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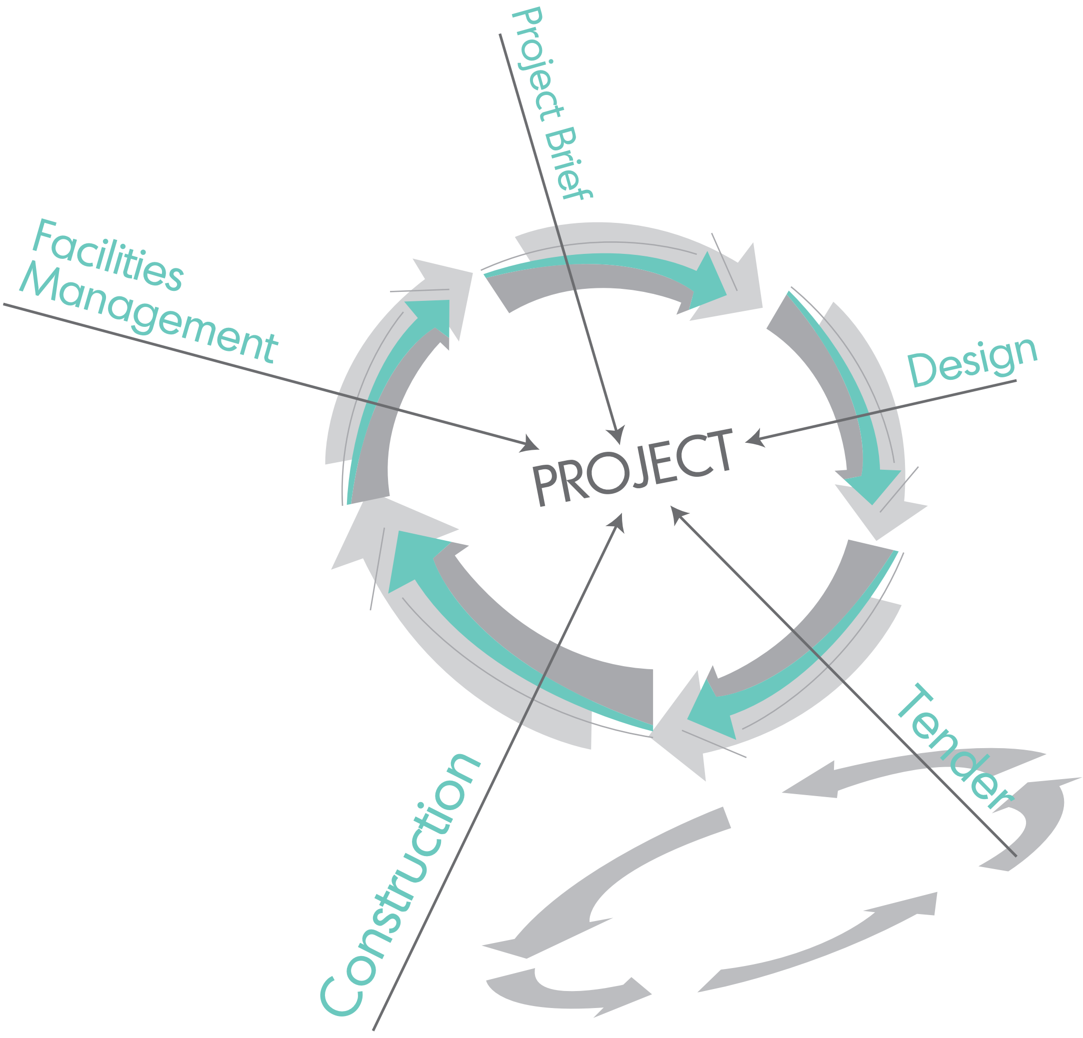

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Construction Research Institute of Malaysia (CREAM)
Level 14, CIDB 520, The MET Corporate Towers,
No. 20, Jalan Dutamas 2,
50480 Wilayah Persekutuan,
Kuala Lumpