultimate stress over yield stress ratio of the web element and flange element is described to be 1.0493 and 1.0488, respectively. However, when the ultimate stress is divided by the yield stress factory is noted as having 1.133 for the web element and 1.166 for the flange element. The yield stress factory value is 450 MPa. From the observation and analysis, the CFS lipped channel section is considered a high ductility material with a more gradual strain hardening behaviour.

Additionally, the material properties result of WBA concrete are determined by calculating the average compression stress of concrete cubes at 3, 7, 28 and 60 days of curing age, and summarised in Figure 8. The normal concrete is also tested and compared with WBA concrete. From the figure, the average compression stress of normal concrete exceeds that of WBA concrete at all curing ages, but both concretes exhibit identical line patterns. The compression stress for both the concrete increased with increasing curing ages. The WBA concrete has not achieved the concrete grade 30 for 28 days of curing because of high water absorption and dry conditions. However, the WBA is still suitable to fill in the built-up CFS due to its compression stress of more than 20 MPa. The percentage difference of compression stress between normal concrete and WBA concrete for 3, 7, 28 and 60 days is reported to be 44.19%, 28.42%, 27.16% and 24.41%, respectively. There is a 21.77% variation in

compression stress between 7 and 28 days, and a 43.65% variance between 3 and 7 days. 10.95% is reported when the compression stress of 28 days compared with 60 days. Essentially, prioritising the compression stress of concrete before its incorporation into built-up CFS is a crucial measure for guaranteeing the safety, durability, performance and compliance of composite structures. This is an essential quality control procedure that directly affects the structural integrity of the completed structural component.

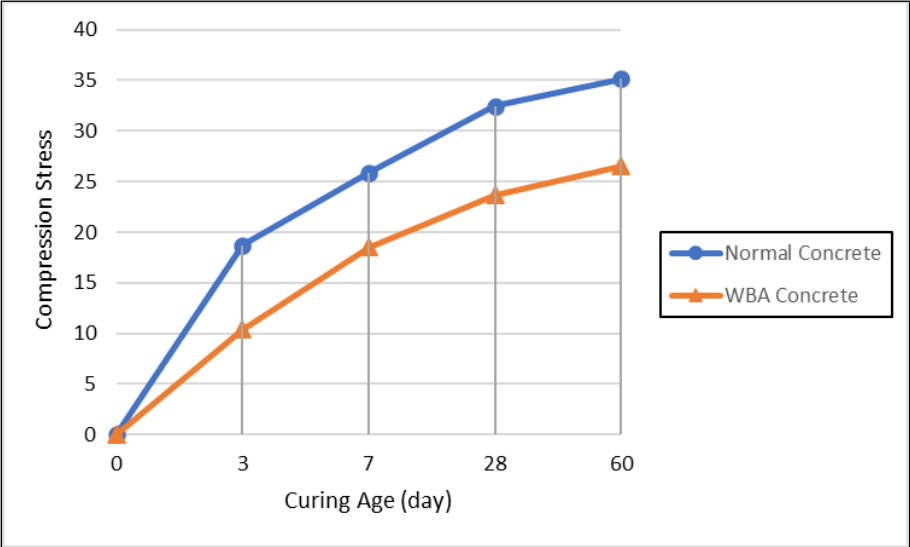


Figure 8. The Average Compression Stress of The Concrete Cube Between Normal and WBA Concrete

Compression Behaviour of Built-up CFS Column

The result of the compression behaviour, especially the ultimate load and failure mode of the built-up CFS column is tabulated in Table 3. The ultimate load of BCFS1 has increased by about 33.87% when the section is filled with normal concrete and 31.34% when the section is filled with WBA concrete. The ultimate load percentage difference between BCFS2 and BCFS3 is roughly 3.69%. Local buckling and distortional buckling failures of the BCFS1 are absolutely reduced by combining with other materials, especially normal concrete or WBA concrete. BCFS3 is suitable for further action and classified as a sustainable composite section because the section does not use natural sand, which promotes environmental impact and is known as a lightweight section, which is able to lessen the production cost and maintenance cost when compared with BCFS2.

Table 3. The Result of The Compression Behaviour and Failure Mode of The Built-Up CFS Column		
Specimen Labels	Ultimate Load (kN)	Failure Mode
BCFS1	503.6	Local and distortional buckling
BCFS2	761.5	Local buckling
BCFS3	733.4	Local buckling

Figure 9 shows the failure mode of BCFS2 with the critical point or key moment of failure highlighted in red. The concrete surface on the top of the column is noted as having a crack in a diagonal line on the joint between the lipped element and the web element. Furthermore,

the web element of the built-up CFS section is shown to exhibit local buckling at the midspan of the column. The section with double thickness still cannot reduce the buckling effect when subjected to a compression load. When the web element of the built-up CFS section fails, the flange element will also fail in both parts. The connection between the two lipped channel sections as a flange element has caused a slight opening. The parts without normal concrete are illustrated obtaining a lot of local buckling failure however, the part with normal concrete is reported not having any local buckling failure on the CFS section. The top side and bottom side of the column, especially at the location of the normal concrete failed in a small amount of curving deformation because the stress of normal concrete is reduced the failure. The highest value of compressive stress of the normal concrete does not influence the stress of overall stress of the column structure and facilitates other parts of the column without concrete failing, especially for the short column.



Figure 9. The Failure Mode of The BCFS2 Specimen

The failure mode of BCFS3 as shown in Figure 10 is not as critical as BCFS2, which failed on the web and flange element without concrete. The failure occurs in analogous locations, namely at the top and bottom of the column, as well as local buckling at the midspan of the web and flange element. The failure mode is similar to the study conducted by Wang et al. (2025). The top and bottom of the column for BCFS3 are reported to have large curving deformation due to the WBA concrete, which has less compression stress when compared with normal concrete. Then, WBA concrete, which is classified as porous concrete is able to reduce the load on the entire column section due to the existence of elastic capacity that can

reduce failure when subjected to compression load. The concrete surface of the BCFS3 is stated to have a crack, but not in a diagonal line and larger than BCFS2. The crack is still in the same location as BCFS2 at the joint between the lipped element and web element, which proves that the location is the weakest area of the combination of CFS and concrete. There are no openings or failures at the joint between the web and flange element, especially in the back-to-back configuration. Although the compression behaviour of built-up CFS with WBA concrete is not as good as built-up CFS with normal concrete, including the failure mode, the use of WBA instead of sand has been able to reduce environmental impacts and indirectly reduce the production costs of the structural component.



Figure 10. The Failure Mode of The BCFS3 Specimen

CONCLUSION AND RECOMMENDATION

Currently, there is an absence of information on the design and fabrication of built-up CFS columns with a six lipped channel section in both face-to-face and back-to-back configurations within the relevant codes of practice or design standards. The data on the built-up CFS section using either normal concrete or WBA concrete as a column has not been previously reported or is not currently under investigation by researchers. However, extensive debates exist over built-up CFS sections using normal concrete, employing two lipped channel sections arranged in either face-to-face or back-to-back configurations for use as

columns. Based on the observation and analysis of experimental data, the built-up CFS column with normal concrete or WBA concrete is produced in a section which is able to minimise the local buckling and solve the distortional buckling and shows that the section is improved by adding value in the design. The potential added value to emphasise is the production process, characterised by simplicity, little reliance on advanced technology or expensive equipment, the absence of need for specialised labour and ease of maintenance.

The experimental data indicate that the percentage difference of the ultimate load between the built-up CFS with normal concrete and the built-up CFS with WBA concrete column is 3.69%. The built-up CFS column with WBA concrete exhibits a 31.34% variance in ultimate load relative to the built-up CFS without concrete. The WBA concrete with a lower value of compression stress when compared with normal concrete demonstrated its ability to help reduce the failure of the entire structure from the observation of column failure modes. Ultimately, WBA concrete will gain popularity due to the benefits, such as lightweight, and reduction of the environmental impact and production cost shown in this study and its suitability as a replacement for normal concrete in all hollow structural components.

For further study, the built-up CFS column should be designed as an intermediate and slender column for determining the relationship between the compression behaviour and slenderness ratio. In addition, the built-up CFS is appropriate to study the section as a flexural member and tried to form and test in a variety of lengths. The WBA concrete should be improved by adding a superplasticiser for strength and workability purposes.

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DELPHI-BASED ASSESSMENT OF ECONOMIC INDICATORS FOR TRANSIT-ORIENTED DEVELOPMENT (TOD) IN MALAYSIA

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Abstract

As Malaysian cities accelerate the implementation of transit-oriented development (TOD) initiatives to catalyse sustainable economic growth, there is a pressing need for assessment tools tailored to the local urban context. This study aimed to assess key economic indicators that optimised the performance and economic impacts of TOD strategies in Malaysian urban areas. The study employed a three-round Delphi method, engaging a panel of experts in the TOD-related field in an iterative process that included questionnaires, ratings of potential indicators, and qualitative feedback. The final phase yielded a validated set of 31 economic indicators specifically tailored to the Malaysian urban context. Through Round 1, a group of 16 experts assessed 77 potential indicators identified through a systematic literature review, reducing them to 48 highly relevant ones. Round 2 engaged 14 experts to re-evaluate and refine the shortlist, yielding 34 core indicators. In the final phase, the 14 experts provided qualitative feedback to contextualise and finalise the 31 economic indicators. The economic indicators provide urban policymakers, developers, and relevant stakeholders with a comprehensive set of localised economic measures, including land use, density, transit facilities, value earnings, and economic attributes. The Delphi method's strengths lie in triangulating quantitative ratings with qualitative expert perspectives to establish a grounded and pragmatic assessment that reflects Malaysia's unique economic landscape. This study addresses a critical gap by providing evaluated economic indicators tailored to assess TOD's role in sustainable urban development in Malaysia.

Keywords: *Delphi method; Economic indicators; Sustainable urbanisation; Transit-oriented development (TOD); Urban development*

INTRODUCTION

Transit-Oriented Development (TOD) is an urban planning concept that integrates land use and transportation strategies to create compact, walkable, and sustainable communities centred around high-quality public transit systems (Appleyard et al., 2019; Liang et al., 2020; Thomas & Bertolini, 2020). The primary goal of TOD is to promote sustainable modes of transportation, reduce dependency on private vehicles, and foster economic growth and development near transit stations (Hasibuan & Mulyani, 2022; Ibraeva et al., 2020). In Malaysia, rapid urbanisation and the increasing demand for efficient transportation have highlighted the need for TOD as a viable solution to address urban challenges (Knowles et al., 2020; Yap et al., 2021). Malaysia is committed to sustainable development. The growing awareness of the economic, environmental, and social benefits of TOD has motivated the implementation of various TOD initiatives, particularly in major cities in Klang Valley (Ali

et al., 2021; Ibraeva et al., 2020). The significance of TOD in Malaysia lies in its potential to enhance accessibility and connectivity through integrated land use and transportation planning. This includes promoting compact, mixed-use developments around transit stations, seamless integration of various modes of transportation, and walkability and pedestrian-friendly environments (Gomez et al., 2019; Khalid & Samsudin, 2023; Yap et al., 2021). TOD holds enormous significance as it has the potential to promote economic development by attracting businesses, investments, and employment opportunities around transit nodes (Abdi & Lamíquiz-Daudén, 2022; Tornabene & Nilsson, 2021). It also has the potential to reduce traffic congestion and carbon footprint by encouraging public transit usage (Ibrahim et al., 2024).

While the implementation of TOD projects in Malaysia has had positive results, there is a need for a comprehensive and systematic approach to assessing the economic vitality and performance of these developments (Abdi & Lamíquiz-Daudén, 2022; Yap et al., 2021; Yusoff et al., 2021). Economic indicators play a crucial role in assessing the effectiveness of TOD initiatives and informing the decision-making process for future planning and investment strategies (Smith et al., 2022; Uddin, Tamanna, et al., 2023). The primary objective of this research is to develop economic indicators for assessing TOD initiatives in Malaysia. These economic indicators will be a valuable tool for urban planners, policymakers, and stakeholders related to TOD projects. It helps to assess the economic performance and impacts of these developments effectively. This research includes conducting a Delphi survey to gather expert opinions and reach a consensus on the most relevant and significant economic indicators for TOD assessment in Malaysia.

LITERATURE REVIEW

Definition and Principles of Transit-Oriented Development (TOD)

Transit-Oriented Development (TOD) is a planning and urban design concept that aims to create compact, walkable, and mixed-use communities centred around high-quality public transportation systems (Nafi et al., 2021; Thomas & Bertolini, 2020). TOD emphasises pedestrian-oriented design, ensuring amenities and services are within comfortable walking distance from transit stations to promote walkability and pedestrian-friendly environments (Yao et al., 2024). It promotes a mix of residential, commercial, and recreational uses, creating vibrant and diverse communities (Omole et al., 2024). Transit stations encourage higher-density development to support ridership and establish a critical mass of residents and businesses (Basheer et al., 2020; Farnes et al., 2024). TOD facilitates the seamless integration of multimodal transportation (trains, buses, bicycles, and pedestrian infrastructure), promoting intermodal connectivity (Tamakloe et al., 2021). Additionally, it aims to create a sense of place and promote community interaction through well-designed public spaces and amenities, contributing to placemaking and community building (Akbar & Edelenbos, 2021; Murshed, 2022).

Economic Benefits and Impacts of TOD

The implementation of TOD initiatives can generate significant economic benefits and impacts. Properties located near transit stations often experience higher property values due to improved accessibility and amenities (Ibraeva et al., 2020; Renne & Listokin, 2019; Zhang

et al., 2021). TOD can attract businesses and investments, leading to job creation and economic growth in the surrounding areas (Farnes et al., 2024; Tornabene & Nilsson, 2021). By encouraging public transit usage, TOD can generate an increase in transit ridership and revenues for transit agencies (Chan & Farber, 2020). Residents and commuters in TOD areas will experience reduced transportation costs due to reduced reliance on private vehicles (Farnes et al., 2024). Moreover, TOD optimises the use of existing infrastructure and reduces the need for costly expansions or new infrastructure investments, leading to the efficient use of infrastructure (Yap et al., 2021).

Gaps and Limitations in The Current TOD Assessment Framework

While existing frameworks for TOD assessment provide valuable insights, there is a lack of comprehensive, standardised economic indicators specific to the Malaysian context (Orieno et al., 2024; Yap et al., 2021). Many existing frameworks focus on specific aspects of TOD, such as transportation and real estate, but lack a comprehensive set of economic indicators tailored to the local economic landscape (Cucuzzella et al., 2022). Moreover, the development of most frameworks for specific regions or cities limits their transferability and applicability to the unique context of Malaysia (Li et al., 2022). Furthermore, many developed frameworks lack extensive stakeholder involvement from various TOD-related personnel, potentially overlooking the significant economic vitality of TOD considerations relevant to the local context (Liu et al., 2020; Nolan, 2020; Yap et al., 2021).

METHODOLOGY

Rationale for Using The Delphi Survey

The Delphi survey method is a structured and systematic approach that is well-suited for this research (Beiderbeck et al., 2021). It is highly suitable when there is a lack of comprehensive information or when the problem under investigation is unique and requires the collective expertise of the subject matter stakeholders (Beiderbeck et al., 2021; Landeta & Lertxundi, 2024). The Delphi method facilitates the solicitation of expert opinions and the development of a consensus on economic indicators for TOD assessment in Malaysia (Hazmi et al., 2023). This method was chosen to gather and synthesise diverse expert perspectives from TOD-related fields, ensuring a comprehensive and well-rounded approach to the research problem (Beiderbeck et al., 2021; Karakikes & Nathanail, 2020).

The Delphi Survey Process

A panel of experts representing diverse TOD-related fields participated in a modified three-round Delphi process to evaluate and gain consensus on economic TOD indicators for Malaysia. In a Delphi technique, panellists completed two or more iterative questionnaire rounds to reach a consensus based on expertise in the relevant field (Beiderbeck et al., 2021; Boulkedid et al., 2013). This study implemented a modified Delphi approach by adding a physical focus group meeting with the panellists after the first questionnaire round. The in-person discussion helped clarify indicator wording, validate collective conclusions, and enable more complex group decision-making (Esmaily et al., 2008; Gagliardi et al., 2005; Hsu & Sandford, 2019; Vakil et al., 2006). Prior to data collection, the preliminary questionnaire underwent a pilot test with three (3) experts in TOD who were not part of the

panel. This pilot test aimed to evaluate the questionnaire’s design and content. Based on the recommendations provided, the questionnaire was amended to ensure its relevance and effectiveness in capturing the necessary insights. The iterative process of refining the questionnaire before data collection guarantees alignment of the data collection instrument with the research objectives.

Criteria of Expert Panellists

The experts for the Delphi survey were selected based on a top-down approach across the federal, state, and local governments in Malaysia. This study deliberately focused on government experts as they are the primary policymakers and regulators for TOD implementation in Malaysia. The criteria for selection included years of experience, familiarity, and involvement in TOD projects locally. The experts were top management officers who were involved in formulating policies, making decisions, and overseeing the approval process for TOD. They had a minimum of three projects, ranging from medium- to large-scale schemes. The selected government officers were involved in massive projects such as Kuala Lumpur Sentral (KL Sentral), KL Eco City, Kajang 2, Cheras South, Kwasa Sentral, and MKH Boulevard II. A total of 16 experts consented to participate in the first round of the Delphi survey. The selection of experts for the Delphi survey is crucial to ensure the proposed list of economic indicators reflects both global best practices and local relevance. Table 1 provides a detailed breakdown of the experts who participated in the Delphi survey.

Table 1. List of Experts in TOD

Organisation's Level	Organisation	Experts' Designation	Number of Officers	Years of Experience in TOD	Number of TOD Projects
Federal	PLANMalaysia HQ	Deputy Director (R&D Unit)	1	15	5
		Head of Division (Sustainable Development Unit)	1	10	3
		Head of Division (Heritage and Urban Design Unit)	1	10	3
		Senior Town Planner	1	15	4
		Senior Town Planner	1	12	4
		Senior Deputy Director	1	20	6
State	PLANMalaysia Selangor	Head of Unit (Development Control)	1	10	4
		Senior Town Planner	1	10	3
		Director	1	20	7
Local Authority	Subang Jaya City Council	Deputy Director	1	20	5
		Senior Deputy Director	1	18	5
		Senior Town Planner	1	15	5
		Senior Town Planner	1	12	4
		Senior Town Planner	1	10	4
		Senior Town Planner	1	10	3
		Senior Town Planner	1	10	3
		Senior Town Planner	1	10	3
Total	3	16	16	-	73

(Source: Researcher, 2024)

Data Collection

Round 1

The first round of the Delphi technique contained 77 potential economic indicators for TOD assessments extracted from the literature review. These indicators were systematically categorised under specific economic dimensions that aligned with core principles of TOD, such as density, land use, and transit facilities. Email reminders were sent to encourage a 100% response rate, which was achieved, with all 16 experts completing the first-round survey. This systematic analysis of the experts' perspectives guided data collection and questionnaire revisions for the subsequent Delphi rounds.

Round 2

The expert panel refined the initial set of 77 potential economic TOD indicators down to 48 indicators with high importance and feasibility ratings based on analysis of the first-round responses. The second round of the Delphi survey used a revised questionnaire containing these 48 refined indicators. In the second round of the Delphi survey, 14 experts participated in this subsequent round, representing an 87.5% retention rate. The two experts who did not participate in Round 2 cited time constraints due to involvement in multiple projects. This retention rate exceeds the recommended minimum of 80% for maintaining validity in Delphi studies, indicating strong and sustained involvement in the process. In this round of the Delphi survey, a physical meeting was convened with all 14 experts to facilitate the iterative consensus-building process.

Round 3

The 14 experts from the previous round (Round 2) participated in the third and final round of the Delphi survey. The third round aimed to refine the list of economic indicators further and achieve panel convergence. Based on the feedback from Round 2, the experts received a refined list of 34 potential economic indicators in this round. In this final round, the experts had the option to maintain or modify their ratings from the previous round. They were also given a final opportunity to offer additional comments on the suitability and practicality of the recommended indicators within the Malaysian context. After Round 3, the final ratings and experts' comments were thoroughly analysed, and 31 of the highest-rated economic indicators with strong agreement were identified as the core set of indicators.

Data Analysis Techniques

The modal class of descriptive analysis was used to analyse the ratings obtained from the Delphi surveys. The ordinal data gathered through Likert scales can be effectively utilised using modal class analysis, a robust statistical technique widely recommended for synthesising ratings in Delphi studies (Rith-Najarian et al., 2021; Von Der Gracht, 2012; Worrell et al., 2013). The modal class denotes the indicator rating that was most frequently selected by the experts across the three rounds (Ollen, 2006; Rith-Najarian et al., 2021). Additionally, principal component analysis (PCA) was conducted to complement the descriptive analysis and further validate the results. This helped identify the economic indicators that achieved the strongest consensus. Additionally, principal component analysis

(PCA) was conducted to complement the descriptive analysis and further validate the results. PCA was used to validate the modal class results by confirming the dimensional structure of the five main indicator categories (Land use, Density, Transit facilities, Value earnings, and Economic attributes). The PCA results supported the thematic group and confirmed that no indicators were excluded based on dimensional analysis. All 31 final indicators loaded appropriately onto their respective component dimensions, validating the expert consensus achieved through the Delphi rounds. PCA, a statistical technique, reduces the dimensionality of large datasets by transforming a set of interrelated variables into a smaller number of non-correlated variables known as principal components (Guidea et al., 2020; Singh et al., 2004).

RESULTS

Key Economic Indicators for TOD Assessment

Through 3 iterative rounds of the Delphi survey, the expert panel identified a comprehensive set of economic indicators for TOD initiatives' performance and impact assessment for the Malaysian context. Initially, a systematic literature review using PRISMA protocols identified 77 potential indicators, categorising them into seven indicator categories. After the first round of the Delphi survey, the list was consolidated to 48 indicators across five categories, based on the expert feedback and preliminary ranking. In the second round, further refinement and prioritisation were conducted, reducing the number of indicators to 34 and categorising them into five domains. The remaining domains include Land use, Density, Transit facilities, Value earnings, and Economic attributes. In the final round, the expert panels reached stakeholder validation on the proposed indicators, which included 31 key economic indicators for TOD assessment in Malaysia, and were categorised into five indicator categories. The expert panels deemed these indicators most relevant and significant for assessing the economic performance and impacts of TOD initiatives in the Malaysian context. The results of the 3-round Delphi survey are seen in Table 2.

Table 2. Delphi Survey Results				
Variable	Initial Item	Round 1 Results	Round 2 Results	Round 3 Results
Land use	11	7	3	3
Density	8	6	6	5
Population	5	0	0	0
Transit facilities	13	8	7	7
Property development	6	0	0	0
Value recapture	7	6	6	6
Economic attributes	27	21	12	10
Total	77	48	34	31

(Source: Researcher, 2024)

Validation and Reliability of the Proposed Economic Indicators

To ensure the validity and reliability of the proposed economic indicators, several measures were carried out. Firstly, it is the Delphi survey process itself. The iterative rounds and anonymous feedback contributed to the validity of the results by minimising potential bias and allowing for a comprehensive consideration of diverse perspectives (Karakikes & Nathanail, 2020; Khodyakov et al., 2023). Additionally, the demographic diversity of the expert panel and their extensive experience in TOD-related fields enhanced the content

validity of the indicators, ensuring they captured the most important economic aspects of TOD assessment in Malaysia (Abdullah et al., 2024; Ibraeva et al., 2020).

DISCUSSIONS

Round 1 Delphi Survey

The experts from the Round 1 Delphi survey unanimously agreed to propose five main variables for the TOD indicators. The findings established the positive correlations between the essential characteristics of TOD, more specifically, Land use, Density, Transit facilities, Value recapture, and Economic attributes. This finding is consistent with Nyunt and Wongchavalidkul (2020), which suggests that the selection of indicators should be based on the essential characteristics of TOD.

Round 2 Delphi Survey

Building upon the results from Round 1, the second round of the iterative survey further refined the economic indicators for TOD assessment. The expert feedback in Round 1 emphasised the five main variables, including Land use, Density, Value recapture, and Economic attributes. In Round 2, the expert validated the significance of these variables in assessing the economic vitality of the TOD initiatives. This consensus aligns with the multidimensional nature of TOD and the need to capture a variety of aspects in urban form, transportation, and economic development, as emphasised by Su et al. (2022), Higgins and Kanaroglou (2016), and Mathur and Smith (2013). Following Round 2 of the survey, the indicators were further refined to 34, reflecting the experts' consensus. The refinement includes consolidating redundant indicators and suggesting new ones based on the experts' opinions.

Round 3 Delphi Survey

The final round of the Delphi survey achieved panel convergence. Building upon the previous rounds, the five main variables were finalised and confirmed. The panel of experts emphasised the importance of land use indicators in promoting mixed-use development, optimising land utilisation, and achieving sustainable urban growth within TOD areas. This key point is consistent with studies by Yu et al. (2022); Liu et al. (2020); and Cervero and Kockelman (1997), which highlighted the positive impacts of land use diversity and mixed-use development on economic vitality, sustainable urban form, and transit ridership.

Comparative Analysis with International TOD Indicators

The Malaysian TOD indicators developed in this study demonstrate both similarities and unique differences compared to international frameworks. While countries like Singapore and Hong Kong emphasise high-density development and transit integration, the Malaysian indicators place greater emphasis on value recapture mechanisms and government systems, reflecting the country's federal structure and development financing challenges. Unlike Australia's TOD framework, which focuses primarily on walkability and connectivity metrics, the Malaysian indicators incorporate specific economic attributes such as household income distribution and sustainable urbanisation rates, addressing Malaysia's socio-economic

development priorities. The inclusion of governance and enforcement indicators is particularly distinctive, reflecting the importance of regulatory oversight in Malaysia's planning system.

Practical Implications for Malaysian Urban Development

The 31 indicators provide Malaysian urban planners with standardised metrics for TOD assessment, enabling evidence-based decision-making for infrastructure investments. For policymakers, these indicators offer benchmarks for TOD project approval and monitoring processes. The indicators facilitate systematic comparison across different TOD projects and locations within Malaysia. For developers and investors, the indicators provide clear performance expectations and investment guidance, potentially reducing project risks and improving financial outcomes. The value earnings indicators specifically support the development of innovative financing mechanisms for TOD projects, which is crucial for Malaysia's infrastructure development goals.

Proposed Economic Indicators for TOD Assessment

The proposed economic indicators for TOD in Malaysia are designed to provide a comprehensive and systematic approach to assess the economic performance and impacts of TOD initiatives in the Malaysian context and are organised into categories and sub-categories. This structure provides a clear understanding of the various economic aspects that should be considered in the TOD assessment. It consists of five main categories of economic indicators. Each category is divided into sub-categories to capture the specific economic aspects of TOD assessment. The categories and sub-categories of the proposed economic indicators are presented in Table 3.

CONCLUSION

Key Findings and Contributions

The research aimed to assess economic indicators for the TOD initiative assessment, tailoring them to the specific context of Malaysia. A thorough Delphi survey with a wide range of experts in TOD-related fields developed consensus-based economic indicators. These comprised 31 key economic indicators that were organised into five main categories. The proposed economic indicators significantly address the gaps and limitations of the existing TOD assessment, making them suitable for application in the Malaysian context.

Practical Implications and Applications

The involvement of a diverse panel of experts from various stakeholder groups ensures that the proposed indicators reflect the collective expertise and perspectives of professionals engaged in TOD initiatives in Malaysia. The indicators will streamline the integration of economic indicators with other dimensions of TOD assessment, including environmental and social aspects, thereby enabling a comprehensive and all-encompassing evaluation of TOD projects in Malaysia in the future. The proposed indicators will aid urban planners, developers, and key stakeholders in making precise decisions on TOD strategies, infrastructure investments, and resource allocation, thereby facilitating the development of sustainable and economically viable urban development.

Table 3. Categories and Sub-Categories of The Proposed Economic Indicators	
Category	Sub-Category
Land Use	Efficient land use patterns
	Location efficiency
	Diversity of housing types
Density	Population density
	Business density
	Land use density
	Retail density
	Maximum intensity for TOD area
Transit Facilities	Information display system
	Frequency transit service
	Safety of commuters at transit stops
	BRT facilities
	Number of public facilities
	Average distance from public facilities to the commercial area
Value Earning	Connecting walking facilities from all modes of transport
	Increase in property value
	Tax earnings of the municipality
	Value recapture
	Financial return
	Private investment
Economic Attributes	Incentives from Federal Government and Local Authority
	a. Economic Sustainability
	i. Economic Growth
	Economic development
	Real per capita income
	Transport and communication
	Sustainable urbanisation rate
	Strengthening national and regional development planning
	ii. Distribution of Income
	Number of business establishments
	Household income
	iii. Economic Statistics
	Average car ownership
	Increase property ownership
	b. Governance System
	Enforcement and monitoring

(Source: Researcher, 2024)

Limitations and Future Research Directions

This study focused on government experts as primary policymakers and regulators. Future research should include private developers, NGOs, and community representatives to capture broader stakeholder perspectives. Additionally, empirical validation of these indicators through case study applications in Malaysian TOD projects would strengthen their physical utility. Further research could explore the weighting and prioritisation of these indicators for different types of TOD projects and urban contexts within Malaysia. the development of a comprehensive TOD assessment tool incorporating these economic

indicators alongside environmental and social dimensions would provide a holistic assessment framework for Malaysian urban development.

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DESIGN PERFORMANCE CRITERIA IN GREEN BUILDINGS AS PIVOTAL STRATEGIES FOR SUSTAINABLE CONSTRUCTION

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Abstract

In the past few decades, scholars have extensively conducted research and held discussions on sustainable development to elevate the awareness of mitigating environmental problems. In sustainable construction, green building practices are considered imperative, and they have emerged as pivotal strategies to minimise environmental impact and enhance long-term viability. Green buildings are characterised by resource efficiency, reduced carbon footprint, and improved occupant health; these characteristics are crucial in fostering sustainable development. However, based on some previous research, the intended sustainability goals are not met when the actual performance of the green building during occupancy indicates a contradiction. Hence, this paper entails the expert's practical point of view and their interview narratives on green office buildings' design performance criteria. A semi-structured interview with eight (8) respondents was conducted, using open-ended questions. The interviews were conducted in different sessions, focusing on the relevancy of the green building performance criteria, which were collated from literature reviews, and whether there are additional criteria to be considered while designing green office buildings. The interviews were later transcribed, analysed, and tabulated based on the agreements of each criteria coded. From the analysis, twenty-eight (28) criteria were considered relevant, and eight (8) were excluded as the criteria were reviewed as irrelevant to design performance criteria in green buildings.

Keywords: *Content Analysis; Design Performance; Green Building; Qualitative; Sustainable Construction*

INTRODUCTION

Globally, the construction industry is presently undergoing a substantial and swift transformation, propelled by factors such as the expansion of the world economy, technical breakthroughs, modernisation of construction techniques, and increasing demands for sustainability (Buzio, 2023). Since then, the nation has supported green projects in Malaysia, as seen by the advancement of numerous green business incentives, industrial legislation, environmental awareness, and an economy favouring sustainable development (CleanMalaysia, 2015). The Construction Industry Transformation Programme 2016-2020, which focuses on the three sustainable challenges of the environment, society, and economy, was introduced by Malaysia in 2015 at Putra World Centre (PWTC). However, the construction industry has utilised between 30-40% of the world's natural resources; 50% of energy was used for building's heating and cooling system, 40% of the materials consumed globally were used for the building environment, and 30% of energy was used for operational concern (Khan et al., 2018). Since the construction sector plays a significant role in the

depletion of non-renewable resources, there is a direct relationship between sustaining the development and the growth of the construction industry.

Thus, the green building concept is one of the initiatives made to solve the climate change challenges, and it will be a pointer to ensure that new buildings in the future are built and erected more sustainably and energy-efficiently. In general, the growth of green buildings has the potential to not only solve the problem of climate change but also to generate prosperous, sustainable communities and stimulate economic growth (WGBC, 2021). In a research conducted by Dodge (2018), 2078 respondents provided information on what constitutes a green building and the requirements that must be met for a structure to be classified as one. In general, a green building must promote good indoor environmental air quality, make efficient use of resources (energy, water, and others), reduce pollution and waste by permitting reuse and recycling, and take environmental needs into account throughout the project's lifecycle, from design and construction to operation

However, the performance of green buildings in providing an absolute sustainable impact still needs to be determined. It is highlighted in the findings from a study (Bajraktari et al., 2019; Moore & Iyer-Raniga, 2019; Zhao et al., 2015) in which discrepancies between the designed and the actual performance of green buildings were found, proving that the green buildings did not ultimately fulfil its design performance goals as determined by the design rating. Altomonte et al. (2019) stated that building designers often encounter challenges in adopting sustainable criteria during the design process, adversely affecting overall building performance and occupant satisfaction. Moreover, discrepancies between predicted and actual building performance—often called the “performance gap”—further complicate designers’ efforts, resulting in buildings that do not meet expected sustainability outcomes or occupant comfort standards (de Wilde, 2014). This study aims to validate the design performance criteria of green office buildings from the perspective of practising building designers, with the objective to align practical insights with established findings in the literature.

LITERATURE REVIEW

Green Building Concept

Green building is a concept developed to mitigate the negative influence caused by construction activities. The concept of its development emerged as the resolution to reduce environmental degradation, sustain the national energy, and positively impact the surrounding environment and its occupants (CleanMalaysia, 2015; Watch, 2022). Generally, the primary concern of green building design is on the aspect of energy and water efficiency and the usage of sustainable construction materials during its development and throughout its operational lifetime (Watch, 2022), from inception to design, construction, operation, maintenance, renovation, and deconstruction (Ohueri & Enegbuma, 2018).

The green development focuses on six main principles: optimisation of site design by selecting sites with easy access to basic infrastructure and designing the building orientation, envelope, windows, and others based on the site conditions; efficient use of water; use of cost-efficient and environmentally friendly materials with less Volatile Organic Compound (VOC) emissions; improved indoor environmental quality by maximising daylighting, and use of appropriate ventilation and moisture control, enhanced building acoustic performance

through strategic positioning of the building farther from outdoor noise sources, right-sizing of rooms and use of materials with high insulating value (Purwaningsih et al., 2019); and reduction of construction and demolition waste via the establishment of waste management strategies.

According to Soussi (2022), the five primary elements of green building design include sustainable site design, water conservation and quality, energy and environment, indoor environmental quality, and conservation of materials and resources.

Green Building Performance Definition

Douglas et al. (1996) defined building performance as the process of evaluating the asset value and performance of a building, which is a key component of facilities management. The overall building performance includes notions of use and effect on human performance because performance is assessed in terms of how buildings and building systems affect the comfort, effectiveness, and well-being of building users (Preiser, 2005). Gupta et al., 2019 and Seminara et al., 2022 further explored that building performance shall cover the whole project life-cycle from the design stage until the occupancy stage, when occupancy and behaviour data are gathered during the operation stage. The assessment of a building shall be categorised into five (5) performances: functional, technical, behavioural, environmental, and process performances. Table 1 presents the measurement of each performance.

Table 1. Building Performance Criteria and The Aspect of Measurement

Performance	Aspect of measurement
Functional	Measuring how well the building supports the institution's organisational goals and aspirations and how well the user needs are supported.
Technical	The structural and physical systems performance, for example lighting, energy use, ventilation, and acoustics.
Behavioural	Physical status of building occupants, which include the physiological response on building performance (Physiological), condition of mind and behaviour which includes emotions, perceptions, level of acceptance of a performance (Psychology), and human interactions, communications, and quality of life (Sociology).
Environmental	The building features and characteristics relevant to its impact on the environment.
Process	Delivery of the project from inception to handover and operational management.

(Source: Blyth & Gilby, 2006; Lützkendorf et al., 2005)

METHODOLOGY

The objective of the study is to validate the green office building performance attributes, which were previously collated from the literature review. This study adopts a qualitative approach, applying a semi-structured interview as a data collection tool. The participants' inclusion criteria are designers with experience in green building design. Eight (8) participants were involved in the interview, which typically lasted 45 minutes to an hour for each session. For this study, the purposive sampling method was adopted as the sampling technique. The participants are the construction stakeholders mainly involved in green building design, represented by mechanical and electrical engineers, green building facilitators, architects, and interior designers. Eight interview sessions were conducted separately; three were in direct interactions through physical meetings, and the remaining were conducted online.

The questions asked in the interview were themed according to building performances gathered from the literature. Five building performance attributes were themed, and they were asked about their relevancy in real industry practice, starting with functional performance, technical, behavioural, environmental, and process performance. Firstly, the interview transcripts were entered into ATLAS.ti software in text file format (docx.). Interviewees' responses regarding validating the green office building performance attributes during the design stage were highlighted and quoted as quotations in the software. Afterwards, each quotation was assigned to codes, and finally, the codes were categorised into the five main themes.

RESULTS AND DISCUSSION

From the interview, the insights are recorded and documented. Table 2 summarises the relevance of each code discussed as green office building design performance indicators, and network diagrams of the narratives are illustrated using ATLAS.ti as a method of analysing the qualitative data.

Table 2. Category, Codes, Frequency of Codes, Percentage of Codes Relevancy and Interviewees' Overall Comments

Categorisation/ Theme	Codes	Frequency	Agreement on Codes' Relevancy (%)	Interviewees feedback
Functional Performance	1. Strategic value	8	100	Relevant
	2. Aesthetic & Image	8	100	Relevant
	3. Space	8	100	Relevant
	4. Comfort	8	100	Relevant
	5. Serviceability	8	100	Relevant
	6. Operational Cost	8	100	Relevant
	7. Life Cycle Cost	2	25	Irrelevant
	8. Building Ownership	0	0	Irrelevant
	9. Occupant Information	0	0	Irrelevant
	10. Green Project Direction			New Suggestion
	11. Energy and Water Policy			New Suggestion
Technical Performance	1. Physical	8	100	Relevant
	2. Envelope	8	100	Relevant
	3. Structural	8	100	Relevant
	4. Interior Design	1	12.5	Irrelevant
	5. Durability	8	100	Relevant
Behavioural Performance	1. Physiology (Health and Safety)	8	100	Relevant
	2. Psychology	8	100	Relevant
	3. Sociology and Wellbeing	8	100	Relevant
	4. Social justice	0	0	Irrelevant
	5. Culture and Neighbourhood			New suggestion
Environmental Performance	1. Energy Efficiency	8	100	Relevant
	2. Water Consumption	8	100	Relevant
	3. Load Capacity	0	0	Irrelevant
	4. Renewable Energy and Water	8	100	Relevant
	5. Landscape	8	100	Relevant
	6. Innovation/Green Technology	8	100	Relevant
	7. Low Emitting Material	8	100	Relevant
	8. Green Material and Resources	8	100	Relevant
	9. Location and Transportation	8	100	Relevant
Process Performance	1. Sustainable Site and Planning	8	100	Relevant
	2. Operation and Maintenance	8	100	Relevant
	3. Facility Management	8	100	Relevant
	4. Green Certification	8	100	Relevant
	5. Energy Modelling	8	100	Relevant
	6. Project Cost	8	100	Relevant

Functional Performance

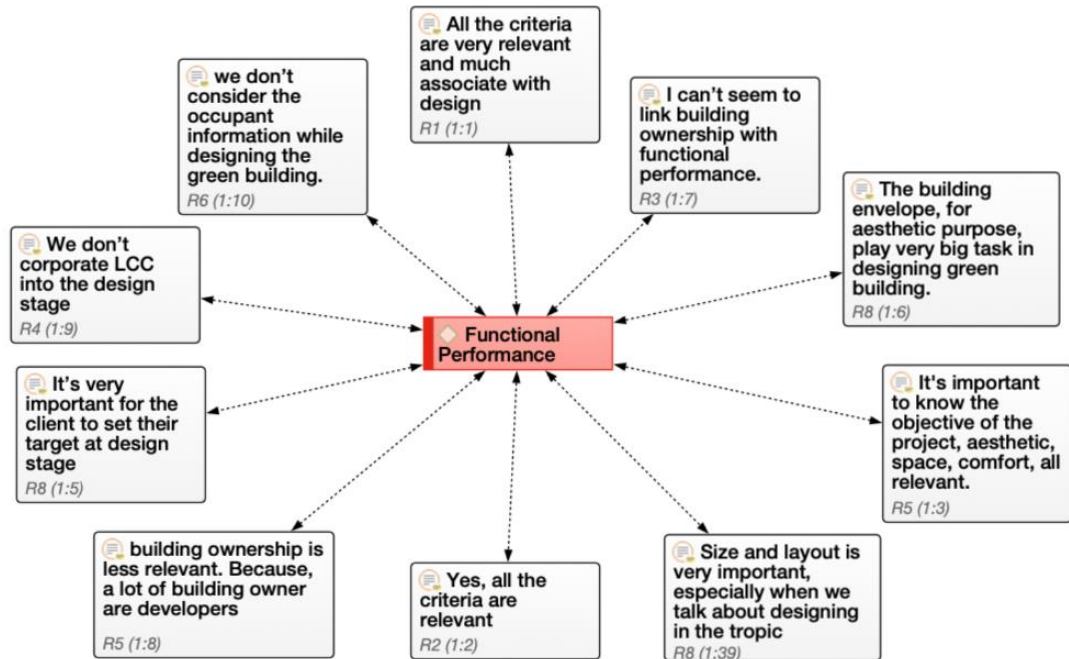


Figure 1. Interview Responses on Functional Performance Aspects

Figure 1 shows the respondents' excerpts on the functional performance attributes in green office buildings. Nine sub-criteria were discussed, and only six (6) of the sub-criteria were agreed upon as the criteria to be considered while designing green buildings. The remaining three (3) criteria considered irrelevant were 'life cycle cost', 'building ownership', and 'occupant information'. The interview narratives are as follows:

"As designers, we do not take into consideration the lifecycle cost, so that is why our maintenance is really bad" (R3, R4)

However, the above statement on the lifecycle cost criteria challenges one of the green construction approaches, which is the use of Life Cycle Cost (LCC) through the adoption of Building Information Modelling (BIM), which has been said to improve the sustainability in construction by providing and sharing the project information during the design stage, estimating project's end-of-life costs, and addressing challenges in the process (Alasmari, 2022). Despite a higher initial investment, the life cycle costs (LCC) analysis shows that operational savings in green buildings can offset higher construction costs over time (Li, 2020). Dwaikat & Ali (2018) further added that the application of Life Cycle Cost Analysis (LCCA) can assist the designer in selecting the most cost-efficient building design options for cost efficiency. Hence, despite the disagreement on incorporating LCC during the design stage, adopting LCC analysis is crucial to ensure long-term value and cost-effectiveness during the building's operation and maintenance.

“There is no direct influence of building ownership on green building functional performance. Many building owners are developers, building operators and building owners. We might not know who the actual occupants and users are. When the building or the space is leased, or sold out, the building ownership will be different” (R5)

“As a designer, the occupant information is not being considered while designing a green building, as who the occupant or the end user may change later” (R6)

Most respondents considered ‘building ownership’ and ‘occupant information’ irrelevant factors to consider during the design stage, as the actual building ownership is not determined in the initial stage. Meanwhile, Shin et al. (2021) differ from the statement by stating that aligning design strategies with long-term goals is essential to mitigate future conflicts during the occupancy, which can be achieved by understanding the ownership structure and clients’ intentions. This includes the flexibility of standard area design, allocation of co-ownership shares, and ownership space boundaries. Caixeta et al. (2019) and Artan et al. (2022) further added that user involvement during the design process can assist designers in establishing occupants’ needs and preferences and, hence, mitigating the issues of usability and dissatisfaction, which include space allocation, layout, and furniture. This contradiction indicates that some practising building designers continue to overlook these two critical criteria during the design process, despite the potential of such an approach to significantly reduce the likelihood of future disputes and the need for renovations.

Meanwhile, the other six (6) functional performance criteria are agreed as relevant to be incorporated in designing green buildings, which are strategic value, green project direction, aesthetics and image, space and layout, temperature and visual comfort, serviceability, operational cost, and energy and water efficiency policy.

“It is essential that the client and the designer know the strategic value and project objective, which has to be set right during the design stage. For example, to know the building’s aesthetic value and image is the designer’s main objective, for the building to be iconic, and for the designer to be known in the industry.” (R5)

The above statement highlights that it is essential for building users to have a clear project direction to assist the designers in incorporating sustainable design strategies early in the project. Hence, clients and the building users must be aware of the operation and maintenance of the building’s green features to sustain its performance over time. For instance, sustainable analysis tools like Building Information Modelling (BIM) can support this by evaluating and improving energy efficiency and occupant comfort (Zhou, 2020; Hilal, 2021) during the design process. Additionally, BIM proves to be useful for managing safety, maintenance, and energy use (Bhardwaj, 2018). Additionally, during the project brief, the clients must be certain of the rating level they aim for the project. Green-certified buildings offer considerable market advantages, enhancing the return on investment through better marketability, higher lease renewals, and lower vacancy rates (Hsieh, 2017; Devine, 2015). Therefore, it is imperative for designers to provide comprehensive guidance to the clients regarding the project’s direction, including the selection and integration of sustainable tools, as these choices significantly influence the building’s strategic value. Next, the internal layout of the building is an important design consideration, especially in a tropical climate. The design of the spaces

can influence emotional reactions to create engagement and meaningful spaces in the building (Juan-Vidal et al., 2015). Respondent 8 quoted:

“The size and internal layout of the building are crucial things to consider, especially when designing green buildings in tropical climates. For the occupant’s comfort, especially. Meanwhile, the external layout and the orientation of the building are also important criteria.” (R8)

The above statement proves that internal space layout strongly correlates with occupants’ comfort and operational cost of a building. The spatial arrangement within buildings significantly affects both functional and psychological aspects of comfort, influencing factors such as acoustic quality, visual privacy, and the ability to concentrate (Zhang et al., 2022). Additionally, façade design and building orientation can directly impact a building’s energy consumption, which includes heating and cooling loads, and artificial lighting utilisation (Lee et al., 2022). Thus, a well-optimised internal layout not only promotes user comfort but also contributes to reduced operational costs over the building’s lifecycle. However, to ensure the building operates cost-effectively, perceived policy and regulations are essential in guiding green building users to take advantage of sustainability benefits. Quoted from the interview;

“I suggest including the energy and water policy for the building user. The policy shall be from the organisation’s upper management. For example, a policy that supports the direction towards energy efficiency, and this policy shall be implemented during the Operational and Management stage” (R1)

In green building projects, it is vital for an organisation’s top management to clearly understand and commit to sustainability goals from the design phase. This alignment helps preserve the original design intent and ensures that building systems function as intended during operation. The discrepancies between targeted energy consumption set during the design stage and actual energy consumption during occupancy mainly occur when building users are unaware and do not understand how to utilise the system greener, despite the application of green technologies. Li et al. (2020) mentioned that a higher energy and water consumption in green buildings may be caused by the user’s rebound effect, whereby green building users tend to consume more energy than they demand. Therefore, the upper management must address user behaviour through targeted policies and initiatives, such as green behaviour awareness programs, to encourage responsible energy and water use. This underscores the need for collaboration between designers and top management to uphold the building’s sustainability.

Technical Performance

Figure 2 network reviews technical performance in designing green office buildings. Five (5) criteria were discussed, and only one (1) was considered irrelevant, which is the interior design.

“As designers, we do not think in depth about the interior design because the end user will later decide on the interior design. For example, if we decide a certain position for curtain or air conditioning position, the end user might not like it and change it later” (R2)

“We do not know who the end user of the space is. So, we do not know their preference for the interior design. However, we do think about the internal space, the lighting, view to the outside, etc.” (R7)

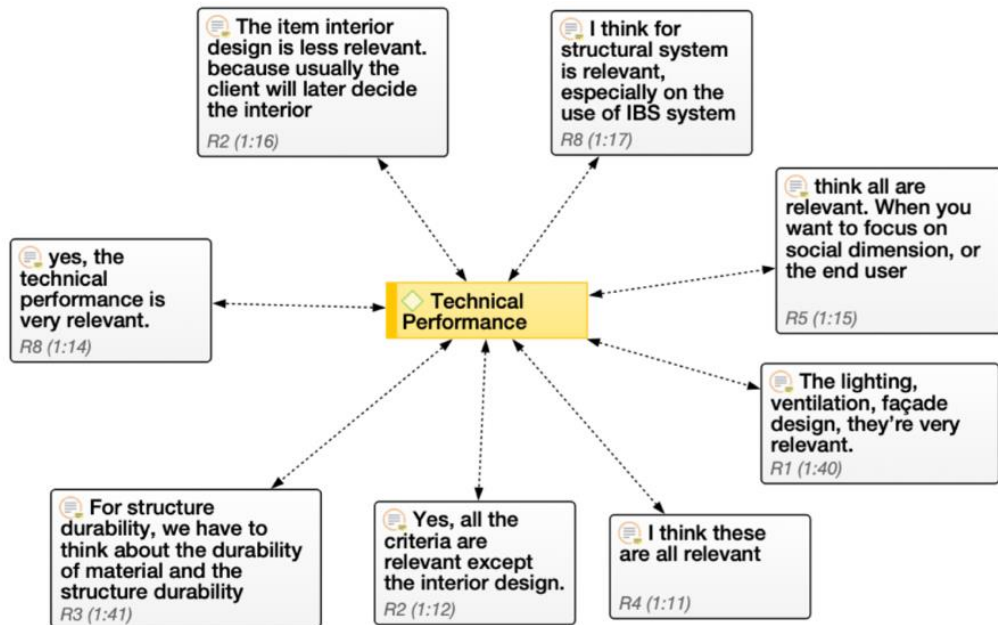


Figure 2. Interview Responses on Technical Performance Aspects

From this statement, the respondents suggested that the interior design may not be a crucial factor in green design consideration, as there is a likelihood of the end-user undertaking renovations to suit personal preferences. His perspective highlights architects' challenges in ensuring sustainable interior elements remain effective post-occupancy. Hence, it is suggested that designers incorporate flexible and adaptable interior design strategies that accommodate future modifications without compromising the building's sustainability goals (Barbulianno, 2021). For instance, designing spaces with modular elements and reconfigurable layouts allows for personalisation while maintaining the integrity of sustainable design principles.

As for the other four (4) criteria, the physical system, envelope system, structural system, and structure durability were considered relevant to green building design factors.

“The criteria in technical performance, such as the lighting, ventilation, façade design, are realistic. It can be achieved in the design element, and the designer can implement it in their design.” (R1)

“Structure durability is a criterion that needs to be incorporated during the design stage because the design and the material chosen must be durable.” (R3)

“I think the structural system is relevant, especially in the use of the IBS system because, in GBI, we give points to the IBS component.” (R8)

Green building aims not only to minimise environmental impacts but also to enhance the sustainability and longevity of structural systems. At the design stage, incorporating structural systems into green building assessment frameworks encourages a more unified and holistic evaluation across the building’s lifecycle. Thus, structural engineers must critically select materials based on their recyclability and local availability, which directly influences the building’s environmental footprint (Komarek et al., 2009). However, Chaudary & Piracha (2013) mentioned the lack of involvement of structural engineers in sustainability efforts despite a significant impact of structural elements on a building’s embodied energy. They advocated for greater integration of structural considerations, such as material efficiency, robustness, and adaptability, within green rating methodologies. Additionally, technological advancements in steel-composite structures have demonstrated potential in delivering both resource efficiency and structural performance. Innovations in construction materials—such as corrosion-resistant reinforcements, green concrete, ultra-high-performance concrete, and advanced crack control techniques—further improve the resilience and safety of buildings (Nie et al., 2018). Navarro-Rubio (2019) also emphasised the benefits of prefabricated structures in enhancing eco-efficiency, reducing construction time and cost while maintaining structural soundness.

For the envelope system, the energy-efficient façade system is essential in designing green buildings as it can promote energy savings by reducing the heat gain in the building and reducing the environmental impacts (Moghtadernejad, 2020; Abediniangerabi, 2020). The application of automated dynamic facades and climate adaptive building façades, for example, provides the ability for manual configuration, as it is essential for the user to have control over the external view and natural lighting (Tokbolat & Al-Zubaidy, 2014; Mohammadpour et al., 2015). Thus, integrating structural engineering into green building design is essential for achieving sustainability, requiring active participation from designers and the adoption of innovative materials and prefabricated systems to improve environmental and structural performance.

Behavioural Performance

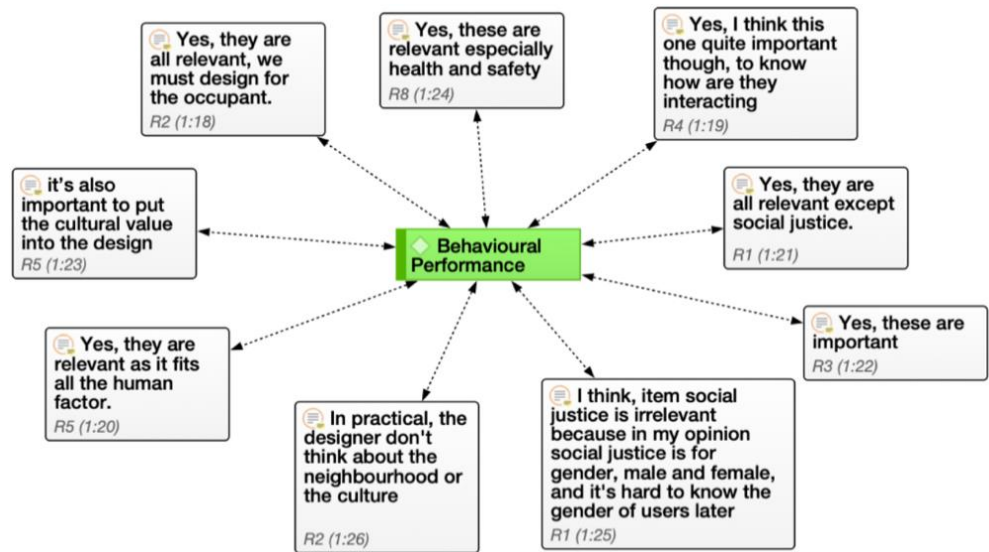


Figure 3. Interview Responses on Behavioural Performance Aspects

Figure 3 illustrates the respondents' reviews of behavioural performance criteria in green office buildings. Five (4) criteria were discussed, and four (3) criteria are considered relevant in green building design, namely physiology (health and safety), psychology, social and well-being. Schertz et al. (2022) summarised psychology as the environmental-behaviour studies that examine the interaction between environments and human affect, cognition, emotions, and behaviour. Generally, psychological practices often aim to address mental health and improve the well-being of users. Khalil et al. (2024) also revealed that the social characteristics in green buildings are influenced by the evaluated building category and the users' category which includes the building owners, designers, and the occupants. Hence, it is crucial for the designers to incorporate psychological considerations in the design process, especially in high-density urban environments where the built environment is closely related to occupants' health and productivity. Khalil et al. (2024) also added that the performance evaluation from the occurrence of issues in building accessibility can be a feed-forward cycle to the future design and construction of green buildings.

Meanwhile, physiology examines the functions and mechanisms of living organisms, including the physical condition (cardiovascular, respiratory, and nervous systems). Quoted from the interview;

“Designers often overlook the importance of comfort in designing open spaces and outdoor areas. For example, a sheltered zone that allows people to interact comfortably. We can easily control the indoor temperature, but not the outdoor spaces” (R6)

Hence, effective site planning and building layout are crucial for optimising microclimates and user comfort, especially in dense urban areas with limited horizontal space. For instance, prioritising landscape system planning using computer simulations and optimising walking spaces can significantly improve outdoor environments. Furthermore, the presence of green spaces can improve thermal comfort and overall well-being (Wang et al., 2017; Gamero et al., 2021). Meanwhile, R5 suggested that social justice criteria are considered irrelevant and shall be replaced with another term, which is the cultural and neighbourhood criteria.

“A designer must not only design the building but also design for the environment. So, even during site analysis, it is important to embed cultural values into the design. It is a sense of belonging to the community. The criteria also include in SDG17, about inclusivity” (R5)

However, R2 disputed that designers mostly need to consider neighbourhoods and culture in their design. It contradicts the opinion expressed by R5, whereby it is essential to consider the cultural value in the building design. Lazar (2021) suggested that designers should incorporate cultural elements into the design to promote sustainable development, offering advantages such as cultural interactions, shaping the location's character, optimum use of resources, and job opportunities for the locals. In addition, Sustainable Development Goal (SDG) 17 highlights the importance of acknowledging cultural practices in the development effort (McLntosh & Marques, 2017; Marques et al., 2018). For instance, engaging the community, vernacular architecture, and participatory planning are the approaches in incorporating cultural values and neighbourhood context into the design process.

Collaboration among local communities, cultural experts, and stakeholders facilitates the alignment of architectural design with culturally embedded values and practices (Iwuanyanwu et al., 2024). Thus, designers must consider multicultural settings during the design process by fostering spaces that honour diverse cultural perspectives.

Environmental Performance

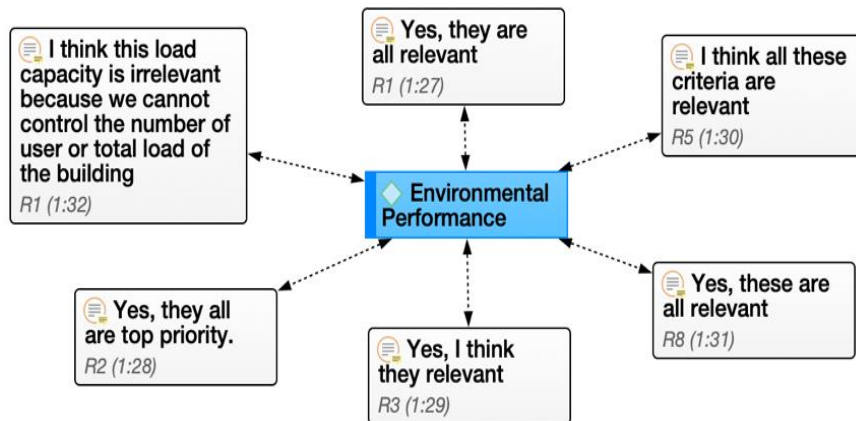


Figure 4. Environmental Performance Network

The respondents' opinions on environmental performance are illustrated in Figure 4. Among the nine (9) criteria discussed, only one criterion was considered irrelevant, which is load capacity.

"The thermal load capacity is irrelevant as a factor to be considered in designing green buildings because we cannot control the number of users or the total load in the building. It is the total load that needs to be extracted from the space." (R1)

Despite the statement from the interview, the building user must manage the thermal load capacity during the occupancy stage to ensure energy efficiency and occupant comfort. For instance, a study by Husain et al. (2017) demonstrated that incorporating green building envelope features, such as green roofs and reflective coatings, can significantly reduce buildings' sensible heat transfer load. Therefore, while thermal load capacity may not be regarded as a primary consideration during the design phase, implementing passive design strategies during the design process can effectively mitigate heat gain and create more thermally comfortable indoor environments.

Meanwhile, most criteria in this theme were considered relevant to environmental performance, complementing the green building design factor, which includes energy efficiency, water consumption, renewable energy and water, landscape, green technology innovation, usage of low-emitting material, green material resources, and green vehicle transportation. Energy efficiency represents a fundamental principle in sustainable design and architecture, aiming to minimise energy consumption while ensuring a comfortable and productive environment for the occupants. For instance, in an office building, effective energy-saving strategies may include the application of energy-efficient lighting systems such as LEDs, the installation of occupancy sensors for electrical fittings, the use of large windows to enhance natural daylighting, and the integration of smart HVAC controls that adjust cooling

based on occupancy patterns and climatic conditions (Siregar et al., 2019). In addition, renewable energy and water conservation approaches through the adoption of solar panels on roofs can generate clean electricity and reduce the dependence on fossil fuels. This green technology and innovation can save energy and reduce carbon emissions, especially in balancing energy and water consumption. Awan et al. (2018) added that by integrating solar photovoltaic (PV) panels, the electricity consumption can be minimised by over 90% for a large office building.

In green building design, landscape features also serve an essential role by contributing to environmental sustainability, improving energy efficiency, and promoting occupant well-being. Zhai (2022) stated that building with landscape elements that are strategically planned can foster healthier surroundings by mitigating heat gain through the use of vegetation. For instance, incorporating green roofs and vegetated facades can effectively lower cooling demands and enhance indoor thermal comfort (Wang, 2018; Guo, 2010). Meanwhile, low-emitting and green materials are essential in sustainable construction, reducing the environmental impact and improving indoor air quality. Low-emitting material generally made from low VOC-emitting substances meanwhile green material often contain recycled or bio-based contents and designed to be environmentally friendly (Kubba et al., 2012; Wang et al., 2018). Applying low-emitting materials and finishes in office interiors helps lower the concentration of pollutants in an indoor environment. However, the indoor pollutant levels depend on other factors, such as ventilation, electronic equipment, and cleaning and maintenance practices (Karve et al., 2023).

While integrating green technologies and sustainable features in office buildings offers significant environmental and operational benefits, end users may not fully realise these advantages if the systems are poorly maintained or neglected. Inadequate maintenance can lead to reduced performance, increased energy consumption, and diminished occupant comfort (Apriani et al., 2021; Li et al., 2020). Therefore, architects must incorporate maintenance strategies and user-friendly operational considerations during the design phase to ensure green features' long-term functionality and effectiveness throughout the building's lifecycle.

Process Performance

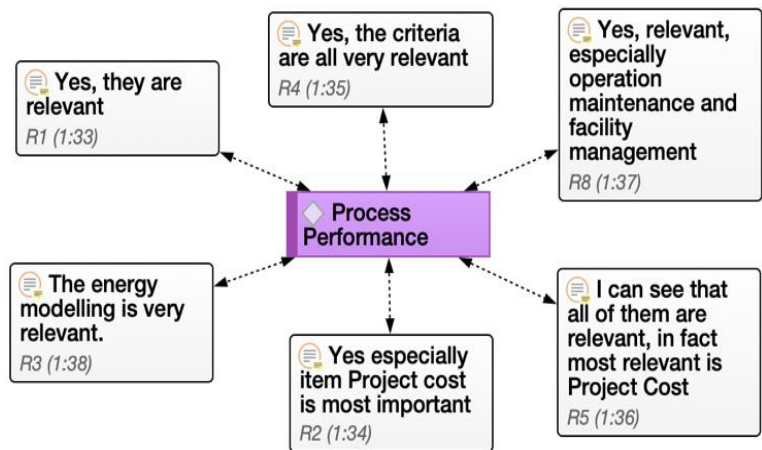


Figure 5. Process Performance Network

Figure 5 represents respondents' remarks on the relevancy of process performance criteria in green office buildings. All criteria were considered relevant, including sustainable site planning, operation and maintenance, facility management, green certification, energy modelling and project cost. Quoted from the interview;

"The criteria are very relevant, especially the project cost." (R2)

It is known that green buildings often require higher initial costs due to sustainable materials, advanced technologies, and design features that improve energy efficiency and water management. Due to the higher upfront cost, green buildings are often cited as a barrier to adoption (Dwaikat, 2016). Despite a higher initial investment, the life cycle costs (LCC) analysis shows that operational savings in green buildings can offset higher construction costs over time (Li, 2020). Thus, it is crucial for the designers to align the importance of design's aesthetics, performance and cost-efficiency.

Next, in green building design, energy modelling and simulation are mainly used as a cost-effective method for integrating energy efficiency into the design stage. The green roof simulation, for example, can effectively assist in design decision-making by evaluating the impact of growing depth, irrigation system and vegetation density, which later could affect the overall building energy consumption (Sailor, 2008). Ka'bi (2020) added that the energy simulation results provide design selections and parameters to suit the project requirements. From the interview, all respondents agreed that energy modelling and simulation are critically important during the design stage as they will assist the designers in making the most cost-effective design and optimise building performance.

"The energy modelling and energy simulation are very important at the design stage." (R3)

In addition, Li et al. (2020) address design features in green buildings that often result in higher maintenance requirements, which can impose financial burdens on building owners, particularly when the technologies installed in the building fail to deliver their intended energy-saving benefits due to malfunction or damage (e.g., solar photovoltaic panels). Sustainable management practices and efficient building automation systems are essential to address this issue to ensure that green buildings meet current and future user demands (Miraj et al., 2021). Quoted from the interview;

"The operation, maintenance, and facility management are all important. Nevertheless, in green buildings, there are specific approaches mentioned to do maintenance, the system used, for example, the Building Automation System (BAS) and Building Management System (BMS)." (R8)

The utilisation of Building Automation System (BAS) and Building Management System (BMS) can enhance building performance and optimise maintenance efficiency. Maintaining high performance in green buildings necessitates collaboration among interdisciplinary professionals and stakeholders to realise sustainability benefits fully. Therefore, integrating sustainability and maintainability considerations during the design phase is crucial to support ongoing efforts in energy and water conservation (Asmone et al., 2019; Chew et al., 2017). In addition, the BIM system is widely used in construction nowadays, as it can capture

information and knowledge of building maintenance operations by providing preventive and corrective maintenance decisions (Motawa, 2013), reducing the risk of building system failure (Ismail, 2020).

CONCLUSION

In summary, this study sought to assess the relevancy of green building design performance criteria based on the input from professionals in the construction industry. The interview findings indicate that some criteria identified in existing literature may not be fully applicable in practical settings. For example, referring to the interview feedback, the interior design might not be a critical factor to be considered during the design process. However, building designers must carefully plan the interior spaces for long-term functionality and thus reduce future modifications. In contrast, the newly suggested criteria offer valuable perspectives that can contribute to the development of current knowledge. These findings underscore the necessity for continuous evaluation and refinement of design criteria to support ongoing advancement in sustainable design practices. Furthermore, the study highlights the varying perspectives among designers in implementing green design strategies, often influenced by constraints such as project cost, which affect the design strategies in real-world applications.

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PERCEIVED RISK-BASED MAINTENANCE MANAGEMENT (PRBMM) MODEL FOR PUBLIC SCHOOLS BUILDING PERFORMANCE

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Abstract

Maintaining public school infrastructure is essential for ensuring a safe and conducive learning environment. Despite increasing maintenance challenges due to aging facilities and constrained resources, maintenance management often lacks a structured, risk-informed approach. This research develops and validates a Perceived Risk-Based Maintenance Management (PRBMM) model grounded in the Decomposed Theory of Planned Behaviour (DTPB) to address this gap. The DTPB framework enables a nuanced understanding of how attitudes, subjective norms, and perceived behavioural control influence maintenance decision-making under risk conditions. Employing a deductive theoretical approach with a cross-sectional time horizon, data were collected through a structured questionnaire survey targeting 137 technical experts responsible for public school maintenance in Malaysia. The questionnaire assessed four key determinant factors: financial, operational, performance, and safety risks, and their impact on perceived risk-based maintenance management performance. Structural Equation Modelling (SEM) was applied to test the hypothesised relationships and validate the PRBMM model. Results demonstrate that all four perceived risk factors significantly influence maintenance management performance, supporting the model's theoretical framework. Expert validation further confirmed the model's practical relevance and applicability. This research contributes to the literature by bridging the gap between risk perception theory and maintenance management practice, offering a robust, empirically validated framework for prioritising maintenance activities. The PRBMM model empowers decision-makers to adopt proactive, data-driven strategies that optimise resource allocation, enhance safety, and improve the sustainability of school infrastructure. Ultimately, this research provides a valuable blueprint for enhancing public school maintenance management in Malaysia and similar contexts globally.

Keywords: *Decomposed theory of planned behaviour; facility management, perceived risk; public schools; risk-based maintenance management*

INTRODUCTION

In 2023, Malaysia's education system experienced significant enrolment across all levels with nearly equal gender representation among students of 957,086 in pre-schools, 3,092,312 in primary, and 2,629,154 in secondary schools (United Nations, 2025). While access to education has expanded, the condition of school infrastructure raises serious concerns. Between 2019 and 2022, the number of dilapidated schools more than doubled from 534 to 1,505 nationwide and highlighting urgent infrastructural challenges, particularly in Sarawak and Sabah (National Audit Department Malaysia, 2022). Despite emergency funds and reactive repairs, the underlying problems of inadequate maintenance oversight, funding interruptions, and poor risk management persist, often subsequent in tragic consequences leading to poor school conditions, including collapsing roofs, falling ceiling fans, landslides,

and fires, have endangered student safety and disrupted learning. Malaysia's government has demonstrated dedicated commitment through increased education budgets—allocating RM58.7 billion in 2024, including RM930 million specifically for school maintenance (MoE, 2024).

However, sustained improvements require strategic leadership and systematic risk assessments to prioritise and fund maintenance effectively (Henan, 2024; Marsini, 2023). The challenge is not unique to Malaysia; many countries, including developed unities like the United States, face similar issues with ageing school infrastructure affecting millions of students (Dickerson & Ackerman, 2016; Yusuf et al., 2023). Regular and well-planned maintenance preserves building integrity, enhances safety, and supports student well-being and learning outcomes (Gracki, 2024; Radzuan et al., 2022). According to Abdullah (2021), there is limited research on the perceived risks associated with risk-based maintenance management, which highlights the need for more research into how these perceived risks affect maintenance decisions. Significant gaps in maintenance decision-making processes are noted by Radzuan et al. (2022) emphasise the need for more efficient frameworks to rectify these shortcomings. This research addresses the urgent need for a proactive and considering the perspectives of building owners, facility managers, maintenance staff, and occupants (Wong et al., 2015; Aven, 2016).

Currently, schools rely heavily on reactive maintenance, leading to inefficient resource use, increased safety risks, and compromised educational environments (Aziz et al., 2018; Li et al., 2021). According to Marsini (2023), the buildings and facilities must be maintained at the best possible condition and in addition to protecting investment capital, this proactive approach raises student intelligence and improves education. This argument emphasises the need for perceived risk in maintenance management to fill in the current gaps in theory, evidence, methodology, and population focus. To prioritise funding, increase decision-making efficiency, and improve safety, the Auditor General's Report (2022) emphasises the significance of data-driven risk mitigation strategies in school maintenance and promotes the use of maintenance models that address knowledge gaps (Da Silva et al., 2023; Lateef, 2010; Herath, 2022; Matorell, 2016; Hamzah, 2012).

Although proactive maintenance is frequently recommended in theory, schools typically take a reactive approach, which limits their capacity to effectively address problems (Yong & Suleiman, 2015). Limited empirical research has explored perceived risk, with minimal attention given to public schools (Paci et al., 2020; Aziz et al., 2018). Performance, financial, safety, and operational risks is determinant factors (DFs) that identified significantly affect public school perceived risk-based maintenance management (PRBMM) performance, according to the earlier research. Thus, developing a Perceived Risk-Based Maintenance Management (PRBMM) model that incorporates stakeholder perceptions and risk prioritisation is essential to transforming maintenance practices, ensuring safe, functional, and sustainable public schools. To fully validate and comprehend these perceived risks, contemporary analytical methods like SEM are required. The creation of useful, empirically supported PRBMM frameworks can be greatly advanced by filling in these gaps. Therefore, this research is to examine the relationships between the identified determinant factors (DFs) influencing perceived risk-based maintenance management (PRBMM) performance in public schools.

RESEARCH CONCEPTUAL MODEL

The use of the Theory of Planned Behaviour (TPB) gives a solid ground to understand decision-making strategies in the aspect of risk-based maintenance management for schools and public buildings. Fishbein and Ajzen's (1975) Theory of Reasoned Action (TRA) views the intention to engage behaviour, based on attitudes and subjective norms, as determining a person's behaviour. TRA, however, assumes volitional control and therefore lacks relevance in scenarios where external control constrains actions. Ajzen (1991) completed this gap by envisioning Theory of Planned Behaviour (TPB), which includes perceived behavioural control—the person's belief in engaging behaviour despite obstacles. TPB is particularly relevant to facility managers who rank maintenance activities under conditions of safety, legal, financial, and resource constraints. According to Decomposed Theory of Planned Behaviour (DTPB) deconstructs its core concepts—attitudes, subjective norms, and perceived behavioural control—into measurable components, with better predictive validity (Taylor & Todd, 1995). Decomposition is critical in examining how facility managers' perception of performance, operating, safety, and financial risk influences maintenance priority decisions. The DTPB model therefore offers advanced explanation of how particular beliefs and stakeholder pressures propel action in resource-poor public schools. Perceived Risk Theory (PRT), from its roots in consumer behaviour research, extends further validation to such models by using subjective such as safety risks, budget constraints, and functional disfunctions to decision-making (Bauer, 1960; Aven, 2016). Subjective risks strongly shape schools' strategies for maintenance resource allocation, usually making structural rehabilitation and prevention priorities in tight budgets.

By underpinning the DTPB, and PRT, the Perceived Risk-Based Maintenance Management (PRBMM) model provides a structured framework for data-driven and context-specific maintenance prioritisation. The PRBMM model facilitates proactive maintenance regimes that enhance safety, performance, and sustainability in school buildings (Ajzen, 1991; Fishbein & Ajzen, 1975; Taylor & Todd, 1995). Empirical testing confirms the validity of DTPB to predict intentions to behave in various fields, confirming that attitudes, subjective norms, and perceived behavioural control combined predict behaviour (Lobb et al., 2007; Mullan et al., 2013). DTPB further increases this by enabling thorough analysis of risk perception and stakeholder influence on facility managers' maintenance decisions. The conceptual model was developed based on the four (4) determinants of perceived risk, such as financial risk (FR), operational risk (OR), performance risk (PR), and safety risk (SR). This research concept consists of 20 items for independent variables and 3 items for dependent variables. Consequently, four (4) hypotheses were established for this research based on the research conceptual model as shown in Figure 1. Below are the hypotheses established from the conceptual model:

Hypothesis 1: There is a significantly influence between performance risk (PR) towards the perceived risk-based maintenance management (PRBMM) performance of public schools. This hypothesis suggests that effective management of performance risk can enhance the overall performance of public schools. This hypothesis consists of equipment functionality, facility functionality, impact on educational outcomes, learning environment, and maintenance response time.

Hypothesis 2: There is a significantly influence between financial risk (FR) towards the perceived risk-based maintenance management (PRBMM) performance of public schools. This hypothesis suggests that effective management of financial risk can enhance the overall performance of public schools. This hypothesis consists of budget provision, cost efficiency, funding stability, impact on long-term sustainability, and resource availability.

Hypothesis 3: There is a significantly influence between safety risk (SR) towards the perceived risk-based maintenance management (PRBMM) performance of public schools. This hypothesis suggests that effective management of safety risk can enhance the overall performance of public schools. This hypothesis consists of emergency preparedness, health and sanitation, physical hazards, safety measures, and structural integrity.

Hypothesis 4: There is a significantly influence between operational risk (OR) towards the perceived risk-based maintenance management (PRBMM) performance of public schools. This hypothesis suggests that effective management of operational risk can enhance the overall performance of public schools. This hypothesis consists of disruptions in daily operations, staff productivity and morale, student's experiences, operational efficiency, and stakeholder satisfaction.

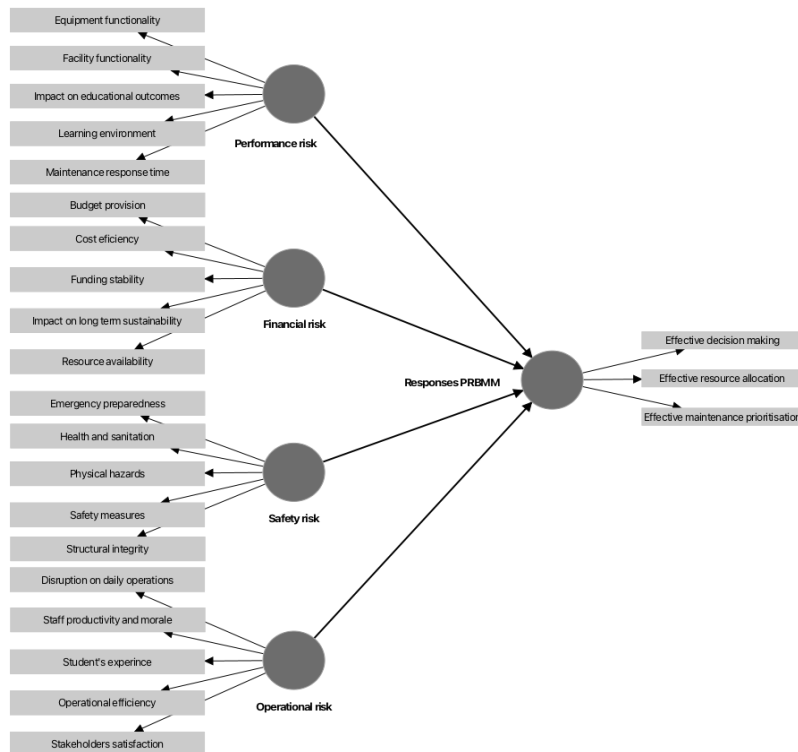


Figure 1. Research Conceptual Model

METHODOLOGY

The objective of this research is to examine the relationships between the identified determinant factors (DFs) influencing perceived risk-based maintenance management (PRBMM) performance in public schools. These determinant factors (DFs) are derived from

multiple constructs identified in previous studies. It employs positivism, philosophical, and deductive approaches that uses a questionnaire survey strategy for data collection.

Sample

For this research, selecting technical professionals as respondents provides a more valid and specific perspective on maintenance and risk management in public schools. Technical experts, with their specialized knowledge and experience, are uniquely positioned to understand the complexities of performance, financial, operational, and safety risks that impact the effectiveness of maintenance practices (Ryberg, 2024; Burn, 2024; Derder, 2023; Linardakis, 2023; Ali & Nsolezi, 2023; Lavy & Shohet, 2016). As Amiruddin and Baharuddin (2023) point out, administrators may lack awareness of day-to-day risks that are critical for maintenance management. In contrast, technical experts provide essential insights on how to streamline maintenance practices, apply appropriate technologies, and implement interventions that can prevent long-term infrastructure problems (Štok, 2023; Wada, 2023; Zulu et al., 2022; Sharma & Pundir, 2018). This research targets 137 technical experts in maintenance management at government public schools in Petaling, Selangor, Malaysia, each with at least one year of relevant experience. By focusing on these experts, the research aims to gain a more informed and precise understanding of the risks associated with aging school infrastructure. Expert input ensures that the identified risks and proposed solutions are realistic, comprehensive, and tailored to the specific needs of Malaysian public schools. To ensure the reliability of the sample size, confidence levels and intervals were applied, providing a positive and negative range for extrapolation to the broader population. Throughout the process, the research adhered to ethical standards, including informed consent, impartiality, confidentiality, and respect for participants' privacy (Fouka et al., 2020). All possible steps were taken to protect volunteers from potential harm during and after the research.

Instrumentation

The questionnaire used in this research consisted of 20 independent variables (IVs) and 3 dependent variables (DVs), measured using a 5-point Likert scale, based on the conceptual framework. It was divided into four sections: Section A covered instructions and demographic information; Section B focused on perceived risk-based maintenance management (PRBMM); Section C explored responses to perceived risks in public school maintenance; and Section D included an open-ended question for further insights. The survey aimed to identify significant relationships between financial, operational, safety, and performance risks affecting PRBMM. A web-based survey was distributed through social media platforms, including Telegram and WhatsApp.

Data Analysis

The data were processed using Structural Equation Modelling (SEM) with SmartPLS v4.1.0.3 software. SEM was applied in two steps: measurement model testing to validate construct reliability, and structural model testing to analyse relationships among determinant factors (DFs) influencing PRBMM performance in public schools. SPSS v29 was used for Exploratory Factor Analysis (EFA), and SEM was bootstrapped to test the significance of the relationships.

FINDINGS

Respondent's Profile

In this research, a total of 137 responses were successfully gathered, achieving a 100% response rate. With a 100% response rate, all collected questionnaires were thoroughly examined, confirming that there were no missing values across the dataset. This level of response completeness eliminated the need to omit any data, providing a fully intact and comprehensive dataset of 137 respondents. A minimum sample size of 107 with a 95% confidence interval of 5% error and 121 with a 99% confidence interval of 5% error were required for this research. This implies that the data and findings were valid. Therefore, this dataset allowed for reliable and thorough analysis, ensuring that all responses contributed to the final research findings without any exclusions. The analysis was subsequently conducted further with SEM, and the results are revealed in the following sections. Table 1 details the demographic profiles of the main survey respondents. Technical experts in public school maintenance answered the questionnaires. The majority of 137 participants (44.5%) had a bachelor's degree, followed by a diploma (31.4%) and a master's (19.0%). 45.3% had more than 10 years of experience, while 23.4% had 2-4 years. Assistant Engineers/Architects (38.0%) and Engineers (28.5%) were the most common positions, followed by Building Surveyors (10.2%) and Quantity Surveyors (8.0%). Facilities managers, assistant facilities managers, administrative officers, and a few others were also surveyed.

Table 1. Respondent's Profile

	Profiles	Frequency	Valid Percent	Cumulative Percent
Qualification	Certificate	5	3.6	3.6
	Diploma	43	31.4	35.0
	Bachelor	61	44.5	79.6
	Master	26	19.0	98.5
	PhD	1	0.7	99.3
	Others	1	0.7	100.0
	Total	137	100.0	
Experiences	None	10	7.3	7.3
	0 – 1	8	5.8	13.1
	2 – 4	32	23.4	36.5
	5 – 7	15	10.9	47.4
	8 – 10	10	7.3	54.7
	More than 10	62	45.3	100.0
	Total	137	100.0	
Position	Facilities Manager	2	1.5	1.5
	Assistant Facilities Manager	1	0.7	2.2
	Building Surveyor	14	10.2	12.4
	Quantity Surveyor	11	8.0	20.4
	Engineer (Civil, Electrical, Mechanical)	39	28.5	48.9
	Architect/Landscape Architect	1	0.7	49.6
	Assistant Engineer/Architect	52	38.0	87.6
	Assistant Quantity Surveyor	3	2.2	89.8
	Administrative and Diplomatic Officer	3	2.2	92.0
	Assistant Diplomatic Officer	4	2.9	94.9
	School Administrative	4	2.9	97.8
	Others	3	2.2	100.0
	Total	137	100.0	

Measurement Model Assessment

Testing scale reliability and validity require measurement assessment. Also measures manifest and latent variables (Loehlin, 1998). This measurement model was tested for independent and dependent variable convergence and discriminant validity. Except for AVE loadings, all loadings exceeded 0.40, and most exceeded 0.80. Factor loads were 0.501–0.963. Items with loadings below 0.70 were significant (Hair et al., 2010). High factor loadings suggest convergent validity. All constructs factor loading exceeded 0.50 except AVE. The research examines public school PRBMM and perceived risk determinants. Performance Risk (PR) has moderate validity and good reliability. Both Operational Risk (OR) and Safety Risk (SR) have acceptable validity and strong reliability. Financial Risk (FR) shows excellent validity and reliability. The PRBMM Response has low validity but high reliability. Despite high reliability scores, performance risk and PRBMM response AVE values suggest convergent validity issues. Operational, safety, and financial risk are well-defined and reliable according to PRBMM framework criteria shown in Table 2. To improve research validity, future research should refine measurement items and explore new constructs. This method will improve public school maintenance management by understanding perceived risks.

Table 2. Convergent Validity

	Determinant Factor	AVE	Cronbach's Alpha (CA)	Composite Reliability (CR)
PR	Performance Risk	.416	.843	.779
OR	Operational Risk	.622	.821	.891
SR	Safety Risk	.622	.866	.891
FR	Financial Risk	.833	.842	.938
RES	Response of PRBMM	.404	.898	.768

Table 3 shows good discriminatory validity. Performance, operational, and safety risks are strongly correlated. PRBMM of financial risk and response have high internal correlations, confirming their distinctiveness.

Table 3. Discriminate Validity

	Determinant Factor	AVE	PR	FR	SR	OR	RES
PR	Performance Risk	.416	.645*				
OR	Operational Risk	.622		.789*			
SR	Safety Risk	.622			.789*		
FR	Financial Risk	.833				.913*	
RES	Response of PRBMM	.404					.636*

Structural Model Assessment

Subsequently, the path coefficients of all perceived risk factors are compared using beta (β) values. The path coefficients represent hypothesised relationships, with the highest β value indicating the strongest impact of perceived risk factors (independent variables) on PRBMM responses (dependent variables). Hair et al. (2010) state that path coefficients must exceed 0.10 to influence the model. However, a t-value test is necessary to evaluate the significance of the c value.

The previous study used non-parametric bootstrapping (Chin, 1998). The statistical significance of each path coefficient was assessed using bootstrap re-sampling (Henseler et al., 2016). For stable estimates, 5000 resample iterations were done. According to Hair et al. (2014), acceptable two-tailed test t-values are 1.64 (significance level = 0.10 or 10%), 1.96 (0.05 or 5%), and 2.58 (0.01 or 1%). The hypothesis testing shows in Table 4 indicates that financial risk, operational risk, performance risk, and safety risk significantly affect PRBMM responses. Path coefficients and t-values showed that these factors were related, highlighting their importance in improving public school maintenance management. The path coefficients for Performance Risk, Operational Risk, Safety Risk, and Financial Risk surpass the 0.01 threshold, according to the bootstrapping results underscoring these determinant factors (DFs) significantly influence on the PRBMM responses.

Table 1. Results of Hypothesis Test

Hypothesis	Relationship of Determinant Factors → Response of PRBMM	Path Coefficient (β)	T Value	P Values	Remarks
H1	Performance risk > Response of PRBMM	0.087	1.854***	0.032	Significant
H2	Operational Risk > Response of PRBMM	0.091	3.827***	0.000	Highly Significant
H3	Safety Risk > Response of PRBMM	0.116	1.815***	0.035	Significant
H4	Financial Risk > Response of PRBMM	0.093	1.657***	0.049	Significant

RESULTS AND DISCUSSION

Performance Risk

H01: Performance risk (PR) significantly influences the perceived risk-based maintenance management (PRBMM) performance of public schools. Thus, the hypothesis is accepted.

Performance Risk affects PRBMM responses with a path coefficient of 0.116, t-value of 1.815, and p-value of 0.035. This suggests that improving maintenance management requires addressing performance risks. Performance Risk significantly affects PRBMM responses, emphasising the importance of performance management in public school maintenance. Performance risks like poor maintenance quality and inefficiencies may affect maintenance programmes (Duncan et al., 2019; Tang et al., 2018; and Kauppi et al., 2016). Although the framework correctly notes these issues, it would be advantageous to incorporate a more thorough understanding of performance risk that considers not only the physical circumstances but also the psychological effects on staff and students. This psychological factor, which is frequently disregarded, has the potential to have a substantial impact on opinions about safety and general satisfaction, which could have an indirect effect on academic results (Okudan, Budayan & Dikmen, 2021). Therefore, a more comprehensive understanding of how school maintenance impacts learning outcomes may be possible through a holistic approach that considers both the tangible and intangible aspects of performance risk. These risks must be addressed to ensure maintenance activities meet standards and achieve their aims. Failure to manage performance risks could compromise school facilities, affecting learning and safety.

Therefore, school maintenance management must prioritise performance improvement initiatives with strict quality controls and efficiency measures.

Financial Risk

H02: Financial risk (FR) significantly influences the perceived risk-based maintenance management (PRBMM) performance of public schools. The hypothesis is accepted.

Financial risk is significantly correlated with PRBMM responses, with a β of 0.087, a t-value of 1.854, and a p-value of 0.032, demonstrating the importance of finances in maintenance management. Public school maintenance requires effective financial planning to avoid risks of delaying essential maintenance due to financial constraints. Adequate budgeting ensures efficient resource use, prompt maintenance, and cost savings (Al-Najjar, 2007, Lee, 2009, Shapiro et al., 2019, and Shehata et al., 2021). Maintaining a maintenance schedule requires consistent funding, and long-term financial planning ensures sustainability and the availability of resources to keep facilities safe and functional (Arrondel et al. (2013) and Rabaya et al. (2018)). Poor financial management makes educational institutions more vulnerable and less efficient in maintenance. For instance, it has been demonstrated that financial risk includes budgetary allocation, cost effectiveness, and funding stability, emphasising the necessity of a stable resource base to handle both planned and unforeseen maintenance tasks. According to researchers, a lack of funding may cause maintenance to be neglected, which could raise future repair expenses and jeopardise the structural soundness of school buildings (Buban & Janer, 2024; Beauregard & Ayer, 2018). Although this framework places a strong emphasis on financial risk as a key component of maintenance effectiveness, some academics disagree, contending that while financial constraints do have an impact, they shouldn't take precedence over strategic planning and resource allocation abilities, which can make better use of the resources at hand to make up for tight budgets (Myles, 2011; Hassanain et al., 2019).

Safety Risk

H03: Safety risk (SR) significantly influences the perceived risk-based maintenance management (PRBMM) performance of public schools. Thus, the hypothesis is accepted.

Safety Risk significantly affects PRBMM responses with a path coefficient of 0.093, t-value of 1.657, and p-value of 0.049. Safety must be prioritised for effective maintenance management. The strong correlation between safety risk and PRBMM responses demonstrates how important safety is in maintenance. Safety funds must be sufficient for cost efficiency and funding stability. Funding and resources support immediate safety needs and long-term maintenance sustainability (Dagunduro et al., 2024, Falco et al., 2021 and Alkhadim et al., 2018). Addressing safety risks can reduce accidents and equipment failures and improve public school maintenance management. From a research standpoint, the framework's emphasis on safety is consistent with the larger risk management goal of safeguarding the health and welfare of building occupants. However, detractors contend that many educational institutions' safety procedures are still reactive rather than proactive, mostly because of underestimating risks or a lack of resources (Chandrappa & Das, 2024; Janius et al., 2024).

According to Al-Worafi (2024), an integrated safety management approach is required in this context. This approach should include regular audits, risk assessments, and updates to safety protocols as part of a continuous improvement process. However, this continuous evaluation necessitates administrative and financial assistance, which is frequently lacking in schools with limited resources. According to the authors, to continuously create a safe learning environment, schools must make safety a top priority.

Operational Risk

H04: Operational risk (OR) significantly influences the perceived risk-based maintenance management (PRBMM) performance of public schools. Thus, the hypothesis is accepted.

Operational Risk significantly affects PRBMM responses with a path coefficient of 0.091, t-value of 3.827, and p-value of 0.000. Improving public school maintenance requires effective operational risk management (Chen et al., 2015; Chen et al., 2013; and Chernobai et al., 2011). Operational risk is a crucial but frequently underemphasised aspect of maintenance management. This risk type encompasses disruptions to daily school activities due to equipment breakdowns or inefficient maintenance practices. The framework rightly emphasises that operational risks can undermine school productivity and stakeholder satisfaction, including students, parents, and staff members (Mitchell, 1992; Tezel et al., 2016). Poorly managed operational risks can lead to reputational damage and reduced morale, which in turn affects the school's ability to provide a stable educational environment. However, the framework could further explore the long-term implications of operational disruptions, such as increased turnover among maintenance staff and burnout among teaching staff due to continuous interruptions (Savolainen, 2023; Najeeb, 2024). Alavi et al. (2014) argue that proactive operational risk management should go beyond simply scheduling repairs; it should involve comprehensive planning, including predictive maintenance and contingency plans for rapid response to disruptions. This approach requires a robust data collection and analysis system to predict potential disruptions, which may not be feasible for all schools. Nevertheless, in resource-limited settings, adopting even small-scale predictive tools can lead to more reliable maintenance practices and reduced operational risks.

Validation of Research Findings

The purpose of this process is to ensure that the proposed model meets a reasonable level of acceptance by the partitioners and is appropriate for use within the industry context. Consequently, ten (10) practitioners experienced in managing maintenance in public schools participated in an interview to mark their level of acceptance on determinants of perceived risk and to validate the research model of PRBMM for public schools. These experts were selected based on criteria of Pertinent/ relevant and verifiable previous experience/ knowledgeable in managing maintenance in public schools, direct involvement/ recent handling in managing public schools maintenance and experts have more than 20 years of experiences in managing maintenance management in public schools or an academic qualified as a professional engineer, registered under the Board of Engineers Malaysia (BEM) and Institute of Engineers Malaysia (IEM), Board of Architects Malaysia (BAM), Institutions of Engineers of Malaysia, Project Management Professional, Royal Institution of Surveyor Malaysia (RISM) and Malaysian Society for Occupational Safety and Health (MSOSH).

Results of the acceptance level are summarised in Table 5 where each expert and mean rating of each validation aspect of confirmation.

Table 5. Validation Results Based on The Responses of 10 Validators

Level of Acceptance	Validators										Mean Rating
	1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	
PR	5	5	5	5	5	5	5	5	5	5	5.00
OR	5	5	5	5	5	5	5	5	5	5	5.00
SR	5	5	5	5	5	5	5	5	5	5	5.00
FR	5	5	5	5	5	5	5	5	5	5	5.00
RES	5	5	5	5	5	5	5	5	5	5	5.00

Note: 1=Not all satisfied 5=Extremely satisfied

Note: *Experts who had participated in developing of PRBMM Model

According to 10 expert validators, the PRBMM model is highly approved. Each validator gave the model a mean score of 5.00 for all determinant factors, including Performance Risk (PR), Operational Risk (OR), Safety Risk (SR), Financial Risk (FR), and Response (RES). The consistent rating of 5, indicating "Extremely satisfied," confirmed the model's acceptance and perceived effectiveness in public school maintenance management. This expert consensus confirms the PRBMM model's industry relevance and applicability.

CONCLUSION

Perceived Risk-Based Maintenance Management (PRBMM) model was designed and verified for public schools, highlighting the importance of Performance Risk, Financial Risk, Safety Risk, and Operational Risk in maintenance management solutions. The research found that the effectiveness of maintenance practices for public school performance is significantly influenced by these four risk factors, as evidenced by the rigorous analysis of data collected from 137 technical experts using Structural Equation Modelling (SEM). As a result of decaying school infrastructure, which creates safety dangers and disturbs learning environments, this model addresses a major need in the education sector in Malaysia. The PRBMM model provides a rigorous, data-driven methodology that enables proactive maintenance decision-making, optimises resource allocation, and improves infrastructure. According to the findings, this research not only fills the critical gap in maintenance management literature but also delivers a practical, validated model that empowers technical experts and decision-maker to move beyond reactive repairs towards a proactive and could improve maintenance results even more. The results highlight this model is empirical foundation and expert endorsement make it a compelling blueprint for legislators and school officials to revolutionise school maintenance management, not only in Malaysia but globally. Ultimately, to improve public school maintenance and fostering a conducive learning environment that supports academic excellence and well-being for future generations, this research shows that addressing financial, operational, safety, and performance risks is crucial.

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AUTHOR CONTRIBUTION

All authors are discussed from the presented idea, developed the theory, performed computations, verified the analytical methods and supervised the findings of this research, provided critical feedback, helped shape the research, and contributed to the final manuscript.

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ARCHITECTURAL RESILIENCE IN URBAN UNESCO WORLD HERITAGE SITES: A COMPARATIVE ANALYSIS OF PHYSICAL AND NON-PHYSICAL BUILDING FEATURES

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Abstract

This study presents a comparative analysis of the UNESCO World Heritage Sites of Melaka and George Town: Historic City of the Straits of Malacca in Malaysia and the Historic City of Vigan in the Philippines, exploring how they preserve architectural heritage in urban settings. The research assesses the interplay of physical and non-physical features to enhance the resilience and sustainability of the sites. The analysis highlights the importance of both physical features - such as structural integrity, design and materials - and non-physical features - including management, community and cultural - in urban heritage conservation. The outcomes of conservation efforts vary due to the unique historical, cultural and socio-political fabric of each site. Vigan's conservation focuses on Spanish colonial architecture and traditional skills, while George Town leverages its multicultural heritage through community collaboration and diverse influences. Key findings highlight the need for carefully crafted policies, effective resource allocation and inclusive stakeholder collaboration for successful heritage conservation. The research supports context-sensitive approaches to reconcile conservation with contemporary use, thereby promoting heritage longevity. Overall, the study identifies Vigan and George Town as models for integrating heritage conservation with sustainable urban living, emphasizing historical integrity alongside vibrant culture. It recommends further analysis of the long-term impact of conservation activities on the socio-economic environment and innovative conservation methods for World Heritage sites.

Keywords: *Architectural resilience; Heritage management; UNESCO World Heritage Sites; Urban heritage conservation; Resilience*

INTRODUCTION

The increasing importance of preserving cultural heritage sites in urban areas, especially with threats from climate change and urbanization (Oyeleye & Bigon, 2025), necessitates a deeper understanding of architectural resilience, particularly for UNESCO (United Nations Educational, Scientific and Cultural Organization) World Heritage sites (Nguyen & Baker, 2023). The resilience of these UNESCO World Heritage sites in urban contexts carries significant implications for safeguarding cultural heritage amidst present-day challenges (Ferreira et al., 2021).

With urbanization and climate change posing continuous threats to historical sites, it is crucial to comprehend both physical (Genadt, 2020) and non-physical (Tavares et al., 2021) elements of architectural resilience for sustainable urban development. Architectural resilience encompasses not only the structural integrity (Mayar et al., 2023), materials (Mayhoub et al., 2021), and design of buildings (Chhabra, 2021) (physical elements), but also

the intangible cultural elements, community engagement (Y. Wang et al., 2018), and management strategies (Shadar & Shach-Pinsly, 2024) that contribute to their enduring significance (Ellis et al., 2022) (non-physical elements). Urban built heritage plays a role in building resilience, particularly in the economic dimension, through tourism, and in the social dimension, by embodying the identity of local populations (Fabbicatti et al., 2020; Walidonna et al., 2024).

While research recognizes the importance of physical and non-physical features, a crucial gap remains: How can conservation practices effectively balance these elements to ensure holistic architectural resilience? Therefore, this study seeks to answer the following research question: How can conservation practices at UNESCO World Heritage sites best integrate physical and non-physical elements of architectural resilience to ensure the sustainable preservation of cultural heritage in the face of urbanization and climate change?

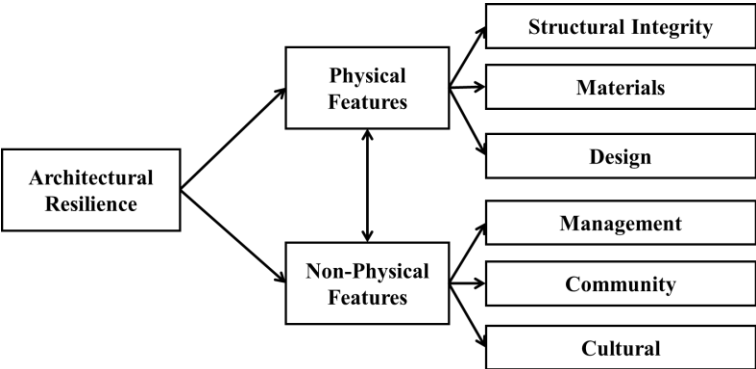
This paper presents a comparative study of heritage sites, assessing the integration of physical and non-physical resilience elements to address this question. The review synthesizes current research to identify key factors used in evaluating resilience. Ultimately, this aims to provide a framework for researchers, practitioners, and policymakers to better understand, assess, and enhance the resilience of architectural heritage sites. To provide a clear roadmap, this paper begins with a literature review, followed by an outline of the methodology. The core of the analysis involves a discussion and comparative perspective. The paper then concludes with a summary, conclusion, and recommendations for future research.

LITERATURE REVIEW

Architecture resilience refers to the ability of a building or site to withstand and recover from various external and internal stresses, such as natural disasters, climate change, social and economic change, and rapid urbanisation (Laboy & Fannon, 2016). This concept emphasizes the importance of preserving not only the physical features, but also the non-physical features, traditions and social meanings associated with these heritage sites. Physical features include structural integrity (Mayar et al., 2023), materials used (Mayhoub et al., 2021) and architectural design (Chhabra, 2021), while non-physical features include intangible cultural elements, community engagement (Y. Wang et al., 2018) and management strategies (Ellis et al., 2022).

UNESCO World Heritage Sites

UNESCO World Heritage sites are selected for their exceptional universal value and the necessity of protection (UNESCO, 1972). These sites can be cultural, natural, or a combination of both. Cultural heritage sites, in particular, undergo selection based on criteria that acknowledge their historical, artistic, or scientific significance (Khalaf, 2020). The physical characteristics of architectural resilience, including structural integrity, traditional construction methods, and the sustainable use of local materials, are key factors in assessing a site's resilience.



(Source: Author)

Figure 1. Research's Theoretical Thinking

Physical Features of Architectural Resilience

The physical features of architectural resilience are of fundamental significance for the durability and sustainability of heritage sites in urban contexts. An understanding of these characteristics is important for the development of preservation strategies to maintain the authenticity of heritage sites.

Structural Integrity is a fundamental aspect of architectural resilience is ensuring the building's structural integrity. This refers to the ability of a building's framework to withstand forces without collapsing or suffering critical damage (Mayar et al., 2023). It involves careful engineering and construction techniques to ensure that loads are properly distributed throughout the structure (Zekry & EL-Taweel, 2023). This encompasses several key elements: the structural system, which dictates how loads are transferred throughout the building; the structural condition, which highlights the importance of regular maintenance and timely repairs; and environmental adaptation, which is the structure's ability to withstand environmental stressors (Kioumars et al., 2022). For heritage sites, maintaining structural integrity often requires regular inspection, timely repairs, and, in some cases, the retrofitting of existing structures with modern reinforcement methods (Damas Mollá et al., 2022). Understanding the original construction methods and materials is crucial for effective intervention.

The selection of appropriate construction materials plays a vital role in fostering resilience within architectural designs. Durable materials that can resist weathering, decay, and the impacts of natural disasters are essential (Giglio et al., 2024). Traditional materials, like locally sourced stone or timber, often possess inherent resilience due to their adaptation to the regional climate (Leskovar & Premrov, 2021). However, modern materials, such as reinforced concrete or certain composites, can also enhance resilience when used strategically (Piccardo & Hughes, 2022). This involves consideration of material types, where durable and locally sourced options are preferred, as well as material authenticity, which is important for preserving the historical character of heritage sites.

In addition to structural and material considerations, the architectural design itself plays a key role in resilience. Climate-responsive design considers local climate conditions to minimize energy consumption and enhance occupant comfort (Lin et al., 2022). This includes

the consideration of architectural styles (Chhabra, 2021), and decorative elements (Srimuang et al., 2023). In the context of heritage sites, design must also respect the building's historical character and aesthetic value (Cotter & Karsono, 2023). This may involve adapting traditional design principles to meet modern performance standards (Rebec et al., 2022). Architectural resilience involves structural strength, durability of buildings, use of sustainable materials, and consideration for local climate and environmental factors against natural disasters and climate change impacts. These features are critical to maintaining heritage site integrity over time.

Non-Physical Features of Architectural Resilience

Non-physical elements, such as traditional knowledge and practices, are essential to the conservation of heritage values. Local traditions and crafts also play an important role in enriching the cultural significance of heritage sites and fostering community identity (Onecha et al., 2021). Community involvement in site management is essential to ensure the sustainable protection of these sites (Y. Wang et al., 2018). Effective management strategies such as monitoring (Masciotta et al., 2016), adaptive reuse (G. Wang & Liu, 2021) and sustainable tourism practices (Lusetyowati, 2015) contribute significantly to the resilience of sites to urbanization and external pressures on UNESCO World Heritage sites.

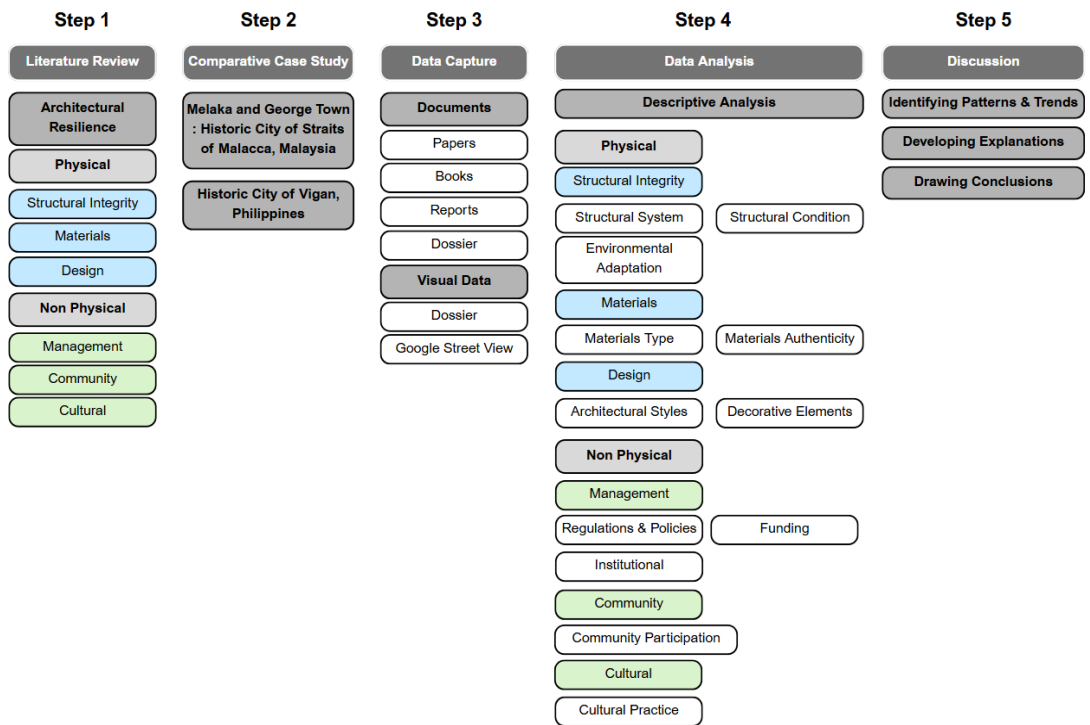
Community engagement is vital for fostering a sense of ownership and shared responsibility in the preservation of heritage sites (Ellis et al., 2022). Community participation in site management ensures that local voices are heard and that preservation efforts align with community values (Fabbricatti et al., 2020). Empowering communities to actively participate in the protection of their heritage can lead to more sustainable and culturally sensitive outcomes (Shadar & Shach-Pinsly, 2024). Recognizing and respecting the cultural significance of heritage sites is paramount for their preservation (Khaznadar & Baper, 2023). This involves understanding the traditional knowledge, practices, and beliefs associated with a site, and incorporating these elements into conservation efforts (Jokilehto, 2006). By safeguarding the cultural heritage values embedded within these sites, we strengthen their ability to contribute to community identity and resilience.

In conclusion, the resilience of architectural heritage hinges on a holistic approach that integrates effective management through regulations, funding, and institutions, active community participation to foster ownership and align preservation with local values, and the safeguarding of intangible cultural significance rooted in traditional knowledge and practices. By weaving these non-physical elements into the fabric of conservation efforts, we can ensure the enduring value, identity, and adaptability of heritage sites in the face of ever-evolving challenges.

METHODOLOGY

This study examines the physical and non-physical aspects of architectural resilience in UNESCO World Heritage Sites in urban areas of South East Asia. The selection criteria focus on the significance of the sites within major urban areas, as well as the demographic and economic challenges they face. In selecting UNESCO World Heritage sites in Asia, an approach is taken to ensure that the sites selected are representative of the diversity and issues that exist in urban heritage settings. The UNESCO World Heritage List, available at

<https://whc.unesco.org/en/list/&order=region> , serves as a key resource for this purpose. These sites will be selected to showcase different resilience strategies, management methods and community involvement, providing valuable insights into heritage conservation in the changing urban landscapes.



(Source: Author)

Figure 2. Research Methodology

The comparative analysis will therefore focus on two different UNESCO World Heritage sites in South East Asia: Melaka and George Town: Historic City on the Straits of Malacca, Malaysia and Historic City of Vigan, Philippines. These sites have been selected for their unique physical and non-physical features, which together contribute to their architectural resilience within the broader context of urban heritage. The next step will be a descriptive analysis to understand the specific factors that influence the architectural resilience of these sites. This will help to identify consistent patterns of strengths present in these heritage sites that directly contribute to their sustainability and resilience to external pressures. Furthermore, the analysis will help researchers to understand the relationship between these factors and the sustainability of heritage sites over time. This analysis will provide insights for the development of maintenance strategies to enhance architectural resilience, enabling stakeholders to develop more targeted approaches to the conservation of UNESCO World Heritage sites in urban areas.

For the purposes of this comparative analysis, Melaka and George Town: Historic City on the Straits of Malacca, Malaysia, will be considered as a single entity and will be referred to as 'George Town' for brevity. This simplification allows for a focused comparison with the Historic City of Vigan, Philippines ('Vigan'), highlighting key aspects of architectural resilience in these UNESCO World Heritage Sites.

A key limitation of this study arises from its reliance on documentary data, encompassing sources such as academic publications, governmental reports, and UNESCO dossiers, to characterize the architectural resilience of Vigan and George Town. While these secondary sources provide a foundational understanding of the cities' heritage and conservation efforts, they inherently reflect the perspectives and priorities of the authors and institutions involved, potentially overlooking nuances present in the lived experiences of local communities. Furthermore, the utilization of visual data from platforms like Google Street View and the UNESCO dossier offers a constrained observational field compared to immersive, on-site ethnographic fieldwork. This constraint may limit the depth of understanding regarding the complex interplay between the built environment and daily life. To mitigate these limitations, future research should prioritize the incorporation of primary qualitative data, gathered through methods such as semi-structured interviews with residents, participatory observation, and archival research within local historical societies, to provide a more holistic and nuanced understanding of architectural resilience in these UNESCO World Heritage Sites.

RESULT

Melaka and George Town : A Historic City of the Straits of Malacca, Malaysia

Melaka and George Town, inscribed on the UNESCO World Heritage List in 2008, exemplify the successful fusion of Malay, Chinese and European architectural styles in their enduring shophouses (Ahmad & Abdullah, 2010). Their preservation is ensured by adaptive reuse and a strong sense of local identity, nurtured by intangible cultural practices (Khoo et al., 2015). Essential to their maintenance are effective management (S.L., 2020), community involvement (Sazali et al., 2023) and sustainable tourism (Miza Suhaimi, 2023), which together safeguard the rich heritage of these Malaysian cities.



(Source: Gary Arndt, 2024 ; Shutterstock, 2024)

Figure 3. Melaka and George Town: A Historic City of the Straits of Malacca, Malaysia

Physical Features in Melaka and George Town: Historic City of the Straits of Malacca, Malaysia

The historic cities of Melaka and George Town, Malaysia, showcase a rich architectural tapestry woven from diverse cultural influences (Hassan et al., 2019). Their structural integrity is evident in the interplay of traditional Malay timber framing techniques with

Portuguese and Dutch colonial influences, resulting in unique building forms like shophouses with arcades and Chinese-inspired elements (Yusof & Ahmad, 2018). Continuous restoration efforts and structural reinforcements ensure the buildings' longevity while respecting their historical significance (Empili & Husain, 2024). Furthermore, these structures demonstrate environmental sensitivity through features like bamboo canopies for shading, highlighting an awareness of the local climate (Khoo & Woo, 2024). The use of readily available materials such as tropical hardwoods, laterite stone, clay roof tiles, ceramic tiles, brick, and timber further emphasizes this resourcefulness (Siang, 2023). While original materials are prioritized, the use of substitute materials is carefully considered to balance preservation with practicality (Aziz, 2017). Finally, the fusion of Traditional Malay, Portuguese, Dutch, and Chinese architectural styles, adorned with intricate details like European and Chinese-inspired elements, ceramic tile work, and woodcarving, creates a unique and visually captivating urban landscape.



(Source: Google Street View, 2020 ; Google Street View, 2014)

Figure 4. Buildings at Melaka and George Town, Malaysia

Non-Physical Features in Melaka and George Town: Historic City of The Straits of Malacca, Malaysia

The historic cities of Melaka and George Town, Malaysia, benefit from a robust framework of non-physical features that contribute to their ongoing preservation. Effective management strategies are implemented through clear regulations and policies (Lee et al., 2008), including zoning regulations, building codes, and conservation guidelines, ensuring development aligns with heritage values (Amat, 2019). Financial support is provided through initiatives like the George Town Heritage Habitat Seed Funds and various incentives, encouraging community involvement in preservation efforts (Mui & Leng, 2022). Institutionally, organizations like George Town World Heritage Incorporated (GTWHI) and The Penang Government play a crucial role in overseeing conservation efforts. Community participation is actively fostered through collaborations with GTWHI, community groups, and events like the George Town Heritage Festival, fostering a sense of shared responsibility for their heritage (Suhaimi & Bustami, 2020). Furthermore, vibrant cultural practices, including performing arts, culinary experiences, the George Town Heritage Festival, and religious and cultural celebrations, ensure the continued relevance and vitality of these cities' heritage (Foo & Krihnapillai, 2019; D. Omar et al., 2018).



(Source: gtwhi.com, 2024)

Figure 5. Festivals Flyer at Melaka and George Town, Malaysia

Historic City of Vigan, Philippines

Located in Ilocos Sur, the UNESCO-listed city of Vigan is a relic of the Spanish colonial era, with a unique blend of Asian and Filipino architecture (UNESCO National Commission of the Philippines, 1999). Its cobbled Calle Crisologo is lined with well-preserved ancestral homes that embody Vigan's rich heritage. The town's use of terracotta and wood epitomises its aesthetic charm and practicality. Vigan preserves its cultural identity, which includes traditional crafts and rituals (Rose et al., 2020). Vigan seamlessly blends its historic Spanish influence with local traditions to create a vibrant cultural mosaic (Montero & Lozano, 2015).

Physical Features in Historic City of Vigan, Philippines



(Source: UNESCO, 2025)

Figure 6. Buildings at Historic City of Vigan, Philippines

The city of Vigan in the Philippines, known for its well-preserved Spanish colonial architecture, exhibits a distinct set of physical features that contribute to its structural integrity. The dominant architectural style, bahay na bato (house of stone) (Pahimnayan-Pagador et al., 2025), features sturdy wooden structures on the upper level and brick or stone on the lower level, showcasing a blend of indigenous and colonial influences (Lico, 2021). Continuous restoration efforts and structural reinforcements ensure the buildings' longevity while preserving their historical character (Cruz, 2017a). Environmental adaptation is evident in features like capiz shell windows, which allow for natural ventilation and light while filtering direct sunlight (Pahimnayan-Pagador et al., 2025). The use of local materials like brick and stones, hardwoods, terracotta roof tiles, and cobblestones further emphasize the city's architectural identity (Tabunan, 2022). While original materials are prioritized, the use of substitute materials like galvanized iron sheets is carefully considered to balance

preservation with practicality (Pahimnayan-Pagador et al., 2025). The fusion of Spanish and Chinese architectural styles is evident in the buildings' design, further enriched by intricate wood carvings, wrought iron grilles, and religious decorative elements, creating a unique and visually captivating streetscape (Amistad, 2010).

Non-Physical Features in Historic City of Vigan, Philippines

The city of Vigan in the Philippines benefits from a robust framework of non-physical features that contribute to the safeguarding of its cultural heritage. Stringent regulations and policies, including heritage zoning regulations and conservation guidelines, ensure that development respects the city's historical character (UNESCO, 2010). Funding initiatives, such as the UNESCO Heritage Emergency Funds, provide financial support for preservation efforts (Dolor et al., 2019). Institutionally, organizations like the City Government of Vigan and ICOMOS Philippines play a crucial role in overseeing conservation activities (Sur et al., 2024). Community participation is actively encouraged, with merchants and traders along the historic streets, community groups, and events like the Ilocos Sur Festival fostering a sense of shared responsibility for their heritage (Royce Chan, 2020). Furthermore, vibrant cultural practices, including the World Heritage Cities Solidarity Cultural Festival and various religious and cultural celebrations, ensure the continued relevance and vitality of Vigan's cultural heritage.



(Source: EAZY Traveller, flickr, 2025)

Figure 7. Binabatan Festival of the Arts at Historic City of Vigan, Philippines

DISCUSSION AND COMPARATIVE PERSPECTIVE

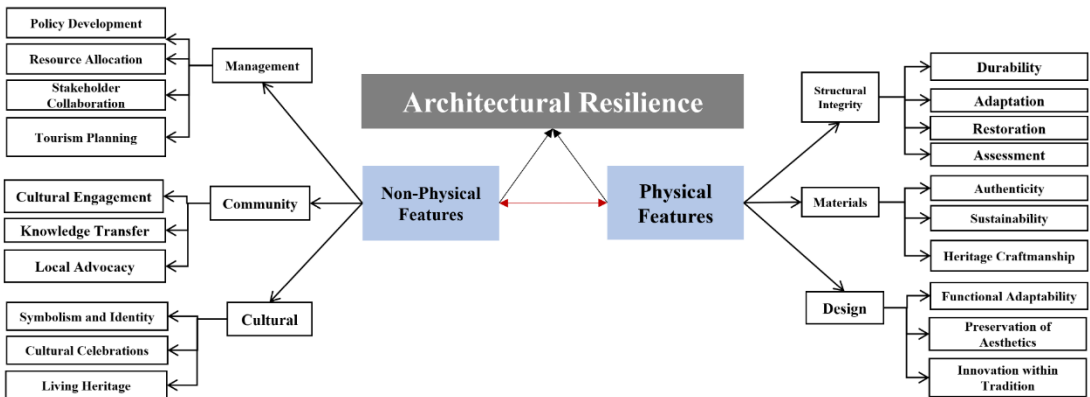
This study embarks on a comparative exploration of architectural resilience in Southeast Asia, focusing on the distinct yet interconnected heritage landscapes of George Town in Malaysia, and Vigan in the Philippines. By analysing the interplay of physical features, such as architectural styles and building materials, and non-physical aspects, including conservation policies and cultural practices, this comparative perspective seeks to unravel the diverse approaches employed in safeguarding their unique heritage. Through highlighting similarities, differences, and potential challenges, this analysis aims to extract valuable insights into the dynamics of urban heritage preservation in the region.

Table 1. Comparative Table Between Two Case Study

Features	Melaka and George Town: Historic City of The Straits of Malacca, Malaysia	Historic City of Vigan, Philippines	Key Factors
Physical Features			
Structural Integrity			
Structural System	Malay timber frame	<i>Bahay na Bato</i>	• Durability
	Portuguese & Dutch Colonial Influence.	Sturdy wooden structures	• Adaptation
	Shophouse with the arcade & Chinese style influence		• Restoration
Structural Condition	Restoration & structural reinforcements implemented	Restoration & structural reinforcements implemented	• Assessment
	Environmental Adaptation	Bamboo canopy as shading element	Capiz style windows panel
Materials			
Material Types	Tropical hardwoods	Brick & stones, hardwoods, terracotta roof tiles, cobblestones, galvanized iron sheets.	• Authenticity
	Laterite stone, clay roof tiles, ceramic tiles, brick & timber		• Sustainability
Material Authenticity	Original materials still in use & use of substitute materials	Original materials still in use & use of substitute materials	• Heritage Craftmanship
Design			
Architectural Styles	Traditional Malay, Portuguese, Dutch, and Chinese Style Influence	Spain-Chinesse Architecture style	• Functional Adaptability
Decorative Elements	European & Chinese style elements	Intricate woodcarving, wrought iron grilles, religious decorative element	• Preservation of Aesthetics
	Ceramic tiles, woodcarving		• Innovation within Tradition
Non-Physical Features			
Management			
Regulations & Policies	Zoning regulations, building codes, conservation guidelines	Heritage zoning regulations, conservation guidelines	• Policy Development
Funding	George Town Heritage Habitat Seed Fund, Incentives	UNESCO Heritage Emergency Funds	• Resource Allocation
Institutional	George Town World Heritage Incorporated	City Government of Vigan	• Stakeholder Collaboration
	The Penang Government	ICOMOS Philippines	• Tourism Planning
Community			
Community Participation	George Town World Heritage Incorporated, Community Groups	Merchant & Traders along the streets	• Cultural Engagement
	George Town Heritage Festival	Community Groups	• Knowledge Transfer
	Building Maintenance Incentives	Ilocos Sur Festival	• Local Advocacy
Cultural			
Cultural Practice	Performing Arts, Culinary Experience, George Town Heritage Festival, Religious & Cultural Celebrations	World heritage Cities Solidarity Cultural Festival	• Symbolism and Identity
		Religious & Cultural Celebrations	• Cultural Celebration
			• Living Heritage

A striking commonality between the historic cities of George Town and Vigan lies in their shared experience of colonial influence, deeply embedded in their architectural styles. George Town exhibits a captivating blend of Portuguese, Dutch, and British influences, Vigan stands as a testament to Spanish colonial grandeur. Despite their distinct colonial pasts, both locations prioritize the use of original materials in restoration efforts, recognizing their crucial

role in preserving architectural authenticity. However, they also acknowledge the practical limitations and embrace the use of substitute materials when necessary, striking a balance between preservation and practicality. Furthermore, both demonstrate a keen understanding of their tropical climate, incorporating architectural features that promote natural ventilation and shade. Beyond the physical, both locations recognize the importance of community engagement in heritage preservation, fostering active participation from residents, merchants, and community groups. This shared emphasis on community involvement contributes to the vibrant cultural tapestry of both locations, evident in their numerous festivals, culinary traditions, and religious practices.



(Source: Author)

Figure 8. Proposed Framework for Physical and Non-Physical Features in Architectural Resilience

Physical Features

Architectural resilience in Vigan and George Town is established through a combination of factors, prominently featuring structural integrity, materials, and design. Structural integrity is maintained by leveraging the durability of traditional vernacular structures in Vigan (Pahimnayan-Pagador et al., 2025) and heritage building techniques in George Town (Lee et al., 2008), adapting them to modern needs through careful restoration assessment (Sementsov et al., 2020). The materials used prioritize authenticity by employing original or similar substitutes, emphasizing sustainability and heritage craftsmanship. Design considerations balance functional adaptability with the preservation of aesthetics, fostering innovation within the traditional style mandated by their status as World Heritage sites, ensuring that buildings can accommodate new functions while retaining their historical character (Sinibaldi & Parente, 2020).

Non-Physical Features

Architectural resilience in Vigan and George Town is significantly shaped by management strategies, community involvement, and vibrant cultural practices. Management includes policy development, resource allocation, stakeholder collaboration, and tourism planning. The presence of funding and incentives is crucial for the ongoing preservation of heritage buildings, ensuring their maintenance and upkeep (Jha et al., 2013; Shao et al., 2016). George Town's heritage management is self-directed by the GTWHI and Penang government, while Vigan relies on the Vigan City Government and ICOMOS Philippines. Community

engagement is fostered through cultural activities, knowledge transfer, and local advocacy. The GTWHI in George Town stimulates the local economy and enhances urban vitality, while Vigan benefits from active community groups and festivals that promote cultural pride. Cultural practices, such as symbolism and identity, cultural celebrations, and living heritage, further reinforce architectural resilience. Both cities host various festivals and maintain cultural practices that animate their heritage spaces, preserving their unique identities. This community involvement symbolizes a ground-up approach to heritage conservation characterized by stewardship, cultural pride, knowledge transfer, and advocacy, leading to sustainable preservation tailored to each city's unique context.

SUMMARY

George Town and Vigan, despite their geographical distance, share a commitment to preserving their distinct architectural heritage. Both demonstrate a deep respect for their colonial past, prioritizing original materials in restoration and incorporating climate-responsive design. Community engagement is paramount in both locations, contributing to their vibrant cultural landscapes.

Historical Context

The historical development of George Town and Vigan significantly shaped their respective approaches to architectural resilience. As a bustling port city, George Town's history fostered a dynamic fusion of Malay, Chinese, and European influences, resulting in a diverse architectural landscape (Omar et al., 2013). This history likely instilled a culture of adaptability and innovation, leading to a more flexible approach to building and preservation, with a greater emphasis on integrating new uses and technologies into existing structures. In contrast, Vigan's development as a Spanish colonial center led to a more homogenous architectural style, characterized by the *bahay na bato* (Pahimnayan-Pagador et al., 2025). This architectural consistency may have fostered a preservation approach centered on maintaining the authenticity of the built environment, reflecting a specific historical identity. Examining these distinct historical trajectories is crucial for understanding the nuances of their resilience strategies.

Governance and Policy

Governance and policy frameworks play a crucial role in shaping architectural resilience efforts in George Town and Vigan. As a designated UNESCO World Heritage Site, George Town likely benefits from more comprehensive management plans and dedicated funding opportunities, which can facilitate large-scale preservation projects and enforce stricter building codes to maintain its heritage values (Mahmoud et al., 2021; Siang, 2023). These policies can ensure that new developments are sympathetic to the existing architectural character and that conservation efforts are aligned with international standards. Vigan, while also recognized for its historical significance, may operate under a different set of regulations and funding mechanisms, potentially impacting the scale and scope of its preservation initiatives. Local support is vital for involving the community, conserving heritage, and participating in decision-making.

Economic Factors

Economic factors, particularly tourism and local industries, significantly influence the resilience strategies of George Town and Vigan. George Town, as a more established tourist destination, faces the challenge of balancing tourism growth with heritage conservation (Farahani et al., 2012). The influx of tourists can strain resources, potentially leading to the degradation of historic sites and the displacement of local communities. Therefore, resilience strategies in George Town must prioritize sustainable tourism practices that minimize negative impacts on the built environment and maximize benefits for local residents. Vigan, while also attracting tourists, may have more opportunities to manage tourism in a way that supports local industries and promotes cultural heritage. For example, Vigan integrates traditional festivities within its heritage sites, serving as living venues for cultural exchange and celebration (Cruz, 2017; Rodiris, 2021). By fostering a symbiotic relationship between tourism and local businesses, Vigan can enhance its economic resilience while preserving its cultural identity.

However, differences emerge in their architectural styles and urban fabrics, reflecting their unique histories and scales. George Town, as bustling port cities, possess a more diverse and layered urban fabric compared to Vigan's intimate atmosphere. These differences influence their management approaches and the challenges they face in balancing tourism growth with heritage conservation. Ultimately, both offer valuable insights into preserving architectural heritage in Southeast Asia, emphasizing contextual sensitivity, community engagement, and a balanced approach to conservation.

CONCLUSION & RECOMMENDATION FOR FUTURE RESEARCH

Architectural Resilience at UNESCO World Heritage Sites

Architectural resilience, particularly within UNESCO World Heritage Sites, encompasses the capacity of buildings and urban environments to withstand various disturbances, both physical and non-physical. While the physical aspects of architecture, like materials, design and structural, are crucial for withstanding environmental stresses, they are insufficient alone. Effective architectural resilience also demands robust non-physical factors, including supportive policies, active community engagement, adaptive management, and preservation of cultural values. These intangible elements ensure that buildings are not only physically sound but also culturally relevant and socially valued. As seen in Vigan and George Town, a holistic approach integrates tangible and intangible aspects to create environments that adapt and thrive. This involves community involvement, cultural pride, knowledge transfer, and advocacy, tailored to each city's unique context. Intangible heritage conservation, encompassing stories, rituals, and traditions, further enriches these sites. Ultimately, architectural resilience in heritage sites fosters a sense of identity and invites active participation in cultural life, enhancing their status as dynamic UNESCO World Heritage Sites.

Policy Implications and Recommendations

The lessons learned from Vigan and George Town suggest several policy implications for heritage managers worldwide. Firstly, it is crucial to integrate intangible heritage conservation

with tangible architectural preservation, recognizing the importance of cultural practices and community engagement in sustaining heritage sites. Secondly, adaptive reuse policies should be encouraged to ensure heritage buildings remain functional and economically viable components of urban life. Finally, sustainable tourism strategies must be developed to minimize negative impacts on heritage sites while maximizing benefits for local communities. The resilience of Vigan and George Town's architectural heritage serves as a compelling testament to the enduring impact of history on urban landscapes. Their stories provide valuable lessons for heritage conservation and community engagement, solidifying their status as exemplary models for sustainable urban living within the context of UNESCO World Heritage Sites.

Recommendations for Future Research

Vigan and George Town showcase architectural resilience in UNESCO World Heritage Sites, balancing sustainable urban living with cultural identities. Future research should explore the long-term sustainability of conservation efforts, assessing current strategies and tourism's impact. Incorporating qualitative research, such as understanding local perceptions and experiences, would provide richer insights into the socio-cultural dynamics of heritage conservation. A comparative study of socio-economic impacts would further reveal heritage conservation's contribution to community well-being. Their resilience offers valuable lessons for heritage conservation and engagement, marking them as models for sustainable urban living.

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SATISFACTION ON SUSTAINABLE FACILITIES MANAGEMENT CONCEPT OF ELDERLY PONDOK VILLAGE (EPV) BUILDINGS

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Abstract

In Malaysia, by 2030, 15% of the Malaysian population will be above 60 years of age and in year 2050 this group of people is projected to reach 23%. Religious education for elderly in Pondok Village in Malaysia has experienced growth over the years. The existing pondok facilities are already built across all states in Malaysia; most of them without considerations of climate and environmental impact, hence there is a need for a Facilities Management (FM) transformation to take place to align the developments of "Pondok" with visions of a sustainable future. This paper evaluates facility satisfaction levels in Malaysian Pondok Institutions and proposes strategic management solutions to enhance their performance. Therefore, the objectives are to rank the satisfaction level of 2 EPVs and to propose a model of Elderly Pondok Village (EPV) for pondok institutions. Mixed method research design was employed, using questionnaire survey for the quantitative part and analysed using SPSS, while the qualitative data was obtained through photo analysis. The findings highlighted the most important facilities needed for elderly residents in EPV and identify key factors that foster cultural sustainability. The implementation of these suggested facilities promotes sustainability and green concepts.

Keywords: *Elderly Pondok Village; Elderly; Facilities Management; Sustainable FM*

INTRODUCTION

The existing pondok concept in Malaysia, mostly built without consideration of climate and environmental impact. Facilities in PV transformation are in need to take place to align the "Pondok" with visions of a sustainable future. The key challenge of managing Elderly Pondok Village (EPV) to date is to ensure efficient and proper management practices to meet demand from the society. The right management practices will contribute to PV performance on the facilities management of pondok facilities. The development of EPV is normally based on very basic facilities. This has been a concept since decade ago, yet PVs are mushrooming with different levels of facilities and upgraded from time to time based on the needs of the residents. Osei-Kyei, Tam, and Ma (2021) discovered 27 critical success factors that have the potential for retirement village success in their study on the development of retirement villages are related to sustainability: "age-friendly village design," "appropriate location," "reliable and accessible health and physical facilities," and "effective social inclusion and integration in villages."

Therefore, needs, expectations and aspirations of the society in the urban and rural areas may differ greatly due urban. With a limited number of PV with proper facilities that can give better quality service to elderly will make them lack options, especially nowadays the elderly are educated and financially stable (Jumadi et al., 2019). From the issue highlighted, research objectives for this study are to identify and rank the most important sustainable elements for EPV. From this initial finding, Sustainable model of EPV is developed to foster the future of EPV existence in Malaysia.

LITERATURE REVIEW

Policy and Guidelines for EPV Development

Several retirement villages exist in Malaysia, including The Green Leaf (Sepang), AraGreens Residence (Ara Damansara), Green Acres (Ipoh), Eden-on-the Park (Kuching), Little Japan, Nobel Care retirement Resort and Sri Seronok (Cheras). These facilities primarily focus on providing leisure, comfort, and social wellbeing through medical and healthcare facilities, lifestyle amenities, clubhouses, live-in maid services, shopping facilities, and physical activity spaces. However, none of these retirement villages offers facilities that specifically cater to the needs of Muslim retirees. This highlights the need for developers to incorporate Muslim-specific amenities in their development plan amenities for Muslim retirees.

Some of the important components of an Islamic retirement village include the preservation of physical vitality, mental capacity, sleeping and resting facilities, food and drink necessities, mercy and love, sensitivity elevations, and women's priorities (Abdul Majid, Hamidi, & Denan, 2018). EPV should embody a dynamic concept by taking into account various factors, such as economic viability, social lifestyle, community sustainability, good values and practices, infrastructure, hygiene, health and safety, alongside religious elements. Ng, Lee, and Wu (2022) emphasize that perceptions of elder care are shaped not only by physical needs but also by cultural narratives and individual values regarding ageing, autonomy, and community belonging. Their study using design fiction suggests that creating environments that reflect the psychosocial and emotional priorities of seniors—such as identity, dignity, and purpose—can significantly influence acceptance and satisfaction with retirement living. In line with this perspective, there is an opportunity for developers to enhance the relevance and appeal of retirement villages by considering how facilities and services can better reflect the cultural and religious diversity of the elderly population, thereby offering more inclusive and meaningful living environments.

Facilities Management Concept

Facilities Management (FM) encompasses multidisciplinary work covering diverse activities, responsibilities, and knowledge domains, integrating into various organisational aspects. This is supported by Abdul Talib (2013) who emphasises that facilities management must ensure clean, safe and in a healthy environmental condition to achieve occupant satisfaction.

Kamaruzzaman and Ahmad Zawawi (2010), concluded in their research that all building types require regular supervision by dedicated maintenance teams to screen and assess the conditions of buildings. These management teams are typically led by maintenance or building managers. According to Nik Mat (2011), building managers oversee various services including maintenance, cleaning, landscaping, lighting, heating, ventilating and air conditioning (HVAC), lifts or escalators, mechanical and electrical systems, sanitary and plumbing facilities, access management, signage, parking and other related. For PVs, these aspects are particularly crucial as the occupants are elderly and may not be equipped to check and identify deficiencies or malfunctions in facilities. This may lead to decreased satisfaction levels regarding the facilities provided.

Sustainable Concept of Pondok System

The concept sustainability rests on three fundamental pillars; firstly, economic pillar which is related to income; secondly, social pillar which is related to human relationship and finally environment pillar which is related to lifestyle (Yakobu and Abdul Aziz, 2018). These three pillars must be integrated with the development process to ensure that the goals introduced by this model are achieved. The concept of sustainability was formally established during Agenda 21 in Rio De Janeiro in 1992, which the Malaysian government is committed to follow for sustainable development. Sustainable development is relevant from an Islamic perspective in the sense that it seeks a balance between economy, society, and the environment, and measures economic performance by putting spiritual or non-material needs on the same footing as material needs. A *Pondok* Village (PV) functions as a community for elderly residents that offers comfortable accommodation, services, and facilities. In fact, it should establish a conducive living environment where elderly residents feel comfort and satisfaction. The PV concept has evolved to incorporate similar features to a retirement village in developed nations. Abdul Majid, Hamidi & Denan (2019), note that the concept created in the retirement village aims to provide a well-maintained, current and age-friendly environment for the elderly. This aligns with Hu et al.'s (2015) identification of four significant types of social support relevant to elderly care which are emotional social support, companionship support, instrumental support, and informational social support. A conducive PV should therefore provide residents with an excellent living environment by providing basic essentials and sustainable needs, which include physical environment, available facilities, and accessibility while addressing the ergonomic requirements of the elderly community.

Research by Yakobu and Abdul Aziz (2018) retrieved the key criteria for retirement villages which include religious factors to suit the needs of modern lifestyle requirements for the elderly such as a resort-like environment, which should be well-equipped with modern knowledge resources, sustainable green features and accessible medical facilities. The proposed resort concept of EPVs can be achieved through the provision of appropriate facilities and an atmosphere that is evoked through building design as well as the architectural styles that accommodate elderly residents' limited mobility between buildings. Facilities like ample parks, lakes, and garden with sports and recreational amenities should be provided to encourage healthy lifestyles among residents. A conducive retirement village is based on five elements: basic needs, sustainability agenda, affordability, social activities, and location of the Retirement Village (RV) (Abdul Majid Hamidi & Denan, 2019). Furthermore, Kojetin et al. (2005) emphasise that the features of sustainability should be added in the concepts of retirement village. The housing design should support their therapeutic needs like green landscapes, natural soothing views, good air quality, energy efficiency, security and easily accessible accommodations.

PVs have evolved by applying similar concept to a retirement village in developed nations. Abdul Majid Hamidi, & Denan (2019) highlight that the concept created in the retirement village is to have a well-maintained, current and age-friendly environment for the elderly. This concept aligns with Hu et al.'s (2015) significant review identifying of four types of social support of relevance to elderly care namely emotional social support, companionship support, instrumental support, and informational social support. In addition, a framework incorporating social capital, social support, and social safety net (3S) for elderly care has emerged as an effective approach to understand the sustainability concept within religious

communities. Therefore, by creating a sustainable EPV, the issues of unaffordability and social isolation could be addressed. A conducive EPV should provide residents with excellent living environment by providing basic essentials and sustainable needs, which includes physical environment, available facilities, and accessibility while addressing the ergonomic requirements of elderly community. Further supporting this view, Rodríguez-Martínez, Martín Cano, de la Fuente Robles, and Jiménez-Delgado (2023) emphasise that specific facility characteristics—such as spatial layout, safety features, and the overall built environment—significantly influence the quality of life of older adult residents.

Facilities like ample parks, lakes, and garden with sports and recreational facilities should be provided to promote healthy lifestyle among the residents. A conducive retirement village is based on five essential elements: basic needs, sustainability agenda, affordability, social activities, and location of the retirement village (Abdul Majid Hamidi, & Denan 2019). According to Kojetin et al. (2005), the sustainability features should be integrated into the concept of retirement village, with housing design supporting their therapeutic needs through green landscapes, natural soothing view, good air quality, energy efficiency, security and accessible accommodations. EPVs in Malaysia are developed by private individuals or organisations, hence the lesser priority placed on the maintenance planning due to financial constraints.

Ejau et al. (2021) reinforce this view by highlighting that sustainable retirement villages should address not only environmental and economic dimensions but also the social needs of the ageing population. Therefore, it is crucial that the management of eldercare centres such as Pondok-style facilities receive adequate support and oversight from local municipalities (Ache & WohnBund-Beratung, 2012). Since most Elderly Pondok Villages (EPVs) in Malaysia are initiated by individuals or private entities, long-term maintenance planning is often deprioritized due to limited financial resources. A collaborative effort involving both public and private sectors may help strengthen the sustainability and functionality of these facilities.

METHODOLOGY

This study adopted a mixed-method approach, combining interviews, observations, and a questionnaire survey to explore sustainable practices in selected *pondok* institutions in Malaysia. The data from questionnaires survey was analysed by generating the categories of data with a descriptive analysis method by using Statistical Package for the Social Sciences (SPSS) Software Version 25.0. A purposive sampling technique was employed in this study to identify key participants with relevant knowledge and experience related to the management and residency in sustainable *pondoks*. Two *pondoks* were purposively selected for the study in two states in Malaysia, namely Pondok Al-Baraqah (PAB) in Manjoi, Perak. and Yayasan Al-Jenderami (YAJ) in Jenderam, Selangor. Selection based on their active involvement in sustainability initiatives and well-established Islamic institutions. The study involved two key respondent groups, the *pondok* management teams and elderly residents aged 60 and above.

Data collection commenced with semi-structured interviews conducted with the management team known as pondok operator during on-site visits to derive the development of questionnaire survey. Concurrently, non-participant observations were conducted, through

the systematically documented the physical setting and residents' daily activities using photographic evidence. Visual data was analysed according to the four sustainable themes, namely (i) environmental (ii) Social, (iii) financial and (iv) Design and Facilities. The questionnaire survey targeted 150 elderly residents, with 114 valid responses (YAJ, 66 respondents and PAB 48 respondents), collected through both hardcopy (distributed during Islamic programs) and online formats (Google Forms). For analysis, survey data were processed using SPSS Version 25.0, applying descriptive statistics to examine patterns in residents' satisfaction and perceptions. Interview data were analysed using content analysis, allowing key themes from management perspectives to be identified and interpreted.

Table 1. Rank of Satisfaction Level for Yayasan Al-Jenderami

No.	Case Study A (Yayasan Al Jenderami, N : 66)	Mean Score
1	Menyediakan bekalan air yang selamat dan bersih <i>Clean and save (treatment) water supply</i>	4.45
2	Rumah dpt dikunci dan diselenggara dengan baik cth: Pintu dan tingkap untuk perlindungan isi rumah <i>Proper lock and regularly maintain i.e all opening such as window</i>	4.40
3	Kemudahan pembersihan sentiasa tersedia dan dalam keadaan baik <i>Proper cleaning service available at times</i>	4.27
4	sistem perpaipan berada dalam keadaan baik <i>Good and manageable piping system</i>	4.27
5	Perabot dan kelengkapan di dalam rumah mestilah sentiasa dalam keadaan selamat dan tiada bucu tajam bagi mengelakkan kemalangan dan sebarang kerosakan <i>Furniture are in safe position and not harming and avoiding potential accident</i>	4.25
6	Sediakan penapis air untuk diminum atau digunakan seisi rumah <i>Water filter are available</i>	4.23
7	Kelembapan di dalam rumah boleh di kawal dengan baik <i>Dampness is not harmful and in a good condition</i>	4.17
8	Maksimumkan privasi di dalam rumah. Cth: keadaan tingkap bilik dan dapur <i>Maximum privacy in the house i.e window and kitchen</i>	4.17
9	Sistem keselamatan yag berfungsi dgn baik <i>Safety systems are functional</i>	4.06
10	Tiada sambungan, plug dan soket di tempat yang bahaya spt kawasan dapur dan bilik air <i>No harmful plaque at kitchen and toilet</i>	4.04
11	Produk mesra alam di siling, dinding, lantai, perabot, kemasan, perabot dan kelengkapan <i>Environmentally friendly product furnishes for ceiling, floor, furniture and others</i>	4.04
12	Persekitaran tidak mempunyai serangga perosak <i>Surrounding has no harmful insects</i>	3.85
13	Integrasi sistem suria. Cth: pemanasan air dan pengeluaran elektrik <i>Solar systems are used ie for water heater or electric consumption</i>	3.56
14	Bersedia untuk Kebakaran - Pemasangan penggera asap dan alat pemadam kebakaran <i>Smoke alarm system are available</i>	3.50
15	Kalis bunyi disembur pada dinding dan siling untuk mengelakkan bunyi yang berlebihan. <i>Sound protections are used for walls and ceiling to avoid unnecessary sound absorb into the house</i>	3.46
16	Sediakan sistem pintar terutamanya CCTV atau penggera di sekitar rumah <i>CCTV are used at surrounding of the house compound</i>	3.39

Table 2. Rank of Satisfaction Level for Pondok Al-Barakah

No.	Case Study B (Pondok Al Barakah, N : 48)	Mean Score
1	Rumah dpt dikunci dan diselenggara dengan baik cth: Pintu dan tingkap untuk perlindungan isi rumah <i>Proper lock and regularly maintain i.e all opening such as window</i>	4.29
2	Tiada sambungan, plug dan soket di tempat yang bahaya spt kawasan dapur dan bilik air <i>No harmful plaque at kitchen and toilet</i>	4.18
3	Perabot dan kelengkapan di dalam rumah mestilah sentiasa dalam keadaan selamat dan tiada bucu tajam bagi mengelakkan kemalangan dan sebarang kerosakan <i>Furnitures are in safe position and not harming and avoiding potential accident</i>	4.17
4	Menyediakan bekalan air yang selamat dan bersih <i>Clean and save (treatment) water supply</i>	4.15
5	Maksimumkan privasi di dalam rumah. Cth: keadaan tingkap bilik dan dapur <i>Maximum privacy in the house i.e. window and kitchen</i>	4.15
6	sistem perpaipan berada dalam keadaan baik <i>Safety systems are functional</i>	4.11
7	Kelembapan di dalam rumah boleh di kawal dengan baik <i>Dampness is not harmful and in a good condition</i>	4.08
8	Sistem keselamatan yang berfungsi dgn baik <i>Safety systems are functional</i>	4.08
9	Produk mesra alam di siling, dinding, lantai, perabot, kemasan, perabot dan kelengkapan <i>Environmentally friendly product furnishes for ceiling, floor, furniture, and others</i>	4.06
10	Kemudahan pembersihan sentiasa tersedia dan dalam keadaan baik <i>Proper cleaning service available at times</i>	4.00
11	Bersedia untuk Kebakaran - Pemasangan penggera asap dan alat pemadam kebakaran <i>Smoke alarm system are available</i>	3.97
12	Kalis bunyi disembur pada dinding dan siling untuk mengelakkan bunyi yang berlebihan. <i>Sound protections are used for walls and ceiling to avoid unnecessary sound absorb into the house</i>	3.94
13	Persekitaran tidak mempunyai serangga perosak <i>Surrounding has no harmful insects</i>	3.92
14	Sediakan sistem pintar terutamanya CCTV atau penggera di sekitar rumah <i>CCTV are used at surrounding of the house compound</i>	3.85
15	Sediakan penapis air untuk diminum atau digunakan seisi rumah <i>Water filters are available</i>	3.82
16	Integrasi sistem suria. Cth: pemanasan air dan pengeluaran elektrik <i>Solar systems are used ie for water heater or electric consumption</i>	3.67

RESULT AND DISCUSSION

Sustainable Elderly Pondok Village (EPV) Satisfaction Level

Table 1 and 2 present satisfaction level rankings from two selected EPVs; Yayasan Al-Jenderami (YAJ) and Pondok Al-Barakah (PAB). The analysis focuses on the first five most significant rankings only. These rankings represent the level of green concept implementation and sustainable initiatives provided in these two EPVs. The findings reveal that the five highest-ranked items in both EPVs predominantly relate elderly-specific concerns such as clean water system, safety, and privacy. According to Jolanki & Vilkkko (2015), these facilities require processes and services to preserve, repair, protect and maintain the building's fabric and engineering services after completion. Such maintenance includes repair, refurbishment or replacement to current standards. This is to enable EPV to serve its intended functions throughout its entire life span without drastically upsetting its basic features and use.

The preservation, repair, and care for a building's physical infrastructure and engineering systems; such as plumbing, ventilation, and safety mechanisms, are critical for sustaining long-term functionality. These maintenance processes are necessary to ensure the facility serves its intended function throughout its lifespan without significantly altering its fundamental characteristics (Jolanki & Vilkkö, 2015).

This aligns with Ferguson et al. (2022) study, which found that elderly residents' satisfaction in retirement villages was strongly tied to how well their basic expectations and living standards were met. Promoters (satisfied residents) appreciated reliable services and a sense of independence, while detractors (dissatisfied residents) expressed frustration with unmet promises, lack of responsiveness, and inadequate infrastructure. Thus, the findings from YAJ and PAB reinforce the notion that tangible, everyday needs such as water quality, safety, and privacy significantly contribute to residents' perceptions of satisfaction and well-being in elderly living environments.

As shown in Table 3 below, the five highest rankings are (i) clean and safe (treated) water supply (4.45), (ii) Proper lock and regular maintenance of all openings such as windows (4.40), (iii) Proper cleaning services available at times (4.27), (iv) Good and manageable piping system (4.27) and (v) Safely positioned furniture to prevent potential accidents (4.25). In PAB, green features rank lowest, therefore, more green features need to be implemented to generate environmentally friendly surrounding. Grum and Grum (2020) emphasise that facilitating living elements, such as physical home characteristics, safety neighbourhood, proximity to schools, public transport accessibility, parking facilities, and green spaces in neighbourhood, increase residents' satisfaction with their real estates and affect their overall quality of life. As shown in Figure 1 below, plate 01-04 proved that those highest ranks are available at this EPV. Plate 01 show good quality entrance door with proper lock. Plate 02 show there are privacy by having a party wall to divide house, Water filter at plate 03 is well maintain and there is no dangerous furniture in the house (plate 04).

Table 3. Top 5 Rank of Satisfaction Level for Pondok Al-Jenderami

No.	Case Study A (Yayasan Al Jenderami, N : 66)	Mean
1	Menyediakan bekalan air yang selamat dan bersih <i>Clean and save (treatment) water supply</i>	4.45
2	Rumah dpt dikunci dan diselenggara dengan baik contoh : Pintu dan tingkap untuk perlindungan isi rumah <i>Proper lock and regularly maintain i.e. all opening such as window</i>	4.40
3	Kemudahan pembersihan sentiasa tersedia dan dalam keadaan baik <i>Proper cleaning service available at times</i>	4.27
4	sistem perpaipan berada dalam keadaan baik <i>Good and manageable piping system</i>	4.27
5	Perabot dan kelengkapan di dalam rumah mestilah sentiasa dalam keadaan selamat dan tiada bucu tajam bagi mengelakkan kemalangan dan sebarang kerosakan <i>Furnitures are in safe position and not harming and avoiding potential accident</i>	4.25

It can be understood that these ranks are important features for healthy and save living i.e., good water supply and good piping system. For safety features, safe furniture and proper lock system are most important to avoid accident and burglary.

Although both elderly villages are in a good condition, there remains a need to increase and implement green initiatives such as providing recycle bins, solar energy systems, and

water harvesting mechanisms. These features can increase sustainability and environmental friendliness. Global citizenship calls for an active role from people in their community and the cooperation with others to make our planet more equitable, fair and sustainable. From a Facilities Management (FM) perspective side this raises questions about how to contribute to the enhancement of their awareness of social issues at the neighbourhood level (Osei-Kyei, Tam & Ma, 2021).

As shown in Figure 1 below, plate 01-04 provides visual evidence of these highly-ranked features available at this EPV. Plate 01 shows good quality entrance door with proper lock. Plate 02 show there are privacy measures by having a party wall for house division, Plate 03 displays well-maintained water filtration systems and Plate 04 illustrate safe furniture arrangement within the house. These findings reveal that that these rankings are important features being prioritised for healthy and safe living i.e., good water supply and good piping system. For safety features, safe furniture and proper lock system are the most important to avoid accident and burglary. Yet, green features ranked lower in priority, due less awareness of the elderly respondent on sustainable features. Therefore, need for more green features to be implemented to generate environmentally friendly as well can foster the awareness among elderly residents.



Figure 1. Pondok Yayasan Al-Jenderami

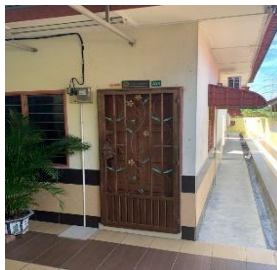
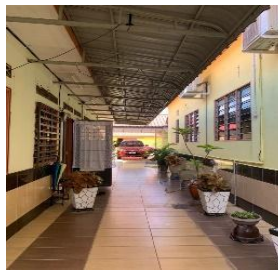
As shown in Table 4, the five highest rankings are (i) Proper lock and regular maintenance of all openings such as windows (4.29), (ii) Absence of harmful plaque in kitchen and toilet areas (4.18), (iii) Safely positioned furniture to prevent potential accidents (4.17), (iv) Clean and safe (treated) water supply (4.15) and (v) Maximum privacy within houses i.e., windows and kitchen areas (4.15).

The visual documentation from Plates 05 through Plate 08 (Figure 2) proved that those highest rankings are available at this EPV. Plate 05 shows that there is added security at the grilled entrance door with proper locking mechanism. Plate 06 shows privacy considerations because it has double frontage with no neighbouring units facing the entrance. Clean water supply for ablution is shown at Plate 07 which is well-maintained and there is no dangerous placement of furniture in the house (plate 08).

It can be understood that these rankings are important features for healthy and safe living i.e., good water supply. For safety features, safe positioning of furniture and proper locking system are the most important features to consider avoiding accident and burglary, as well as to ensure privacy.

Table 4. Top 5 Rank of Satisfaction Level for Pondok Al-Barakbah

No.	Case Study B (Pondok Al Barakah, N : 48)	Mean
1	Rumah dpt dikunci dan diselenggara dengan baik cth: Pintu dan tingkap untuk perlindungan isi rumah <i>Proper lock and regularly maintain i.e., all opening such as window</i>	4.29
2	Tiada sambungan, plug dan soket di tempat yang bahaya spt kawasan dapur dan bilik air <i>No harmful plaque at kitchen and toilet</i>	4.18
3	Perabot dan kelengkapan di dalam rumah mestilah sentiasa dalam keadaan selamat dan tiada bucu tajam bagi mengelakkan kemalangan dan sebarang kerosakan <i>Furniture is in safe position and not harming and avoiding potential accident</i>	4.17
4	Menyediakan bekalan air yang selamat dan bersih <i>Clean and save (treatment) water supply</i>	4.15
5	Maksimumkan privasi di dalam rumah. Cth: keadaan tingkap bilik dan dapur <i>Maximum privacy in the house i.e., window and kitchen</i>	4.15

Proper Lock/Grill
Plate 05Maximum Privacy
Plate 06Clean Water Supply
Plate 07Less Furniture
Plate 08**Figure 2.** Pondok Al-Barakbah

As for Pondok Al Baraqah, green features are at the least of the ranks, therefore, more green features need to be implemented to generate environmentally friendly surrounding. The facilitating living elements, such as physical home characteristics, safety neighbourhood, proximity to schools, public transports, parking, and green spaces in neighbourhood, increase peoples' satisfaction with their real estates and affect their quality of life (Grum and Grum, 2020).

However, both elderly villages are in a good condition but need to increase and imposed green initiatives such as recycle bin, solar energy, and water harvesting. These features can increase sustainable and environmentally friendly. Global citizenship calls for an active role from people in their community and the cooperation with others to make our planet more equal, fair and sustainable, what could be seen from FM side how to contribute to their awareness of social issues at neighbourhood (Osei-Kyei, Tam & Ma, 2021) As Chaudhury and Xu (2022) emphasized, the integration of sustainable and therapeutic environmental elements—such as natural systems and green infrastructure—not only supports ecological goals but also promotes the psychological and physical well-being of elderly residents.

Figure 3 (Plate 09 to Plate 16) shows elements that integrated green concepts in Pondok al-Baraqah (PAB). There are ornamental plants (Plate 09) and edible gardens (Plate 10) planted with strategic position/location, allowing natural watering from rainwater. The public toilet facilities (Plate 14) have ample space specially designed to allow wheelchair accessibility, is dry and clean, and has natural ventilation and natural lighting. Perimeter drains (Plate 15) are clean and well-maintained which promotes healthy living. Plate 12 shows

allowed large space of area that accommodates mobility-impaired residents while serving as emergency assembly points. The outdoor hall (Plate 13) is at an open space allowing natural air movement which reduces artificial lighting. Therefore, this observation reveals that while green concepts have been embedded and practiced within this PAB Pondok Village’s design and operation, it reflects minimum effort, low impact and cost-effective solutions.



Figure 3. YAJ (Plate 09 to 12) and PAB (Plate 13 to 16)

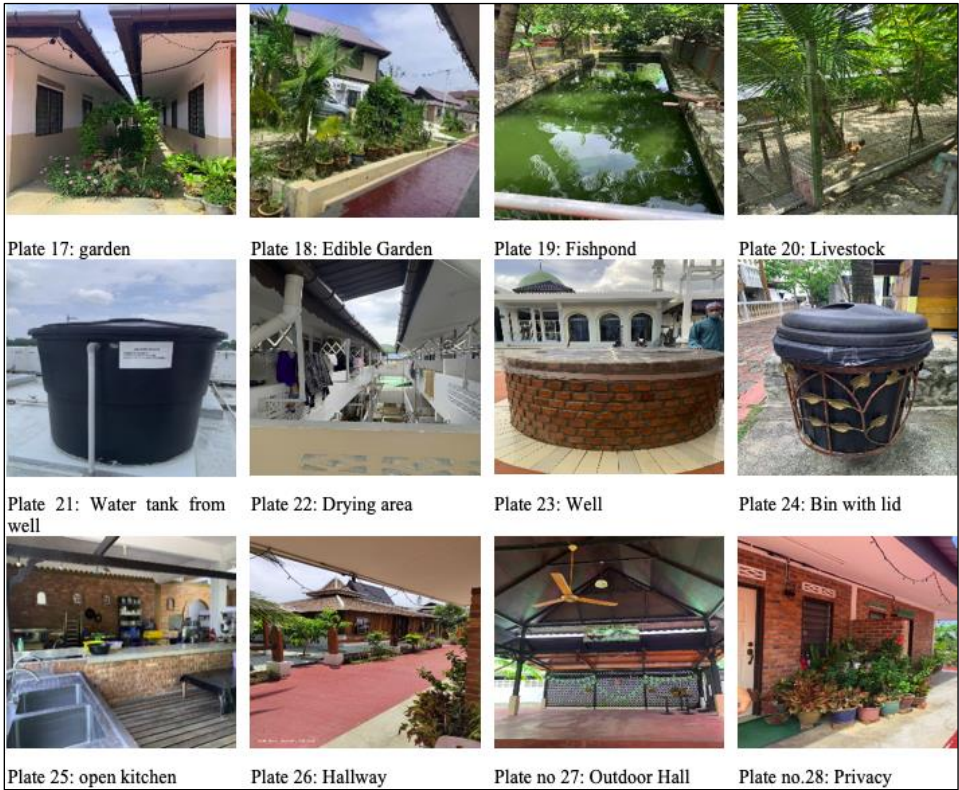


Figure 4. YAJ Sustainable Elements

Figure 4 (Plates 17-28) shows the elements that integrated green concepts in Yayasan Al-Jenderami (YAJ). There are ornamental gardens (Plate 17), and edible gardens (Plate 18) planted, and the position allows natural watering from rainwater. The fishpond (Plate 19) and livestock facilities (Plate 20) allowed sustainable food production which saves money as well as providing access to healthy, non-GMO food sources. The purpose-built clotheslines (Plate 22) allow natural drying that saves energy. Rubish bins with lids and cages (Plate 24) are available yet there are no recycling bins available. The designs for the entrance door (Plate 28) allows privacy. The open kitchen (plate 25) is clean and well-maintained, with natural ventilation and natural lighting. The hallway (Plate 26) with large space accommodates mobility-impaired residents. The open-concept outdoor halls (Plate 27) allow natural air movement and reduce artificial lighting requirements. A man-made well that was dug decades ago (Plate 24) is properly maintained, where the water is collected to a water tank located at the roof top for treatment. Treated water from the well is then bottled and sold to generate income. Therefore, this observation confirms that comprehensive green concepts have been embedded and practiced in this PAB Pondok Village.

Based on Figure 5, a Sustainable Model for EPV has been developed to conceptualise the theoretical framework and findings based on environmental issues found on site. Four sustainable concepts developed from the findings are, (i) Natural Energy Concept (NEC) i.e. solar energy, (ii) Natural Water (NW) incorporating water harvesting system and (iii) Waste Management (WM) featuring recycling facilities. This Sustainable Model encompassed three Sustainable Green Concepts (SGC) to support a holistic approach to EPV development and operation. Expert on green technology and authority should play an important role in realizing these concepts such as giving support on grant, land swap, knowledge transfers by related bodies. These initiatives by government can improve environment and financial. Financial capability is important element to integrate green features in EPV.

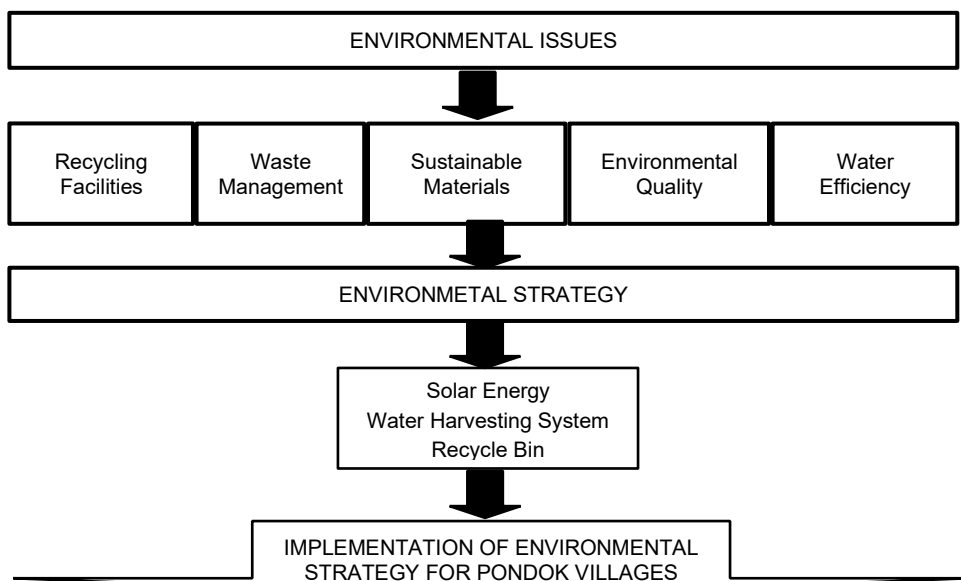


Figure 5. Sustainable Model for Elderly Pondok Village (EPV)

Three SGC mentioned can be visualized in EPVs through low-impact approaches by collaboration, knowledge sharing and crowd-funding initiatives. Firstly, Natural Energy Concept (NEC) like solar energy needs capital, however *Pondok* operators can collaborate with NGOs and related bodies such as Tenaga Nasional Berhad (TNB), University and Solar company to build solar panels. For the second concept, Natural Water (NW), water harvesting can be developed to be low-impact and require low-technology for irrigating edible gardens, feeding livestock or maintaining fishpond. These initiatives can reduce operational cost as well as increase social interaction among residents. Alternatively, man-made wells can be dug to produce natural water for consumption or just for watering and general cleaning purposes. Thirdly, Waste Management (WM) initiatives such as recycling rubbish can support green environment. Those recycled stuff can be sold to recycling companies to generate income. This approach can improve financial ability to run EPVs, where it can reduce utility bills as well as generating income by selling recycle material. The take-away concept of this research is that the quality of social infrastructure leads to the general quality of life in the built environment and that is rounded up to social sustainability and finally resilient EPV.

CONCLUSION

Green technology experts and relevant authorities should play important roles in realizing these sustainable concepts such as giving support on grants, land-swap arrangements, as well as knowledge transfer programmes facilitated by related bodies. Government-led initiatives can improve environmental sustainability and financial viability. Financial capability is an important element to integrate green features in EPVs. Knowledge and awareness also need to be integrated among pondok operator, tenants as well as other related authority. Through coordinated efforts, such as environmental education programs, community clean-up campaigns, and green facility operations. The Facilities management team can contribute meaningfully to the creation of socially conscious and environmentally responsible elderly communities.

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SUSTAINABLE CONCEPT FOR LOW-INCOME HOUSING OF GRIYA MAHONI ALPEN HOUSING ESTATE IN WEST ACEH

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Abstract

Housing policy and practice play a critical role in promoting regional sustainable development, which encompasses environmental, social, and economic dimensions. While sustainability principles have been adopted across various sectors, their application in the housing sector, particularly in low-income residential areas, remains limited. Residents in these communities frequently modify their homes to accommodate evolving needs. However, in the absence of clear planning guidelines, such informal changes can contribute to environmental degradation and undermine sustainable development goals. This study aims to evaluate the implementation of sustainable housing principles and develop a design strategy for the Griya Mahoni Alpen housing complex using a mixed-method approach. A descriptive quantitative method with an evaluative framework was applied, utilizing the Greenship Neighbourhood rating system by the Green Building Council Indonesia (GBCI) to assess sustainability indicators. Simultaneously, descriptive qualitative approaches were employed to analyse the existing conditions through observation, interviews, and literature review. The data were examined using content analysis and presented descriptively. The findings reveal that the Griya Mahoni Alpen housing complex received a Bronze rating, indicating that while some basic features of sustainable housing have been implemented, the overall adoption of green design principles remains limited. Based on these results, the study proposes a set of context-specific design guidelines to enhance environmental performance while reducing ecological impact.

Keywords: *Griya Mahoni Alpen; Housing Estate; Low-Income Housing; Sustainable Concept; West Aceh*

INTRODUCTION

The rapid increase in population has led to a substantial rise in the demand for housing. This growing demand, however, is not matched by the purchasing capacity of many citizens, particularly those in the lower-income brackets, thereby intensifying the housing affordability crisis. In response, subsidized housing has emerged as a strategic policy instrument aimed at mitigating this issue. As stipulated in Ministerial Regulation No. 27 of 2012, the provision of subsidized housing is governed by specific procedures that necessitate coordination with accredited housing developers, who are responsible for constructing and delivering adequate and affordable housing units for low-income communities.

In many developing countries, housing development among low-income populations is frequently characterized by self-initiated efforts (Tipple, 1992; Oni & Famutimi, 2022). Residents often undertake the modification or expansion of their dwelling units independently, typically in the absence of formal planning or compliance with regulatory standards (Aduwo & Ibem, 2017). Consequently, a significant proportion of these housing units fail to meet basic liveability standards and may pose risks to public health (Landman, 2006). In more severe instances, such unregulated housing practices contribute to the proliferation of informal settlements and slum areas (Warouw, 2014).

When low-income communities build their homes, the resulting structures frequently have inadequate planning, disorganized layouts, poor infrastructure, and insufficient waste management systems. These conditions negatively affect both the quality of life within the dwellings and the surrounding environment (Panudju, 1999). Research indicates that unplanned housing transformations, which do not incorporate architectural principles, often lead to uninhabitable living conditions (Mastutie et al., 2016). Additional consequences include higher utility costs, insufficient ventilation and lighting, and inefficient use of natural resources (Sueca, 2004; Ibrahim et al., 2020).

The implementation of sustainable housing, particularly in Indonesia, holds significant potential to address multiple challenges simultaneously, including natural resource conservation, a healthy living environment, and ecosystem protection (Larasati, 2006). Although sustainable development has been integrated into various policy frameworks in developing countries, including Indonesia, such as those promoted by UN-Habitat (2012)—its practical application in the planning and building of subsidized housing remains limited. Recent studies indicate that the level of sustainable development implementation in low-income housing projects is still considerably low (Aini et al., 2021; Hamid et al., 2018; Zakiah, 2023).

Sustainability in housing can be pursued at all stages of development, including planning, implementation, occupancy, and post-occupancy adjustments (Sudarwanto et al., 2014). This study focuses on the occupancy phase of the Griya Mahoni Alpen housing complex in West Aceh, which is considered a critical stage due to its significant impact on both the current quality of life and the future development of residential conditions. Therefore, this research aims to assess the implementation of sustainable housing practices in Griya Mahoni Alpen and to develop a sustainable housing concept specifically tailored to the unique circumstances and needs of this housing estate.

LITERATURE REVIEW

Subsidized Housing and Development

Subsidized housing refers to state-supported financing schemes designed to alleviate housing shortages and facilitate access to adequate and affordable housing for low-income households (Ayu & Elena, 2019). Rapoport, as cited in Saud and Aufa (2012), conceptualizes the home as a dynamic space of human activity that embodies residents' behaviours and modes of self-expression. This understanding underscores the evolving nature of human habitation, wherein the residential environment is continually adapted to meet the shifting needs and aspirations of its occupants. Accordingly, subsidized housing, like other forms of dwelling, is inherently subject to transformation over time as residents respond to changing socio-economic and personal circumstances.

Pakilaran (2006) identified economic and socio-cultural factors as key drivers of change within built environments, including housing. In particular, residents are more likely to make changes to their homes when economic conditions improve. Similarly, Sueca (2005) observed that individuals with more economic capacity prefer to seek better housing conditions and are therefore more likely to upgrade or remodel their residences.

Snyder and Catanese (1989) further emphasized that residential environments are not merely the result of architectural design or physical infrastructure but are fundamentally shaped by the dynamic interplay between human activities and environmental settings. These settings encompass both physical elements—such as buildings, spatial layouts, and natural surroundings—and non-physical factors, including socio-cultural norms, community values, and behavioural patterns. This interaction between people and their environment plays a crucial role in shaping the spatial organization of housing areas, influencing how spaces are used, adapted, and experienced. Moreover, it affects patterns of daily life, community interactions, and even the trajectory of long-term urban and social development. Understanding this relationship is essential for creating residential environments that are not only functional and aesthetically pleasing, but also socially and environmentally sustainable.

Recent studies, moreover, provide empirical support for these theoretical insights. For example, Oni & Famutimi (2022) documented transformations in Nigerian public housing as a result of shifting wealth and cultural practices. Similarly, Ibrahim et al. (2020) highlighted the prevalence of informal, self-initiated housing modifications in Indonesia's low-cost residential areas. These changes, while necessary, frequently result in disorganized layouts and environmentally unsustainable conditions.

Sustainable Housing

Sustainable housing entails the integration of ecological, economic, and social considerations into the planning, construction, and utilization of residential environments (UN-Habitat, 2012). Yakob, as cited in Rosilawati (2016), expands this notion by identifying four key dimensions of sustainability in housing: environmental, social, cultural, and economic. In this context, a sustainable home is expected to be energy-efficient, health-promoting, and adaptable, with the capacity to respond to the evolving needs and lifestyles of its inhabitants over time.

Larasati (2006) emphasized the significance of adaptability in sustainable housing, stating that dwellings should allow for both pre-occupancy and post-occupancy modifications while maintaining their environmental performance. This perspective is particularly relevant in the context of low-income housing, where user-initiated changes are prevalent. Recent studies in Indonesia supported this viewpoint. For example, Aini et al. (2021), examined low-income housing sustainability through an ecological framework, whereas Kerihi et al. (2023) focused on access to water and household needs in Kupang City, demonstrating how local environmental conditions influence sustainable housing practices.

Furthermore, achieving sustainability in housing requires the implementation of various environmentally responsible strategies, such as rainwater harvesting systems, the preservation of green open spaces, thermal insulation, and the use of locally sourced or recycled materials (Syahriyah, 2017; Green Building Council Indonesia, 2014). These strategies contribute to long-term affordability and resilience while reducing the environmental footprint of housing developments.

METHODOLOGY

This study employs a mixed-methods approach to assess the application of sustainable housing principles within the Griya Mahoni Alpen Housing Estate and to develop contextually responsive design strategies. The research integrates both descriptive quantitative and descriptive qualitative methods, enabling a comprehensive analysis that captures measurable data as well as contextual and experiential insights.

Furthermore, the descriptive quantitative approach involves the application of the Greenship Neighbourhood Rating Tools developed by the Green Building Council Indonesia (GBCI). This assessment framework evaluates the environmental sustainability of residential neighbourhoods based on specific criteria, including rainwater management, energy efficiency, waste management, and overall environmental quality. Field data were collected through direct observations of existing conditions within the housing estate and subsequently analysed using the Greenship scoring system to determine the extent to which sustainability benchmarks are being met.

The descriptive qualitative approach entails the collection of primary data through observations and interviews with 20 households/homeowners of type 38 houses. The questionnaire was designed to investigate the factors influencing residents’ decisions to modify or expand their dwellings. Data collection tools included voice recorders and field notes during interviews. The interview data were subsequently transcribed and analysed using qualitative coding methods following the three-stage process proposed by Creswell (2015): open coding, axial coding, and selective coding. Furthermore, a literature review of academic journals, books, reports, and documents from relevant institutions was conducted to enrich the analysis.

Data obtained from both approaches were analysed using content analysis and presented descriptively, aiming to provide a comprehensive understanding of the sustainability level of the housing estate and to inform the development of environmentally responsive design strategies.

Criteria	Descriptor	Criteria	Descriptor
1 Appropriate Site Development	1. Green area 2. Supporting infrastructure 3. Community accessibility 4. Pest control 5. Public transportation 6. Handling of rainwater	4 Material Resource and Cycle	1. Non-ozone depleting refrigerant 2. Recycle material 3. Material from environmentally friendly sources 4. Materials with environmentally friendly production processes 5. Certified wood Prefabricated materials 6. Local material 7. Carbon print
2 Energy Efficiency and Conservation	1. Sub meter 2. Artificial lighting 3. Air conditioning 4. Heat reduction 5. Energy efficient household appliances 6. Renewable energy sources	5 Indoor Health and Comfort	1. Clean air circulation 2. Natural lighting 3. Visual comfort 4. Minimize pollutant sources 5. Noise level 6. Spatial comfort
3 Water Conservation	1. Water meter 2. Water saving devices 3. Recycle rainwater 4. Water saving irrigation 5. Wastewater management	6 Building Environment Management	1. Sustainable design and construction 2. Building guide for housing 3. Environmentally friendly activities 4. Waste management 5. Security 6. Innovation 7. Extended house design

(Source: Green Building Council Indonesia, 2014)

Figure 1. Criteria for Environmentally Friendly Residential Housing

To assess the environmental sustainability of the modified housing units, the study applied the Greenship Homes assessment tool developed by the Green Building Council Indonesia (GBCI). GBCI is a non-governmental organization committed to advancing sustainable building practices in Indonesia through education and certification programs. Its Greenship rating system encompasses five categories: Greenship Existing Building, Greenship New Building, Greenship Interior Building, Greenship Neighbourhood, and Greenship Homes. The Greenship Homes tool specifically evaluates residential properties, whether newly built, existing, or remodelled, based on sustainability criteria. In this study, it was utilized to assess the modified type 38 housing units during the occupancy phase in Griya Mahoni Alpen. The specific assessment criteria adopted from this tool are outlined in Figure 1.

RESULTS

Evaluation Results of Housing Conditions Based on Green Home Criteria at Griya Mahoni Alpen

Based on the assessment using the Greenship Homes Rating Tool developed by the Green Building Council Indonesia (GBCI), housing conditions at Griya Mahoni Alpen were evaluated according to a set of benchmarks. Each benchmark is assigned a specific credit value, reflecting the relative difficulty of its attainment. These credits collectively serve to measure the effectiveness of green housing implementation from the residents' perspective. In this assessment system, a perfect score of 100% is equivalent to a total of 60 points. The evaluation revealed that, while some green home criteria have been fulfilled, several indicators still fall short of the standards for environmentally friendly housing. The detailed findings are shown in the Table 1.

The assessment findings in the table above indicate a total score of 25 for the fulfilment of green home criteria at Griya Mahoni Alpen housing. This score reflects that the residential units currently achieve only a Bronze rating in terms of meeting green home standards.

A more detailed explanation of the assessment highlights several major shortcomings. First, no infrastructure exists to manage rainwater for alternative uses, such as irrigation or other non-potable applications, representing a missed opportunity for sustainable water management. In terms of energy efficiency, the use of energy-saving household appliances and automation systems has not been optimized, and no renewable energy sources have been integrated into the housing complex. Furthermore, water-saving devices, such as low-flow fixtures and efficient irrigation technologies, have yet to be implemented. From a building management perspective, no waste management system encourages the separation of recyclable, organic, and general waste, which could hinder broader environmental sustainability efforts. Additionally, the complex lacks a dedicated security system to ensure the safety and comfort of its residents. Finally, there are no established guidelines for residents who want to renovate their homes, which may result in inconsistencies and quality control issues in future modifications. Therefore, further improvements based on green home design concepts are strongly recommended to enhance the environmental performance of the housing complex and enable it to achieve higher rating levels, such as Silver, Gold, or even Platinum.

Table 1. Green Housing Assessment Evaluation

Criteria	Credit	Descriptor	Checklist
Appropriate Site Development	2	Green Area	✓
	1	Supporting infrastructure	✓
	1	Community accessibility	✓
	1	Integrated mosquito and fly control management	✓
	1	Rodent and cockroach infestation control	✓
	1	Public transportation	-
	2	Handling of Rainwater	-
	Score		5
Energy Efficiency of Conservation	1	Sub meter	✓
	2	Artificial lighting	✓
	1	Air Conditioning	-
	2	Heat reduction	✓
	2	Energy efficient household appliances	-
	2	Renewable energy sources	-
	Score		5
Water Conservation	1	Water meter	-
	3	Water saving devices	-
	1	Recycle rainwater	-
	1	Water saving irrigation	✓
	1	Using a septic Tank	✓
	Score		2
Material Resources and Cycle	1	Non-ozone depleting refrigerant	-
	1	Recycle material	-
	1	Materials from environmentally friendly sources	-
	1	Materials with environmentally friendly production processes	✓
	2	Certified wood Prefabricated materials	✓
	2	Local material	✓
	1	Carbon print	-
	Score		5
Indoor Health and Comfort	3	Clean air circulation	-
	1	Has ventilation in the bathroom	✓
	1	Has ventilation in the bedroom	-
	1	Has ventilation in the kitchen	✓
	2	Natural lighting	-
	1	Visual comfort	✓
	1	Minimize pollutant sources	-
	1	Noise level	✓
	1	Spatial comfort	-
	Score		4
Building Environment Management	2	Sustainable design and construction	-
	2	Building guide for housing	✓
	1	Environmentally friendly activities	✓
	1	Waste management	-
	1	Security	-
	1	Innovation	✓
	1	Extended house design	-
	Score		4

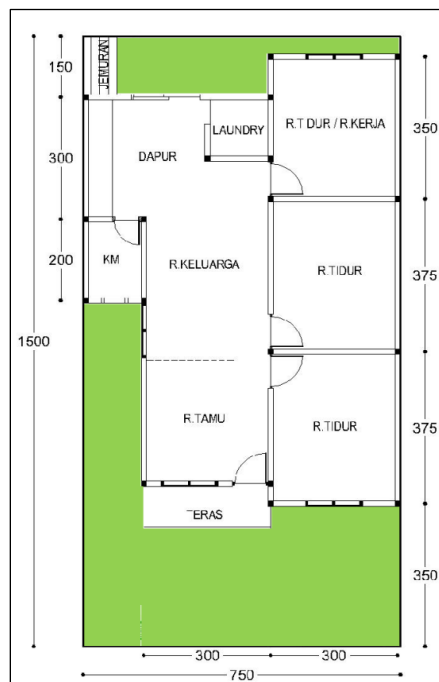
According to the interviewees, housing modifications and extensions were primarily driven by economic and socio-cultural factors. The predominant pattern of spatial development involved utilizing the entire remaining backyard area, often resulting in full hardscaping of the available land. This led to several issues, including poor ventilation and limited natural lighting in certain rooms due to the lack of openings, a significant reduction in green open spaces, and other related environmental problems. Consequently, the expanded dwellings became less environmentally friendly. This finding aligns with the interview results, which revealed that the majority of respondents were unaware of or did not consider eco-friendly housing principles when modifying their homes. While some respondents reported general awareness of sustainable housing concepts, they lacked a detailed understanding of how to implement such practices in their dwellings.

DISCUSSION

The Proposed Sustainability Concept in Subsidized Houses of Griya Mahoni Alpen

The proposed sustainability concept for the subsidized housing in Griya Mahoni Alpen is based on the Green Building Council Indonesia's (2014) environmentally friendly homes requirements. This concept encompasses multiple dimensions of sustainability, including land usage, energy efficiency and conservation, water conservation, material sourcing and recycling, health and comfort of living spaces, and overall environmental management. Each of these areas contains specific indicators that contribute to realizing an environmentally friendly housing model at Griya Mahoni Alpen.

Appropriate Site Development



(Source: Author's Analysis, 2023)

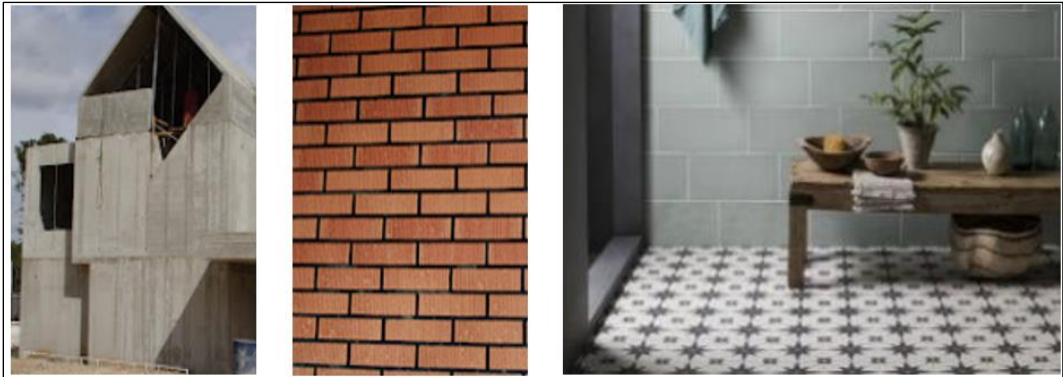
Figure 4. Additional Pavement and Fence at The Front Yard

Effective land use is fundamental to achieving housing sustainability, as it ensures the optimal use of available space (Pambudi & Handayani, 2012). According to the proposed concept, at least 30% of the land area should be dedicated to vegetation, minimizing the extent of paved surfaces. For example, a Type 38 house in Griya Mahoni Alpen, with a land area of 112.5 m², should have at least 33.8 m² of green space (see Figure 4).

When achieving the minimum green area is not possible, an alternative solution is to plant climbing vines on the exterior walls of the house. These plants must be carefully chosen so that their roots do not damage the house’s foundation or the surrounding fence. Furthermore, the vines can contribute to noise reduction and air purification, enhancing the overall environmental quality of the housing area.

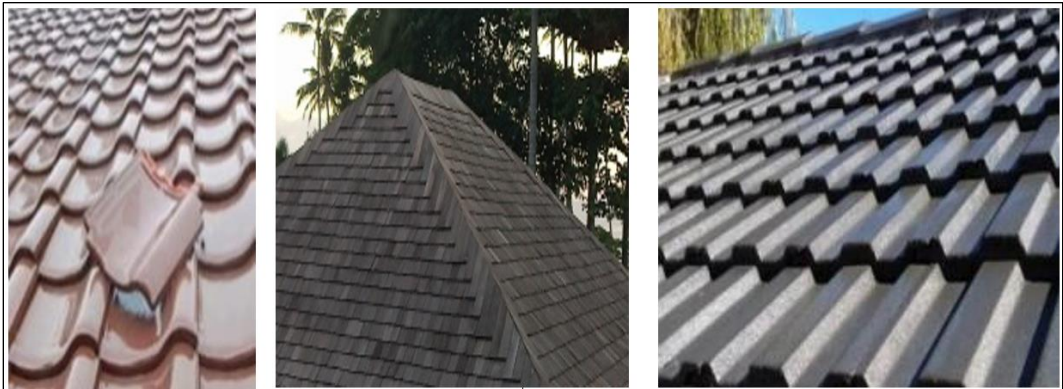
Energy Efficiency and Conservation

Given the scarcity of energy, the adoption of the Greenship Homes concept is crucial for residential areas (Pambudi & Handayani, 2012). The proposed energy efficiency and conservation strategies include the use of sub-metering to monitor and minimize electricity consumption. This can be achieved by installing energy-efficient lighting fixtures equipped with automation features. Low-wattage household appliances are also recommended to further improve energy efficiency.



(Source: Hindarto, 2011)

Figure 5. Using ‘Heat-Reducing Materials’ in Housing



(Source: Marina, 2020)

Figure 6. Using Heat-Reducing Roofing

To maintain comfortable thermal conditions in the house without relying on air conditioning, the design should incorporate effective use of natural ventilation, supported by adequate greenery. Indoor temperatures can be regulated by using heat-reducing building materials such as concrete, brick, and ceramic (Figure 5). Additionally, roof materials such as ceramic tiles, shingle roofs, concrete tiles, and UPVC Avantguard roofing reduce heat absorption (Figure 6). Roof coatings, including aluminium foil, bubble foil, and polyester insulation, are increasingly used to reduce heat from building roofs.

Conserving Water

Water conservation efforts can generally be categorized into two main approaches: lowering overall water consumption and using alternative water sources, such as rainwater. Ensuring the long-term availability of clean water for daily household activities is a critical component of sustainable housing (Lomi et al., 2021). One practical and increasingly adopted solution is the implementation of rainwater harvesting systems. This method consists of three essential components: (1) the catchment area, which is typically the rooftop where rainwater is collected; (2) the delivery system, which includes gutters and downpipes that channel the rainwater from the roof to a storage location; and (3) the storage reservoir, which can take the form of tanks, barrels, or even specially designed ponds where the collected water is stored for future use. Proper filtration should also be considered to ensure the water's safety and usability.

In addition, households are encouraged to adopt water-efficient technologies to minimize consumption. Low-flow toilets, aerated faucets, and high-efficiency washing machines and dishwashers are all designed to use much less water while maintaining performance (Sharpe & Swistock, 2008). Furthermore, behavioral changes play a crucial role in water conservation. Simple practices such as repairing leaks promptly, turning off taps while brushing teeth, and running dishwashers and washing machines only with full loads can greatly reduce unnecessary water waste. Collectively, these measures contribute to a more sustainable and resource-efficient living environment, which is especially important in residential areas that aim to meet higher green building standards.

Material Resource and Cycle

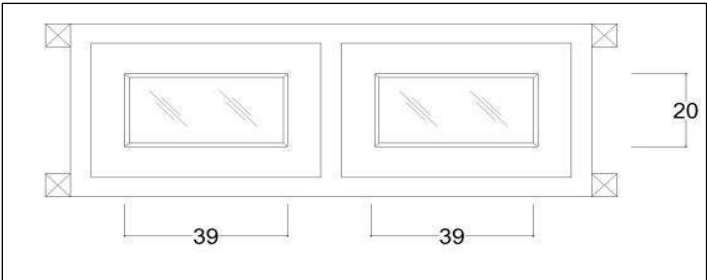
Green materials should be integrated throughout all stages of construction, from planning and construction to occupancy (Syahriyah, 2017). In terms of material sourcing and recycling, it is suggested that reused materials, recycled materials, and refurbished furniture should be incorporated into the building process. Examples include using recycled ceramics for walls and floors, repurposed wood for ceilings and furnishings, and converting waste materials such as paper and plastic into bricks. Additionally, materials derived from renewable sources, such as bamboo, should be prioritized. The use of certified wood, local materials, and prefabricated components can also be incorporated to lessen environmental impact.

Indoor Health and Comfort

Health and comfort within a living space are significantly influenced by ventilation. To improve occupant comfort and air quality, it is recommended that the ventilation space be at least 5% of the total room area (Maulianti et al., 2021) (Figure 7). The positioning of

ventilation openings is also crucial, and cross-ventilation (openings on opposite walls) is recommended to provide effective airflow. Each room should have sufficient airflow, which can be achieved by installing ventilation holes that are openable or made from porous or perforated materials.

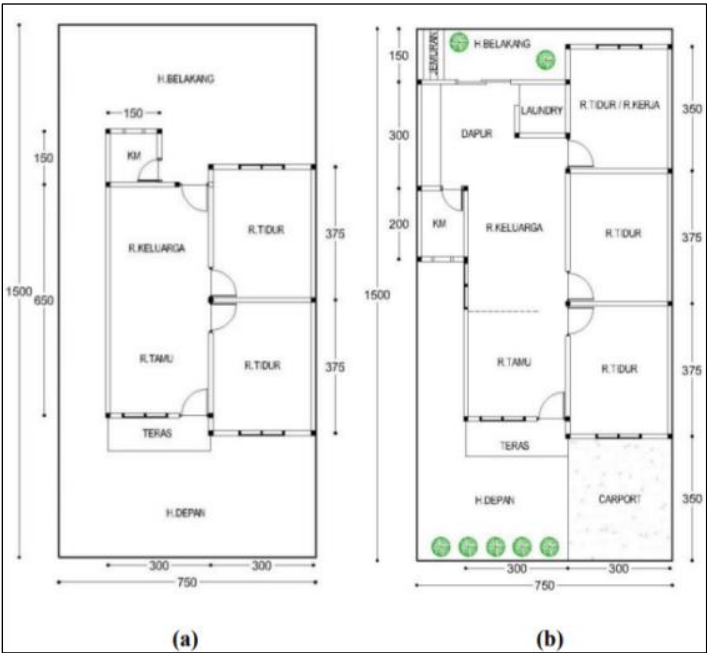
The placement of ventilation openings is as important as their size. Cross-ventilation—with openings on opposite or adjacent walls—ensures balanced airflow, enhancing comfort and reducing reliance on mechanical cooling. Each room should include operable vents or windows, and fixed openings can be made from porous or perforated materials like breeze blocks to support airflow while maintaining privacy. In dense urban settings, ventilation grilles above doors or transom windows can further improve air circulation. Well-designed, climate-responsive ventilation not only promotes indoor comfort but also supports health and energy efficiency in sustainable housing developments.



(Source: Author's Analysis, 2023)

Figure 7. Cross Ventilation is Recommended to Allow Air Circulation

Building Environment Management



(Source: Author's Analysis, 2023)

Figure 8. Using Heat-Reducing Roofing

Developers play a key role in the implementation of environmentally friendly housing by providing clear guidelines on sustainability. Developers need to provide technical guidance on how to build environmentally responsible homes, including health and safety issues during construction, as well as strategies for disaster management and security. Developers should also provide future residents with comprehensive guidelines for sustainable home modifications. Moreover, the design of Type 38 houses should ensure that space requirements are met while adhering to principles of health, comfort, and environmental sustainability, as illustrated in Figure 8.

CONCLUSION

This study reveals that the transformation of subsidized housing in Griya Mahoni Alpen is primarily influenced by two factors: economic conditions and socio-cultural needs. Most residents undertook modifications without adequate knowledge or consideration of sustainable housing principles. As a result, these alterations often lead to issues such as poor ventilation, inadequate lighting, and the loss of green open spaces, all of which harm both health and the environment.

The assessment of environmentally friendly housing criteria reveals that the Griya Mahoni Alpen housing complex only attained a Bronze rating for following green building standards. Many of the 48 indicators used to evaluate the six core aspects—land use, energy efficiency and conservation, water conservation, material use and recycling, indoor health and comfort, and building environmental management—have yet to be fulfilled. The transformation of low-income subsidized houses often leads to issues such as poor ventilation, inadequate lighting, and the loss of green open spaces, all of which harm both health and the environment. These findings highlight a significant gap in awareness and guidance regarding sustainable housing practices among the residents.

To address this gap, the study proposes a sustainable housing model tailored to low-income communities, grounded in the Green Homes framework and the principles outlined by UN-Habitat. The proposed concept emphasizes energy and water conservation, efficient land use, creating healthy indoor environments, using sustainable materials, and promoting community-based environmental management.

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BUILDING THE FUTURE: THE IMPACTS OF MID-PROJECT DESIGN CHANGES IN KLANG VALLEY

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Abstract

In the Malaysian construction industry, design modifications during project execution are common, particularly in high-density regions such as Klang Valley. These mid-project design changes often lead to increased costs, project delays, and workflow disruptions. This study aims to investigate the impacts of such changes by identifying the underlying issues and contributing factors, with a focus on proposing best management practices (BMPs) to mitigate their effects. The research delves into the complexities of design changes in building projects, highlighting their implications on cost, schedule, quality, and stakeholder satisfaction. By analysing both literature and empirical data, this study uncovers patterns and key factors that influence design changes once construction has commenced. Data analysis was conducted using descriptive statistics, the Relative Importance Index (RII), and reliability testing through SPSS Version 28 and Microsoft Excel 2019. The results underscore the importance of adopting proactive and strategic management approaches to reduce mid-project design disruptions. Ultimately, the study contributes to building future-ready construction practices in Klang Valley by promoting more resilient, efficient, and adaptive project delivery methods.

Keywords: *Design; Design Changes; Impact of Design Changes*

INTRODUCTION

The construction industry in Malaysia is projected to rebound strongly in 2022 due to the revival of major infrastructure construction projects such as the Mass Rapid Transit 3 (MRT3). It is expected to grow by 7.1% to reach MYR 181,599 million in 2022 based on a research market 2023 report. Previously, the Malaysian construction sector projected to grow at 8.0% for 2017 and up to 10.3% for 2018. The construction sector is expected to have a sustainable demand of approximately RM170 billion for 2017 and RM180 billion for 2018 (CIDB, 2017). As such, the construction industry is on the upswing, and projects are becoming increasingly complicated (Nurul Huda and Mohammad, 2018). Besides, the project designs are getting bigger and more complex, leaving construction companies with a narrow margin for error. This rapid growth underscores the need for future-ready strategies that can accommodate inevitable challenges, particularly those stemming from mid-project design changes.

Traditionally, there are separate processes for design planning and construction, which has resulted in some scope and design-related changes during the construction process (Samsudin *et al.*, 2023). Separation of design and construction has led to severe problems in which designs are made without concerns for buildability or productive economies, thereby impacting the performance of the projects negatively (Aslam, Baffoe-Twum and Saleem,

2019). To gain a thorough understanding of the problems resulting from design changes, it is important to examine their origins, characteristics, and the reasons they occur.

Design changes may arise from internal or external factors that emerge throughout the project's development phases, spanning from the initial design stage to construction. Matusala Bassa *et al.* (2020) stated that the internal factors are client-related, contractor-related, and consultant-related and the external factors are environmental, third-party, political, and economic. A combination of these has a detrimental effect on the overall project. These implications highlight the necessity of efficient management techniques, especially regarding cost, time, and workflow. Understanding the real-world effects of design modifications is essential for enhancing project performance as the construction industry shifts to increasingly integrated and digitalized delivery methods. By addressing the impacts of mid-project design changes proactively, stakeholders can build greater resilience into future projects, enhancing adaptability, long-term value, and sustainability. Hence, the need for a systematic review of the existing literature in this domain should be amplified. Therefore, this research aims to investigate the impact of design changes during the construction phase in Klang Valley. The study is positioned to support the future development of more robust construction practices in response to recurring mid-project challenges. To achieve this, the following objectives were recognized:

1. To identify the issues that arise with the design changes during construction.
2. To determine the factors that influence the design changes during the construction phase in Klang Valley.
3. To propose the best management practices for the design changes at the construction site.

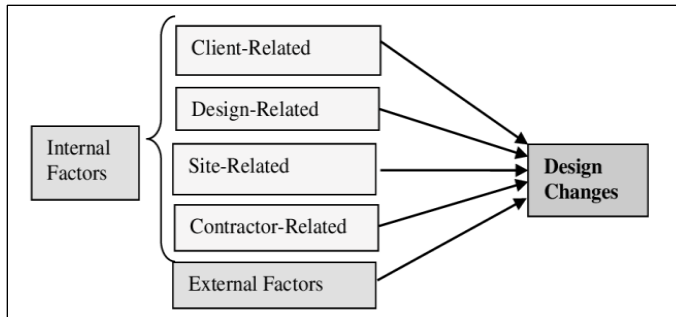
LITERATURE REVIEW

Introduction

Design changes are a common phenomenon in building construction projects, which will inevitably lead to claims and disputes. Yap, Abdul-Rahman and Wang (2016) defined design changes as "design deviations that are related to the design of the project that occur when changes are made in the project design and requirements". These changes are any additions, omissions, or adjustments made to the original scope of work after a contract is awarded that lead to an adjustment to the contract price or contract time.

This chapter discusses the impact of design changes during the construction phase in Klang Valley. To address the three objectives of this study, each section had 10 literature reviews that identify the project complications that emerge due to design modifications during the construction, to determine the factors that influence the design changes during the construction phase in Klang Valley. Following this, the study proposes the best management practices for the design changes at the construction site. Figure 1 represents the conceptual framework for determining factors that contribute to design changes during construction: client-related, design-related, site-related, contractor-related, and external factors. These are grouped under internal factors, indicating they originate within the project environment. Each category reflects specific sources of change for example, shifting client requirements, design errors, site conditions, contractor issues, or external pressures like regulations. Thus, the

framework emphasizes how these interconnected elements lead to design modifications, highlighting the importance of addressing them to ensure smoother project execution.



(Source: Authors, 2024)

Figure 1. Conceptual Framework of Causing Factors Influencing Design Changes

Issues Arise with Design Changes During The Construction

Design is a critical aspect of construction projects, as it involves creating plans, specifications, and drawings that guide the construction process. Inadequate understanding of design principles, codes, and standards can lead to design errors. These errors may include improper sizing or placement of structural elements, incorrect material selections, or inadequate consideration of environmental factors. Faulty or incomplete redesigns lead to costly rework, budget increases, and scheduling delays (Love, Teo and Morrison, 2018). In Nepal, massive bridge projects have been planned during the past ten years, but not all of them have been carried out. There are several interconnected aspects that determine the reasons of bridge design revisions and how they affect projects' budgets and timelines (Mishra and Aithal, 2022). Furthermore, Annamalaisami and Kuppaswamy (2022) looked at the connections between cost overrun sources and according to their research, there is a 17.43% cost variance during construction for non-infrastructure Indian projects due to a number of variables, with design and specification changes and price increases being the most important ones. Aslam, Baffoe-Twum and Saleem (2019) Also report in detail that even in well-managed projects, design changes can increase costs by 2.1% to 21.5% of the total construction value. On top of that, they also do an extensive study in nations like Malaysia and Indonesia, which clearly show that design changes are the main thing that affects project costs overall. This body of evidence reinforces the importance of addressing design-related disruptions early, especially mid-project, to build future-ready construction systems that are more cost-efficient and adaptable. In fast-growing regions like Klang Valley, where construction activity is intense, managing mid-project design changes is critical to securing the long-term viability of urban development initiatives. Many issues arise with the design changes during construction, such as:

- Project Delay
- Increase Cost
- Conflict Among Parties
- Delay in Material Supply
- Reduce Productivity
- Work Quality Drops
- Additional Equipment
- Work Progress Disrupt
- Miscommunication Between Parties
- Method Statement Changes

Factors That Influence The Design Changes During Construction Phase in Klang Valley

Frequent design modifications compromise coordination among multidisciplinary teams, leading to inefficiencies in sequencing, resource deployment, and quality assurance. Construction projects involve coordination among various stakeholders, including architects, engineers, contractors, subcontractors, and suppliers (Samsudin *et al.*, 2022). Frequent requirement changes can disrupt this coordination and result in confusion, rework, and delays in progress. A well-written list of working details sets expectations for both parties, including the responsibilities, milestones, and technical details required to complete the job (Thomas and Wright, 2020). As the construction sector in Klang Valley evolves to accommodate rapid urban growth, managing mid-project changes efficiently becomes critical for delivering high-performing, future-proof infrastructure. By improving coordination and minimizing disruptions, the industry can build a more resilient foundation for future construction practices. That said, some factors influence the design changes during construction, such as:

- Modifications to Design
- Inconsistent Site Conditions
- Design Errors
- Change Requirement
- New Technology
- Unclear Brief
- Alternative Construction Methods
- Underground Conditions
- Material Availability
- Unforeseen Problems

Best Management Practices (BMPs) for The Design Changes at The Construction Site

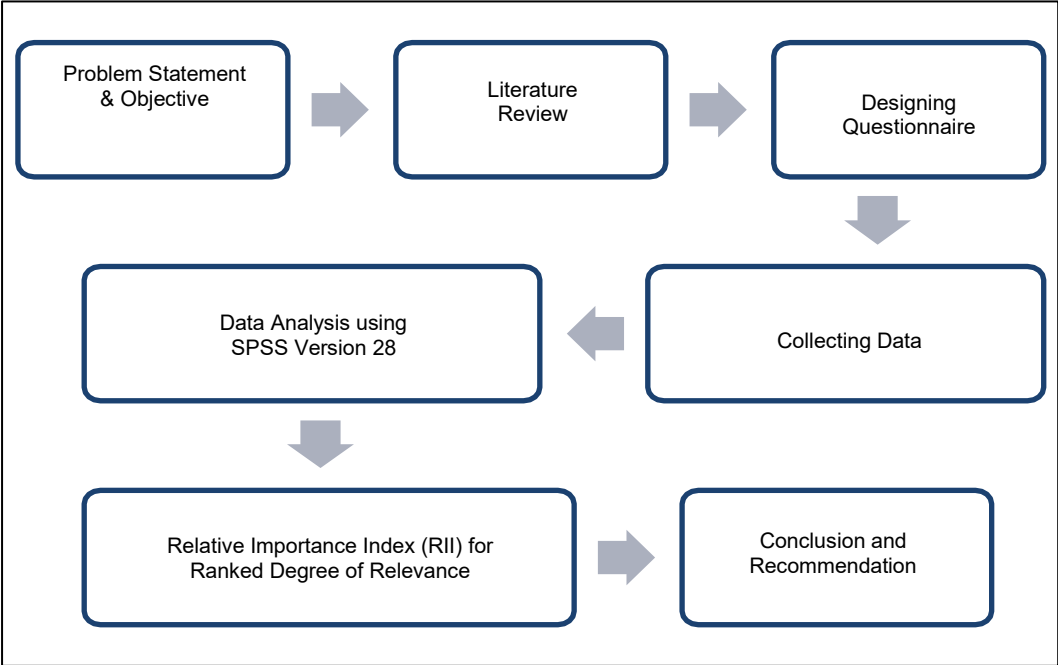
The construction industry is a highly competitive field that requires a wide range of technical skills for successful design and implementation of projects. Construction projects require a great deal of careful planning (Mechanical hub team, 2020). Being aware of the progress of construction during the design stage allows for proactive risk mitigation. In the context of mid-project design changes, especially in dynamic urban areas like Klang Valley, equipping construction teams with forward-thinking strategies is essential to ensure long-term project success. Such measures help not only in minimizing disruption but also in laying the groundwork for future-ready, adaptive project delivery. The strategies that every company can use are:

- Provide Effective Training
- Strategic Planning to Implement New Design
- Develop Technical Skills
- Enhanced Client Awareness
- Build Awareness of Upcoming Changes
- A Continuous Meeting of All Parties
- Increase Productivity through Systematic Management
- Consider the Design Allowable
- Re-evaluate the Scope of Contracts
- Proper Planning

RESEARCH METHODOLOGY

Research methodology is constructed as a strategy to overcome research challenges and difficulties. Guidelines for data collection on target concerns, as well as the gathering of all resources and information for correct reporting via statistics and surveys, are among the

methods used in the project's execution. Data collection conducted from January to March 2024, spanning a period of three months. This timeframe provided ample opportunity to reach the targeted respondents and allowed thorough follow-ups to ensure a sufficient response rate. The articles were all completed papers that addressed or were connected to the topics raised in this study. The report also looks at data-gathering techniques, research methodology, approaches, procedures, and different types of data analysis. This technique should make it simple for this analysis to collect, analyse, and present its findings. The research methodological flowchart is depicted in Figure 2.



(Source: Authors, 2024)

Figure 2. Flowchart of The Research Methodology

The methodology of this report, serving as the initial step in identifying problems and challenges within the construction process, is illustrated in Figure 2. An evaluation platform used during the problem statement investigation phase to assess the significance of the major research objectives. For the purposes of this study, “mid-project design changes” were defined as any design modifications that occur after the commencement of structural or major construction works, but before the completion of the project’s physical components. This typically excludes early-stage changes made during site preparation or foundation works and focuses instead on design revisions that impact work already in progress, such as alterations to floor plans, systems layouts, or facade elements after mobilization and structural development have begun.

The subsequent phase involved utilizing computational tools to gather data and insights from previous authors regarding the issues highlighted in their publications. The literature reveals a limited understanding of the impact of design changes during the construction phase in Klang Valley. The next stage was to create a questionnaire to collect information from these respondents using the quantitative model and methodology. These criteria provide the information needed to propose best practices management (BMPs) for design changes at the

construction site for a better construction future. In addition, the questions and options in the questionnaires must be basic and easy to understand for the respondents. Prior to full deployment, a pilot study is conducted with 10 experienced professionals in the construction industry to evaluate the clarity, relevance, and coherence of the questionnaire items. Based on their feedback, minor modifications were made to improve wording and structure. The questionnaire's internal consistency then verified through reliability analysis using Cronbach's Alpha, with all sections demonstrating acceptable reliability scores above 0.7. After all the information from this query is acquired, SPSS version 28 is used in the data analysis process and Microsoft Excel 2019 is used to determine the Relative Importance Index (RII).

RESULTS AND DISCUSSIONS

Introduction

This chapter covers the development of the questionnaire, the outcomes, and the analysis of the study's quality results, as well as the results and analyses of quantitative data. To identify any overlaps and differences, the results were also contrasted with those from previous research and published works. According to the criterion of "mid-project" used in this study, the majority replies to the questionnaire included design modifications that took place after structural construction got underway. All the findings were based on survey respondents who answered the questionnaire. The study employed purposive sampling to select 94 G7 contractors registered under CIDB Malaysia, who were actively involved in medium to large-scale construction projects within Klang Valley. This group is targeted due to their relevance and capacity to provide informed perspectives on mid-project design changes. A survey questionnaire was used to collect the data for this study because it's good at revealing patterns, averages, forecasts, and cause-and-effect relationships between variables. This study's methodology is comprised of preliminary research, data gathering, findings analysis, and discussion. The dependability and effectiveness of the survey questions will be rigorously evaluated through the use of IBM SPSS Statistics 28 and the Relative Importance Index (RII).

Demographic Background

Table 1 presents a summary of demographic background. The construction players that represent the highest percentage are engineers (50.0%). Most respondents had worked for less than 10 years (52.1%), and the majority are graduates of civil engineering with a bachelor's degree, with the highest percentage (64.9%). Next, the highest percentage, which is 51.1%, represented the company's involvement for more than 20 years. Meanwhile, the infrastructure consists of 37.2% of respondents, which the highest level of company involvement in this research.

Table 1. Summary of Demographic Background

Variables	Classification of Variables	Frequency	Percentage (%)
Work Specialization	Assistant Engineer	2	2.1
	Construction Manager	9	9.6
	Engineer	47	50
	Geologist	3	3.2
	Project Director	13	13.8
	Project Manager	16	17
	Protege	2	2.1
	Quantity Surveyor	1	1.1
	Site Supervisor	1	1.1
	Total	94	100
Working Experience	< 10 years	49	52.1
	> 20 years	24	25.5
	11-15 years	7	7.4
	16-20 years	14	14.9
	Total	94	100
Academic Qualification	Bachelor's Degree	61	64.9
	Diploma	7	7.4
	Master	18	19.1
	PhD	8	8.5
	Total	94	100
Company Operating	< 10 years	20	21.3
	> 20 years	48	51.1
	11-15 years	16	17
	16-20 years	10	10.6
	Total	94	100
Project Type	Amenities Building	7	7.4
	Commercial Building	21	22.3
	Facade	1	1.1
	Geotechnical	4	4.3
	High-rise Building	22	23.4
	Industrial	1	1.1
	Infrastructure	35	37.2
	Interior Design works	1	1.1
	Water management	2	2.1
	Total	94	100

(Source: Authors, 2024)

Reliability Test on Issues That Arise with The Design Changes During The Construction

This represented the primary objective of this research. The researcher identified ten literature reviews addressing the issues associated with design changes during construction. These issues include project delays, increased costs, conflicts among stakeholders, delays in material supply, reduced productivity, declines in work quality, the need for additional equipment, disruptions in work progress, miscommunication among parties, and alterations to method statements. This information is specifically gathered to inform the researcher’s subsequent questionnaire.

The item-total statistic for Section B is shown in Table 2. The table above can help determine whether or not to delete the items. This part is investigated using a corrected column. This column shows how well each item connects with the overall surveys asked in this section. In this table, "Method Statement Changes" has the lowest correction value of 0.607 when compared to the other elements. Therefore, deleting it should be considered to improve the reliability of questionnaires. Finally, all of the other goods should be kept in stock.

Table 2. Item Total Statistics Section B

	Scale Variance If Item Deleted	Scale Variance If Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Project Delay	34.59	56.568	.612	.469	.897
Increase Cost	34.60	56.975	.618	.548	.897
Conflict Among Parties	34.87	53.403	.704	.656	.891
Delay in Material Supply	35.04	52.557	.718	.633	.890
Reduce Productivity	35.32	52.865	.709	.644	.891
Work Quality Drops	35.24	52.187	.691	.700	.893
Additional Equipment	35.15	55.655	.573	.423	.900
Work Progress Disrupt	34.60	56.996	.616	.498	.897
Miscommunication Between Parties	34.86	52.981	.757	.611	.888
Method Statement Changes	34.72	57.191	.607	.415	.898

(Source: Authors, 2024)

Reliability Test on Factors That Influence The Design Changes During The Construction Phase in Klang Valley

This constituted the second objective of this research. The researcher identified ten literature reviews concerning the factors that influence design changes during the construction phase in the Klang Valley. These factors include modifications to the design, inconsistent site conditions, design errors, changes in requirements, the introduction of new technology, unclear briefs, alternative construction methods, underground conditions, material availability, and unforeseen challenges. This information is specifically collected to inform the researcher's subsequent questionnaire.

Table 3. Item Total Statistics Section C

	Scale Variance if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Modification to Design	35.83	43.562	.550	.499	.862
Inconsistent Site Conditions	35.76	43.993	.461	.360	.867
Design Errors	35.97	40.440	.622	.593	.856
Change Requirement	35.80	43.217	.525	.453	.863
New Technology	36.38	39.013	.611	.613	.858
Unclear Brief	36.14	37.174	.787	.724	.840
Alternative Construction Methods	35.97	42.203	.545	.467	.862
Underground Conditions	35.64	42.706	.614	.491	.857
Material Availability	36.00	40.882	.567	.547	.860
Unforeseen Problems	35.76	41.456	.624	.523	.856

(Source: Authors, 2024)

The item-total statistic for Section C is illustrated in Table 3. The item "Unclear Brief" in the sixth column has the highest corrected item-total correlation of 0.787. As a result, the item correlates well with the other ten questions in this section. The inclusion of this item indicates that the majority of respondents agree that "Unclear Brief" is one of the important elements influencing the factors that influence design changes during the construction phase in Klang Valley.

Reliability Test on Best Management Practices (BMPs) for The Design Changes at The Construction Site

This represented the third objective of this research. The researcher identified ten literature reviews proposing best management practices for handling design changes at construction sites. These practices include providing effective training, conducting regular meetings with all stakeholders, developing technical skills, enhancing client awareness, fostering awareness of impending changes, implementing strategic planning for new designs, increasing productivity through systematic management, considering design allowances, re-evaluating contract scopes, and ensuring proper planning. This information is specifically gathered to inform the researcher's subsequent questionnaire.

Table 4. Item Total Statistics Section D

	Scale Variance if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Provide Effective Training	40.13	28.650	.620	.675	.901
A Continuous Meeting of All Parties	40.15	29.698	.480	.365	.911
Develop Technical Skills	39.93	29.360	.743	.617	.894
Enhanced Client Awareness	39.94	30.168	.682	.622	.897
Build Awareness of Upcoming Changes	39.99	29.925	.677	.611	.897
Strategic Planning to Implement New Design	40.00	28.043	.800	.817	.889
Increase Productivity through Systematic Management	40.07	27.876	.796	.815	.889
Consider the Design Allowable	40.10	28.496	.668	.655	.897
Re-evaluate the Scope of Contracts	40.24	27.606	.710	.704	.895
Proper Planning	39.86	30.357	.579	.647	.902

(Source: Authors, 2024)

The item-total statistic table for this part is shown in Table 4. The item "A Continuous Meeting of All Parties" had the lowest correlation value of 0.480 in the second column of this table, indicating that it may need to be deleted from this section. Furthermore, the table's last column shows that there were issues with the item, as removing it from this section would increase the Cronbach's Alpha value. As a result, it is possible to conclude that this item should be eliminated to improve the reliability of this questionnaire for this study.

Relative Importance Index (RII)

In this study, calculating the Relative Importance Index (RII) is essential since the index the value specifies the ranked degree of relevance. It is very useful for Likert-scale

questionnaires. As shown in Eq. 1, the RII formula had been included in Microsoft Excel 2019 to determine the index for sets of items. This study makes an important contribution to supporting project stakeholders in the construction industry in guaranteeing and upholding good construction quality (Yap, Chow and Shavarebi, 2019).

Relative Important Index = $\frac{\sum w}{AN} = \frac{5(n5)+4(n4)+3(n3)+2(n2)+1(n1)}{5N}$

In which is the respondent's weighting of each factor, which can range from 1 to 5, n1 is the number of respondents that strongly disagree, n2 is the number of respondents that disagree, n3 is the number of respondents that average, n4 is the number of respondents that agree, and n5 is the number of respondents that strongly agree. As an outcome, A had the largest weight (in this case, 5), and N is the overall number of respondents. The Relative Importance Index spans a scale of 0 to 1.

Relative Importance Index (RII) Analysis

The analysis in this section encompasses the level of challenges resulting from the design alteration during construction. Table 5 shows the ranking of common complications linked to the design changes during construction under ten (10) levels of divisions. The results indicating that ‘Project Delay’ (RII=0.838) and ‘Increased Cost’ (RII=0.836) were among the most critical issues align with previous findings from Aslam et al. (2019), who also emphasized these as significant consequences of design changes in construction projects. The high rankings given to issues such as ‘Project Delay’ and ‘Work Progress Disruption’ reflect the inherent complexities associated with urban construction environments, particularly in Klang Valley, where projects often face logistical constraints and stringent regulatory processes.

Table 5. Ranking of Common Complications with The Design Changes During The Construction using The Relative Important Index (RII)

Issues	1	2	3	4	5	N	MEAN	RII	RANK
Project Delay	4	4	4	40	42	94	4.19	0.838	1
Increase Cost	1	5	15	28	45	94	4.18	0.836	2
Conflict Among Parties	6	7	12	34	35	94	3.90	0.781	6
Delay in Material Supply	5	14	14	29	32	94	3.73	0.747	7
Reduce Productivity	4	22	18	27	23	94	3.46	0.691	10
Work Quality Drops	6	20	15	24	29	94	3.53	0.706	9
Additional Equipment	4	15	17	34	24	94	3.63	0.726	8
Work Progress Disrupt	2	5	9	36	42	94	4.18	0.836	3
Miscommunication Between Parties	4	9	14	31	36	94	3.91	0.783	5
Method Statement Changes	0	9	13	36	36	94	4.05	0.811	4

(Source: Authors' Own, 2024)

This section will analyse the level of factors that influence the design changes during the construction phase. The analysis includes modifications to design, inconsistent site conditions, design errors, change requirements, new technology, unclear briefs, alternative construction methods, underground conditions, material availability, and unforeseen problems in carrying out the assignment. Table 6 highlights the factors that influenced the design changes during the construction phase in Klang Valley, ranking under ten (10) levels

of divisions. It shows that underground conditions are ranked top with 0.855 (RII), given that the most significant variable is attributed to the factors that influence the design changes. Followed by inconsistent site conditions and unforeseen problems in the second-ranked and third-ranked, respectively, that shared the same RII value, which is 0.832. The identification of ‘Underground Conditions’ as the primary influencing factor (RII=0.855) corroborates the results reported by Matusala Bassa et al. (2020), who highlighted unforeseen site conditions as a frequent cause of mid-project adjustments. However, the lower ranking of ‘New Technology’ differs slightly from the findings of Yap et al. (2019), who considered technological changes as moderately influential. Such differences underscore the context-specific nature of construction practices within the Klang Valley.

Table 6. Ranking of Factors that Influence The Design Changes During The Construction Phase in Klang Valley Using The Relative Important Index (RII)

Factors	1	2	3	4	5	N	MEAN	RII	RANK
Modifications to Design	0	5	15	41	33	94	4.09	0.817	5
Inconsistent Site Conditions	1	5	12	36	40	94	4.16	0.832	2
Design Errors	4	8	12	35	35	94	3.95	0.789	6
Change Requirement	1	6	11	39	37	94	4.12	0.823	4
New Technology	5	20	19	20	30	94	3.53	0.706	10
Unclear Brief	4	16	11	29	34	94	3.78	0.755	9
Alternative Construction Methods	1	10	15	35	33	94	3.95	0.789	7
Underground Conditions	1	4	8	36	45	94	4.28	0.855	1
Material Availability	6	6	11	38	33	94	3.91	0.783	8
Unforeseen Problems	1	8	10	31	44	94	4.16	0.832	3

(Source: Authors, 2024)

Contractors frequently encounter unexpected underground utility placements or geological issues, significantly impacting scheduling and costs, which explains the prominence of ‘Underground Conditions’ as a key influencing factor. Conversely, factors such as ‘New Technology’ were less influential, possibly due to a slower rate of technology adoption or a preference for conventional construction methods among local contractors, emphasizing traditional considerations as more pressing within the local industry context.

The construction industry is a highly competitive field that requires a wide range of technical skills to achieve successful design and implementation of projects. This section analyses the best management practices for the design changes at the construction site based on the answers given by respondents in the questionnaire. Table 7 shows the ranking of best management practices for the design changes at the construction site under ten (10) levels of divisions. It shows that the top one in RII value (0.926) is that contractors need to have proper planning to avoid project delays. Construction projects require a great deal of careful planning. Followed by developing technical skills with an RII value of 0.913. Finally, enhanced client awareness is third-ranked, with an RII value of 0.911. However, contractors ranked re-evaluating the scope of contracts as the least important to propose the best management practices for the design changes at the construction site (Mechanical hub team, 2020).

Overall findings to explicitly align with the research objectives, the findings are structured as follows: Objective 1 (issues arising from design changes) identified ‘Project Delay’ and ‘Increased Cost’ as primary concerns; Objective 2 (factors influencing design changes) highlighted ‘Underground Conditions’ and ‘Inconsistent Site Conditions’ as key drivers and lastly Objective 3 (best management practices) emphasized ‘Proper Planning’ and ‘Developing Technical Skills’ as the most critical strategies.

Table 7. Ranking of Best Management Practices (BMPs) for The Design Changes at The Construction Site Using The Relative Important Index (RII)

Best Management Practices (BMPs)	1	2	3	4	5	N	MEAN	RII	RANK
Provide Effective Training	1	4	9	26	54	94	4.36	0.872	8
A Continuous Meeting of All Parties	2	4	6	30	52	94	4.34	0.868	9
Develop Technical Skills	0	3	2	28	61	94	4.56	0.913	2
Enhanced Client Awareness	0	2	2	32	58	94	4.55	0.911	3
Build Awareness of Upcoming Changes	0	2	4	33	55	94	4.50	0.900	4
Strategic Planning to Implement New Design	1	3	3	29	58	94	4.49	0.898	5
Increase Productivity through Systematic Management	1	3	5	32	53	94	4.41	0.883	6
Consider the Design Allowable	0	6	6	27	55	94	4.39	0.879	7
Re-evaluate the Scope of Contracts	0	8	8	31	47	94	4.24	0.849	10
Proper Planning	1	1	4	20	68	94	4.63	0.926	1

(Source: Authors, 2024)

CONCLUSIONS

The conclusion identifies three primary issues resulting from design changes: project delays, increased costs, and disruption of work progress. These issues can significantly impact the overall success of a construction project, leading to potential financial losses and delays in project completion. The study attributes design changes primarily to underground conditions, inconsistent site conditions, and unforeseen problems. These factors underscore the importance of thorough site analysis and investigation before initiating the design phase of a project. It suggests that designers should conduct an in-depth study of soil investigation reports, review relevant as-built drawings, and perform utility mapping to anticipate potential challenges and minimize the need for design changes during construction. This highlights the importance of comprehensive planning and analysis in the early stages of a project. By strengthening early-stage planning, stakeholders can lay a more solid foundation for building future-ready infrastructure, particularly in rapidly developing urban areas like Klang Valley.

The conclusion emphasizes the importance of adopting best management practices to reduce design changes during construction. It suggests that proper planning, development of technical skills, and enhancing client awareness are essential strategies in this regard. The conclusion provides an example of proper planning by mentioning clash analysis using Building Information Modelling (BIM). This technique allows for the identification and resolution of conflicts between different building systems and components before construction begins, thereby reducing the likelihood of design changes during the construction phase. Furthermore, policy enhancements for design coordination are one of the main tactics

to improve tech integration and resilience in construction. To cut down on misunderstandings and incomplete documentation, regulatory agencies could require design audits and stakeholder workshops prior to construction. On top of that, frameworks for risk mitigation to detect and control design change triggers and facilitate proactive decision-making in project management processes establish a design change risk register at the beginning of the project. These strategies contribute to a more agile and efficient construction process, aligning with the broader goal of building a resilient and forward-looking construction industry. Overall, the conclusion underscores the significance of proactive approaches in addressing design changes, ultimately enhancing the efficiency and success of construction projects. Such proactive efforts are vital for shaping a construction environment in Klang Valley that is not only responsive to present demands but also adaptable to future challenges.

Also in this study, there were a few recommendations that had been identified to minimize the impact of design changes in the construction phase on efficient implementation. The recommendation could be identified as having good coordination between parties and a good understanding of project requirements. In terms of management, developers must hire consultants and contractors with sufficient experience throughout the construction process. Especially considering Southeast Asia is a developing construction sector, coordination is essential for the efficient implementation of construction designs. It guarantees efficiency, economy, and the smooth incorporation of sustainable practices. As the region strives to build more sustainable and liveable cities, strong collaboration will be key in translating design vision into future-proof built environments. The significance of efficient collaboration in design will only increase as the building sector expands and matures.

In addition to the commonly observed impacts on cost, time, and quality, mid-project design changes significantly affect various project stakeholders, both directly and indirectly. Stakeholders such as clients, consultants, contractors, and subcontractors often experience increased tension due to miscommunication, shifting responsibilities, and changes in project scope. These disruptions can lead to reduced morale, loss of trust, and conflict among project parties, which in turn hampers decision-making and project momentum. In the long term, frequent design changes may result in stakeholder fatigue, diminished confidence in the project delivery system, and reputational risks—particularly for developers and contractors working in competitive urban regions like Klang Valley. Furthermore, these changes can compromise end-user satisfaction due to compromised building functionality, suboptimal spatial planning, or maintenance issues that arise from rushed or reactive modifications.

From a systemic perspective, recurring design changes reflect deeper industry challenges such as fragmented project delivery processes, lack of integrated planning, and insufficient early-stage stakeholder engagement. These issues highlight the need for a shift toward more collaborative and proactive project governance frameworks. For instance, integrated design approaches and early clash detection using digital tools like BIM could reduce fragmented workflows and encourage shared accountability. Addressing these systemic concerns not only mitigates current project risks but also contributes to a more resilient and future-ready construction ecosystem—one that is capable of adapting to evolving demands while maintaining performance, efficiency, and stakeholder alignment throughout the project lifecycle.

The foundation of design is a set of requirements. As a result, clear and concise requirements aid in the process of helping developers create the best possible solution. The development team will work on the correct problem without having to make many revisions if the requirements are of high quality. Well-understood requirements can help the team estimate the effort and resources needed to execute a project. Reliable estimation requires some historical correlation between requirements of size and effort. A prioritized requirements baseline helps the construction team incorporate those changes that will deliver the maximum customer value. Establishing such clarity early enables smarter, more accurate decision-making, supporting the evolution of future-oriented construction practices in Klang Valley and beyond.

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UNVEILING THE HUMAN-COMPUTER INTERACTION (HCI) ELEMENTS IN DESIGN PRINCIPLES AND CONSTRUCTION OF SMART HOME

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Abstract

With the rapid development of the Internet of Things (IoT) and artificial intelligence technology, smart home design has become an important part of the modern living environment. As a pivotal factor in smart home user experience, Human-Computer Interaction (HCI) requires optimized modes and attributes to enhance satisfaction. Smart home system provides convenient life experience, but the complex interaction mode and unclear interaction attributes may lead to user operation difficulties and affect user acceptance. Therefore, a further study of the mode and attributes of HCI is of great significance for the design of a more humanized intelligent home system. The purpose of this study is to explore the variables related to the characteristics of HCI in existing smart homes. The key variables are extracted through extensive literature review and the semi-structured interviews, involving ten experts and managers of smart home design in Hefei, China. The findings revealed seven (7) criteria; Fault Tolerance, System Design, Usability, Measurability, Privacy, Fast Response Time, and Security, as design principles in smart homes. It is hoped that the findings will help smart home developers and designers to better understand user needs to design a more efficient, intuitive and satisfactory smart home interaction system.

Keywords: *Design and construction; human computer interactions (HCI), HCI characteristics, Semi-Structured Interview, Smart home design*

BACKGROUND OF RESEARCH AND ISSUES

The concept of smart homes has rapidly evolved from a futuristic vision into a mainstream approach to residential living. Smart home design and construction integrate advanced technologies, automation systems, and sustainable building practices to enhance comfort, convenience, energy efficiency, and security. Yang (2023) described that the smart home improves the safety, convenience, comfort, and artistic sense of the family, and realizes the environmental protection and energy-saving living environment. Unlike conventional homes, smart homes are built around interconnected devices and sensors that can be controlled remotely through smartphones, voice assistants, or centralized management systems. Chatzigiannakis (2016) conceptualizes smart homes as integrated platforms that unify residential facilities via wired/wireless networks, automation, and multimedia systems. In the design stage, smart home planning involves embedding Internet of Things (IoT) infrastructure, energy management solutions, and adaptive layouts that accommodate both current and future technologies. As architects prioritize usability, safety, and experiential quality, HCI emerges as the keystone bridging user intent with intelligent functionalities. During construction, careful selection of materials, wiring systems, and energy-efficient components ensures that the home is not only technologically advanced but also environmentally responsible.

Therefore, it is inevitable that Human-Computer Interaction (HCI) plays a crucial role in smart home systems. The human-computer interactive modes are significant in the age of intelligence. As defined by Huang et al., (2016), human-computer interactive modes (HCI) are the study of how humans interact with computers and to what extent computers are developed for successful interaction with humans. Effective HCI design not only improves device availability but also enhances user satisfaction and loyalty (Czaja et al., 2006; Huang et al., 2023; Li et al., 2023; Tian et al., 2018). Other than that, the ISO 9241-210 (2006) standard established a core framework for human-computer interaction, emphasizing user-centred design that synergizes technological innovation with cognitive capabilities. This framework has been widely adopted in evaluating smart home system interactions. The rapid development of smart home technology has brought about revolutionary changes to the living environment.

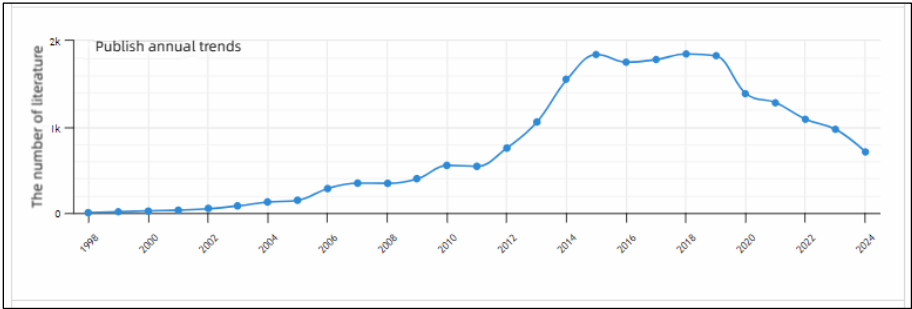
With the continuous progress of these technologies, HCI has diversified challenges in the smart home aspects. Norman's, (1988) stated that the emotional design theory advocates for metaphorical interfaces and feedback mechanisms to foster user-device affinity. Therefore, among the challenges in smart home aspects include emotional companionship as a critical yet understudied factor in smart home satisfaction (Huang, 2020). While Deng (2021) revealed that paradigm frames smart homes as techno-artistic hybrids, demanding harmony between functional needs and aesthetic integration. Other than that, Zhao (2019) also highlights the need for low-cost, minimally invasive modifications to conventional appliances through novel HCI and communication technologies, emphasizing simple operation and inertial motion-based control. It can be seen that studies on emotional interaction patterns between smart home assistants and users remain scarce. Optimizing HCI ensures equitable access across diverse user groups (e.g., elderly, children) while advancing human-centric smart architecture. Moreover, transitioning users from traditional to intelligent appliances requires intermediate solutions that balance cost, adaptability, and user experience. Thus, this study aims to identify the HCI features in smart home design and analyse key variables governing HCI efficacy and its functional interdependencies.

LITERATURE REVIEW: VARIABLES OF SMART HOME DESIGN

To identify the variables of smart home Human-Computer Interaction (HCI), this study was firstly compiled from secondary sources, using systematic literature review. The review involved a careful screening process and finalized 65 articles included as final literature synthesis.

Literature Screening Process

A systematic search was conducted across five major databases (IEEE Xplore, Scopus, Google Scholar, CNKI, and VIP), with China National Knowledge Infrastructure (CNKI) and Scopus selected as primary sources due to their disciplinary coverage and reputation. CNKI, maintained by the Institute of Scientific and Technical Information (ISTIC), represents China's largest academic database. Scopus (Elsevier) is a globally recognized citation index spanning science, technology, medicine, and social sciences. The search query "smart home" + "human-computer interaction" yielded 40,550 publications, reflecting the field's growing prominence (Figure 1).



(Source: CNKI, 2024)

Figure 1. Annual Publication Trends in Smart Home HCI Research

An examination of annual publication trends reveals a substantial increase in smart home-related research output between 1998 and 2015, with particularly accelerated growth observed during the 2009-2017 period, potentially attributable to concurrent technological advancements, expanding market requirements, and growing scholarly recognition of human-computer interaction's critical role in smart home development. The sustained high publication volume post-2018 indicates this domain has matured into an established research area receiving continued and rigorous academic investigation, reflecting both its scientific significance and practical relevance in contemporary technology studies.

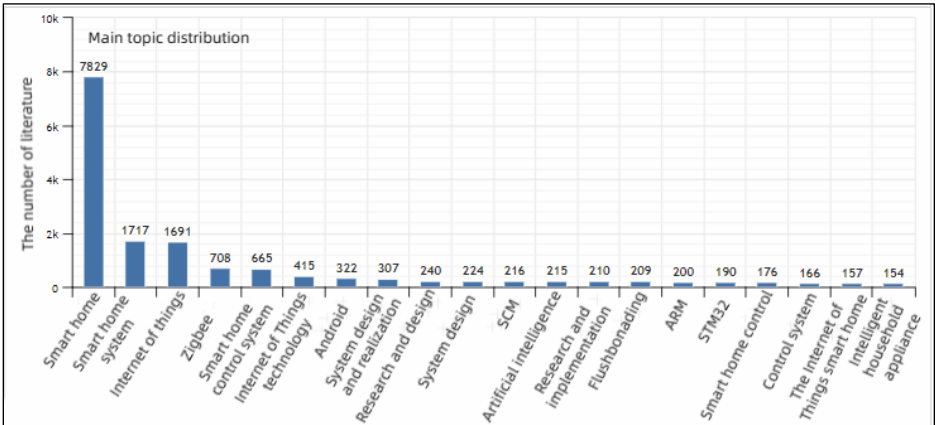


Figure 2. Distribution of major research themes (Source: CNKI, 2024)

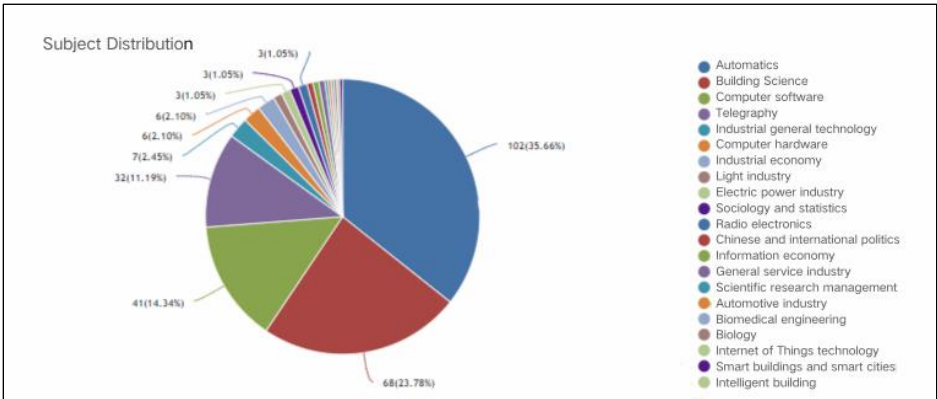


Figure 3. Interdisciplinary Subject Coverage (Source: CNKI, 2024)

The thematic analysis of smart home HCI research reveals substantial disciplinary diversity, demonstrating both the field's intellectual breadth and its inherently interdisciplinary nature, with smart home applications constituting the most prevalent research focus, followed by smart home system architectures and IoT integration studies, while a significant proportion of investigations concentrate on technological innovations, novel methodological approaches, and practical implementations of HCI principles within residential automation contexts.

Formulate research objectives, keywords, exclusion and inclusion criteria, and form a research plan. Keywords "*smart home*" and "*human-computer interaction*" were selected as the search keywords. Article titles, abstracts, and keywords were searched through the CNKI academic search engine, including open access journals, dissertations, and monographs. Inclusion and exclusion criteria were developed, as shown in Table 1.

Table 1. Exclusion Criteria and Inclusion Criteria for Literature Screening

Inclusion Criteria	Exclusion Criteria
The literature must focus on HCI in a smart home environment.	Non-peer-reviewed articles, such as conference abstracts, reports, book chapters, etc.
Research should provide raw data or have a substantive discussion of the user experience.	Studies with no direct association with smart home HCI.
Publication time should be in nearly 10 years to ensure the timeliness of the study.	Marketing literature that focuses on specific product promotion rather than universal design principles.

This study employed a rigorous selection process to identify 65 relevant articles through systematic screening, with content extraction focusing on explicitly stated and conceptually related smart home research components, enabling comprehensive synthesis across three critical dimensions: user demographic variations, behavioural patterns and requirements, and fundamental design principles, while the development of analytical flowcharts derived from these carefully curated publications facilitates deeper examination of core HCI variables and their characteristic manifestations in smart home environments, thereby establishing a methodological framework for investigating interaction design parameters in residential automation systems.

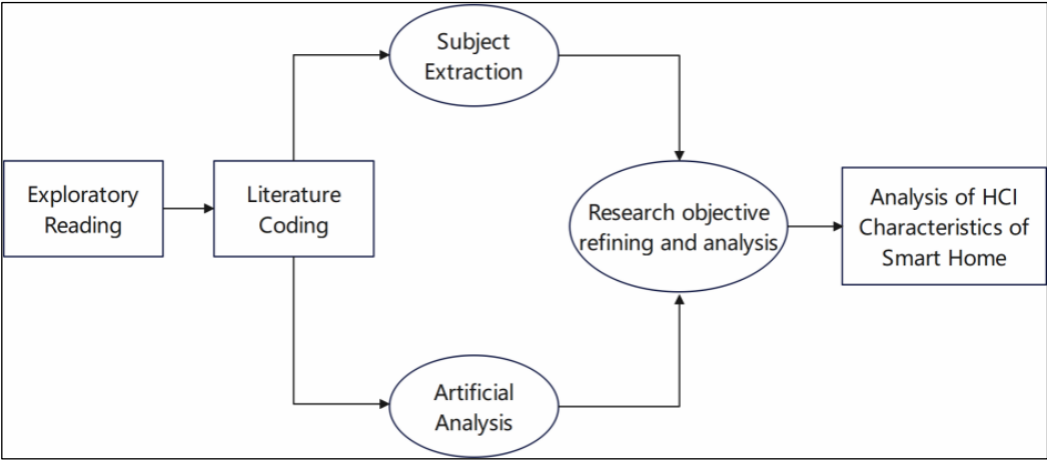


Figure 4. Flow chart of the study analysis (source: Author 's own research)

Literature Findings: Research Dimension and Its Classification Criteria

To recap, 65 articles are included as the final literature analysis. As summarized in Table 2, the 65 selected publications were classified into three core research dimensions; i) users' group, ii) design principles and iii) user behaviour/psychology. The classification criteria under each dimension are summarized in Table 2.

Table 2. Classification Results from The 65 Articles

Research Dimension	Classification Criteria (Ranked Based on Majorly Cited)	No. of Articles
User group	Family members / Multiple users	16
	Elderly people	11
	Children / Adolescents	10
	Specific user groups	9
Smart Home Variables: Design principles in smart home	Fault Tolerance	12
	System Design	10
	Usability	9
	Scalability	9
	Privacy	7
	Fast Response Time	7
	Security	6

i) User Group

Based on Table 2, it was found that 16 articles from the 65 articles mentioned that HCI variables involved majorly family members or multiple users. In the home environment, multiple users share the same system, so it is particularly important to study how to meet the needs of different users, the interaction between users, and personalized services. For example, Li (2022) studied the importance of children's games in the smart home, summarized the key technologies of smart home game design for children's users, sorted out the new changes of children's games in the smart home scene, and put forward the relevant strategies of game design based on cutting-edge cases. Next, 11 articles mentioned the elderly also account for a certain proportion in the research of smart homes. Qian (2021) designed and developed a set of intelligent systems suitable for aging, which has the function of fall monitoring and follow-up linkage alarm setting to solve the daily home life safety problems of the elderly living alone. With the trend of population aging, studying on how to make smart home technology better in serving the elderly and improve their quality of life is crucial. This may include an exploration of ease of operation and accessibility design.

The following findings revealed 10 articles mentioned on children and adolescents occupying a place in the research of HCI in smart homes. This part of the literature tends to focus on the educational and recreational needs of children and adolescents, as well as their adaptability and safety requirements for technology. Next, 9 articles mentioned that HCI variables involved people with disabilities, professionals, or users with special interests as specific user group research involves. This usually focuses on specific needs, such as accessibility, customized functions, and professional applications. However, it was also found that most of the articles did not mention any designated group (no designated group). This shows that a large amount of research is exploring smart home technology not for specific user groups, but more widely considering universal issues, such as the general design of the system, basic interaction mode and universal user experience.

ii) Smart Home Variables: Design Principles

As shown in Table 2, the review analysis from the 65 articles reveals seven (7) core design principles that are critical for developing effective smart home interactive systems. The design principles which are frequently mentioned in the articles are *Fault Tolerance System Design*, *Usability*, *Measurability*, *Privacy*, *Fast Response Time*, and *Security*. These principles ensure both technical robustness and user-centred design.

The most cited criteria, *Fault Tolerance*, must be included into smart home design as HCI integration. This is supported by Zhang et al. (2023) where using multiple input channels when the input is fuzzy or interference can effectively reduce errors and correction and significantly improve the recognition rate. The designer needs to fully consider the possible errors during the design process and take measures to prevent and correct these errors. This helps to improve the stability and reliability of the system and reduce the problems encountered by users during their use.

Next is, *System Design*, emphasizing the design and implementation of smart home systems, including the architecture of the system, the collaborative work between components, and the stability and scalability of the system. This indicates that the overall design, component collaboration, stability and scalability of the system have received considerable attention in the study of smart home HCI. Also, *Usability*, included as one of the design principles in smart homes. It involves designing the design of the user interface, simplifying the operation process, and improving the overall experience. Thus, designers need to focus on their users' needs and expectations to provide them with smart home systems that are easy to use and meet their needs. Other than that, a crucial component in smart homes is *Measurability*. This principle indicates that the quantitative evaluation of performance and effect has a place in the smart home HCI study.

Privacy, also should be considered as one of design principles, which means that the system should be able to adapt to different environments and specific situations of users. In the field of smart home, it involves personalized Settings, environmental adaptability, and context perception. Fast Response Time, focusing on how users can quickly learn and master the use of smart home technology. This involves reducing the learning curve of users and allowing new users to start quickly, which is crucial to promoting smart home products. Lastly, *Security*, ensuring that all users, including those with disabilities or special needs, can use the smart home system. This involves removing both physical and cognitive barriers and providing an inclusive design. This relatively low proportion indicates that few studies in the smart home HCI literature focus on providing the design of accessibility for people with disabilities or users with special needs. This may indicate an area requiring more attention.

METHODOLOGY

To validate the initial variables of smart home design with HCI integration that were compiled from the literature, this study adopted the semi-structured interview. The study was conducted after receiving approval by the UiTM Ethics Committee. The selection of interviewee is following consideration of pre-screening criteria, as shown in Table 3.

Table 3. Inclusion and Exclusion Criteria for Interview Screening

Inclusion Criteria for Interview	Exclusion Criteria
Smart home designers or operators or managers	Do not accept the interview recording; The interview process was interrupted due to personal reasons, and the interview was not successfully completed.
More than 10 years of working experience, and more than 5 years of experience in the intelligent industry;	
Experts and managers have the senior engineer level title	
Good communication skills and language expression skills;	
Understand the purpose of this study and volunteered to participate in this study	

The experts were also selected based on the designers or operators of smart home developer in China; i.e. Xiaomi (Mi Home / Mijia). Due to “at-large” samples, the location of experts is narrowed to Anhui province only in Hefei, China. Based on the screening criteria, 25 experts fit into the criteria and were invited to participate in the interview. Out of 25 invitations, ten (10) participants agreed to be interviewed. The interview questions consist of the followings:

- Q1: Do you agree that one important feature of the smart home interaction design is usability?
- Q2: Do you agree that the smart home interaction design is measurable?
- Q3: Do you agree that smart home interaction design needs to include a system design with user-friendly features?
- Q4: Do you agree that smart home interaction design needs to consider security?
- Q5: Do you agree that smart home interaction design needs to protect privacy?
- Q6: Do you agree that smart home interaction design requires quick response time and quick response ability?
- Q7: Do you agree that interaction design for smart homes needs to be fault-tolerant?

The interview session was physically held in Hefei City, Anhui Province, China and each session took about 30 to 60 minutes. All responses were carefully recorded and transcribed for analysis purposes.

FINDINGS FROM SEMI-STRUCTURED INTERVIEWS

Table 4. Demographic Background of The Participants

Ref.	Designation	Years of Working Experience	Years of Involvement in Intelligent Field
P1	Senior Engineer	22	8
P2	Senior Engineer	15	7
P3	Senior Manager	16	6
P4	Senior Programmer	12	9
P5	Senior Interior Designer	16	5
P6	Intermediate Programmer	8	6
P7	Dealer Manager	9	7
P8	Scholar/Professor	28	10
P9	Scholar/Associate Professor	20	8
P10	Scholar/Associate Professor	18	6

Table 4 listed the demographic background of the interview participants that were included in this study. The ten participating experts represent diverse professional domains encompassing intelligent engineering, programming development, system architecture, and

academic research, with their multidisciplinary expertise ensuring thorough examination of critical HCI design components including usability optimization, security protocols, and privacy preservation mechanisms, as demonstrated by the senior engineering practitioners (P1-P3) and academic researchers (P8-P10), complemented by technical specialists focusing on system development and user experience refinement (P4-P7), thereby mitigating potential biases inherent in singular methodological approaches.

Table 5. Participants, Responses on The Characteristics of Smart Home Interactive Design

Smart Home Design Characteristics with HCI Integration	Components	Source/Participants Ref:	Consensus / Agreement on The Relevancy of Components (%)
Usability	Instruction wakeup	P1-P10	10(100)
	Answer time	P2,P4,P5,P9,P10	5(50)
	Waiting for processing	P1,P2,P4,P5,P6,P7,P8,P9	8(80)
	Command execution	P2,P4,P5,P6,P7,P8,P9,P10	8(80)
	Evaluation and feedback	P1-P10	10(80)
	Effectiveness	New suggestion	10(100)
	Constancy	New suggestion	
Scalability	Extendibility	P1-P10	9(90)
	Remote control	P2-P10	10(100)
	Unified multi-mode linkage control	P1-P10	10(100)
	Speech control Memorability	New suggestion New suggestion	
System Design	Scalability	P1,P2,P4,P5,P7,P8,P9	7(70)
	Identifiable	P1-P10	10(100)
	Reliability	P1-P10	10(100)
	Remind abnormal behaviour	New suggestion	
Security	Ensuring housing safety	P1,P2,P4,P5,P6,P7,P8,P10	8(10)
	Ensure information	P1-P10	10(100)
	Security	P1-P10	10(100)
	Protect privacy	P1-P10	10(100)
	Identify verification Consider safety for people with disabilities	New suggestion New suggestion	
Privacy	Data collection	P1-P10	10(100)
	Reduce privacy data outflow	P1,P2,P3,P6,P7,P8,P9,P10	8(80)
	Hardware maintenance	New suggestion	
	Ecryption technique	New suggestion	
Fast Response Time	Response speed	P1-P10	10(100)
	Response accuracy	P2,P3,P4,P6,P9,P10	6(60)
	Response error correction degree	P1-P10	10(100)
	Active learning	New suggestion	
	Understand the execution Linkage response	New suggestion New suggestion	
Fault tolerance	Guide and prompt	P1-P10	10(100)
	Limit manipulation	P1-P10	10(100)
	Feedback	P1-P10	10(100)
	Help	P1-P10	10(100)
	Correction capability	New suggestion	
	Stable operation Automated testing	New suggestion New suggestion	

The comprehensive analysis of interview data reveals substantial consensus among experts regarding fundamental characteristics of smart home HCI systems, with quantitative agreement metrics systematically documented in Table 5, indicating particularly strong alignment on core design principles and implementation strategies that collectively contribute to enhanced interaction paradigms in residential automation environments.

As shown in Table 5, all experts demonstrated agreement on core features (e.g., usability and security), indicating consensus on key variables. The interviews focused on seven core dimensions (including usability, measurability, system design, etc.), with no new dimensions emerging. Due to ethical review timelines and limited access to experts, a final sample of ten participants was selected.

DISCUSSION OF FINDINGS

The analysis of smart home interaction design characteristics, as substantiated by the data presented in Tables 4 and 5, demonstrates that these systems fundamentally incorporate seven critical dimensions: operational availability, performance measurement, architectural system design, security protocols, privacy preservation mechanisms, rapid response capabilities, and fault tolerance features, which collectively form the foundational framework of intelligent residential systems by synergistically enabling optimized user experiences characterized by efficiency, convenience, and safety within domestic environments. The followings are the justification on the consensus on the relevancy of smart home characteristics, perceived from the interview participants:

Usability

Based on the responses, the participants agreed that **Usability** must be included as smart home design characteristics that need integration with HCI. Among the quoted responses, these are mentioned by the participants:

"Availability is the basis of HCI, and users should have a clear understanding of the current state of the system, including operational feedback and system changes. For example, when the response time of the system is less than 1 second; if the response time is long, the user should be informed by loading animation to avoid being confused." (P2)

"The interface design should reduce the memory burden and help users identify operational options through intuitive layout and marking." (P1)

"The system shall use the language and concepts familiar to the user, rather than the terms of the system itself. This helps users to understand and use the system more quickly." (P4)

ISO9241-210 (2006) indicates the effectiveness, efficiency and satisfaction of the product when used by a specific user in a specific situation to achieve a specific goal. Therefore, Zhang et al. (2023) believes that the product usability is more concerned with the user's subjective perception of whether the product can achieve a specific target and how efficiently. Smart home systems should be easy to use, and users can operate and control them without obstacles. This includes an intuitive user interface design and clear instructions that

are easily mastered by users of all ages. It is associated with the "instruction wake up", response, waiting for processing, command execution, evaluation feedback and other components. This is supported through Dong (2021) that mentioned evaluation and feedback are indispensable components in the process of HCI. Huang et al. (2016) also mentioned that for users, the good availability of an application means that it has the characteristics of easy learning, good task performance, low error rate, high satisfaction, and low user churn rate.

Measureability

All of the participants have achieved consensus that **Measureability** must be included as smart home design characteristics that need integration with HCI. Among the quoted responses, these are mentioned by the participants:

"Measurability means observing and recording user behaviour at specific intervals or moments to obtain a representative sample of user behaviour." (P6)

"Evaluation and measurement through actual user testing and user feedback to ensure that users can easily understand and use the functions of smart home devices." (P7)

"Designers should consider the addition and update of new features in the future to ensure that the system evolves over time". (P5)

Smart home systems should be able to collect and analyse data to assess and measure the efficiency, effectiveness, and experience of interactions between users and computer systems in a quantitative way. Xiao et al. (2022) pointed out that multimodal networks will be an important clue for the construction of future network systems, and polymorphic modelling and design can effectively unify the differences of different network services, different network levels and different network environments. To monitor the home environment and user behaviour, provide personalized services, and easily add new devices, have good expansion functions, and optimize the system through data analysis. This measurability is usually associated with elements such as scalability, compatibility, and unified multi-mode linkage control. He (2022) believes in the internal compatibility between human decisionmakers and agents. In particular, cognitive compatibility, emotional compatibility, and value compatibility. It is the deep reason that affects the performance of man-machine collaborative decision-making.

System Design

The participants also agreed that **System Design** must be included as smart home design characteristics that need integration with HCI. One of the quoted responses from P7 mention as follows:

"In HCI design, both interface design and interaction mode need to be systematically designed, so as to create interaction methods conforming to the law of human cognition. For example, buttons and labels in interface design need to be arranged in certain rules and presented to users with reasonable visual elements" (P7)

The interaction design of the smart home should consider the collaborative work of the whole system to ensure the compatibility and interoperability between the devices, as well as the overall stability of the system. It is first associated with the three elements of measurement, identification, and reliability. Rui et al. (2023) pointed out that the design and integration of man-machine system make the reasonable or best matching relationship between people, machine, and environment in the goal of efficiency, safety, comfort, and economy. Huang et al. (2016) considered a lower cognitive load. Enables users to focus on the identification of the actual tasks, rather than being overwhelmed by too much information.

Security

It was found that all of the participants agreed that **Security** must be included as smart home design characteristics that need integration with HCI. Among the quoted responses, these are mentioned by the participants:

"The basic point of smart home interaction is to ensure safety, which first considers personal safety, and formulates safety norms based on different groups of users." (P4)

"Users' awareness of the security of HCI is also crucial. Users should understand how to safely use interactive devices, and how to protect their personal information and privacy." (P8)

Smart home systems must be based on the three aspects of residential security, information security and privacy security, to ensure the security of users, including physical security and network security. This means that the system should have the ability to prevent unauthorized access to and protect the user data and take comprehensive measures to ensure the security of the HCI process. Huang et al. (2023) expressed his concern in the research study on the data, privacy and security-related research and trends of smart home from the perspective of HCI. Jia et al. (2020) points out that compared with traditional robot safety requirements, the new generation of HCI safety technology emphasizes human-machine integration. Human-computer safety interaction problems are divided into pre-interaction danger warning and post-interaction safety guarantee, that is, collision avoidance, detection, and response in the general sense.

Privacy

The participants also agreed that **Privacy** must be included as smart home design characteristics that need integration with HCI. Among the quoted responses, these are mentioned by the participants:

"Smart home interaction is carried out in private scenes, and it needs to optimize the interaction mode based on human feedback on the basis of considering information security." (P5)

"The masses are more and more educated, pay more attention to personal space and psychological boundaries, and have higher and higher requirements for security and personal privacy." (P6)

"A series of data security measures are required. Including data encryption, access control, anonymization processing and other technical means to prevent data from being illegally obtained during transmission or storage. Users should also understand the privacy risks of using HCI devices and services and learn how to protect their privacy by setting up options." (P9)

Privacy protection is an important aspect of intelligent household design, in the design and application of HCI system, not only should pay attention to the convenience and efficiency of technology, but also fully consider the user's privacy rights and interests, take corresponding protection measures to ensure that the user's personal information and habits are not collected, storage and spread without permission. Allows users to use HCI products and services safely and safely. In the process of sorting out and counting the contents and quantities of literature research in the past five years, Huang et al. (2023) found that understanding user needs, network data privacy and security, and understanding device functions and risks were the research hotspots in the past five years Qian (2021). In his study, the main factors hindered the widespread adoption of smart homes. It includes privacy and security issues, and negative social impacts.

Fast Response Time

All of the participants agreed that **Fast Response Time** must be included as smart home design characteristics that need integration with HCI. Among the quoted responses, these are mentioned by the participants:

"In the control page design of the smart home, fast response can make the functional structure more in line with users' psychological expectations and can effectively reduce users' cognitive and learning costs. In addition, the rapid response ability can also improve the user experience, enhance the user's trust in the product, through the response error correction can reduce the delay and improve the accuracy, so that the communication between users and the computer system is more smooth and efficient." (P3)

"People can make mistakes, and machines need to have a judgment mechanism to respond to instructions to ensure personal safety." (P9)

"Some products need to respond quickly, and some need to be slow. Related to safety do not require too fast operation, such as gas. If the safety threat because of the fault cannot stop the loss in time will cause a safety accident." (P8)

Smart home systems should be able to respond quickly to users' instructions and needs, provide immediate feedback, and enhance the user experience. Response speed, response accuracy and response error correction degree are related to it. Wang et al. (2022) believes that whether the man-machine interface is friendly and beautiful, the response speed is slow, the operation stability and advantages and the operation is convenient directly affects the user's operation experience. He points out that the large-scale independent access and intelligent decision-making nodes emerging in the network generate a large amount of computing power and data asset services, which need to provide ultra-high-capacity intelligent decision-making ability at the edge of users, and require high reliability, low latency, and fast response service quality requirements. Li et al. (2023) mentioned that an

experiment on the response time of the system shows that robots prefer to delay a second before answering, just like a pause in a human conversation, and the delay in human-computer conversation can have a psychological impact on users that cannot be ignored.

Fault Tolerance

The participants agreed that **Fault tolerance** should be considered into smart home design characteristics that need integration with HCI. Among the quoted responses, these are mentioned by the participants:

But (P1) believes that "excessive fault tolerance will bring ambiguity and obstacles and should be more and more accurate ". and

(P10) said: "fault tolerance cannot go beyond the range of users, so as not to lose patience, can provide alternatives in the case of product failure, to ensure that users can still control and manage their home environment."

The system shall be able to handle accidents and errors, avoid service interruption due to failure, and be able to repair itself or prompt the user to intervene. Fault tolerance is an important aspect of HCI design, which helps to improve the user experience and enhance the ease of use and reliability of products. It is associated with elements such as guide prompts, restriction operations, feedback, and help. Through the practice of these elements, designers can effectively improve the fault tolerance of the product, so that users are more confident and comfortable when using the product. Huang et al. (2016) mentioned that the high error tolerance makes the system still present a stable interactive environment in the errors caused by users, environment, and other factors. Qiu (2020) pointed out that the feedback in HCI is a prompt to the user operation status, and error reporting means guidance failure; the increase of fault tolerance rate depends on good interaction feedback, the stability of interactive operation is related to the interaction fault tolerance rate, and the higher the fault tolerance rate, the better the stability.

CONCLUSION

This study investigates the interrelationships among seven critical variables in smart home human-computer interaction (HCI) systems - usability, measurability, system architecture, security protocols, privacy preservation, response latency, and fault tolerance - through a mixed-methods approach combining systematic literature review and semi-structured interviews. These variables collectively form an evaluative framework for designing optimized HCI systems that balance operational efficiency, user experience, and safety considerations. Analytical findings reveal complex interdependencies among these variables, where enhanced system availability necessitates robust security and privacy implementations to establish user trust, while superior architectural design directly influences both usability metrics and system measurability. Furthermore, the synergistic relationship between rapid response capabilities and fault tolerance mechanisms fundamentally determines system stability and reliability, thereby shaping overall user satisfaction.

The proposed framework offers significant implications for architectural practice and built environment research. First, actionable guidelines for integrating HCI requirements into spatial configurations and infrastructure planning, particularly regarding device compatibility and network architecture; Second, evidence-based approaches for adapting intelligent systems to diverse user demographics through universal design principles; Finally, quantifiable metrics for assessing user experience in technology-enhanced spaces. Emerging technologies in artificial intelligence and IoT present both challenges and opportunities for refining these variable relationships across different application contexts, suggesting promising directions for future research focused on developing adaptive, human-centric smart environments that prioritize both technological sophistication and practical usability.

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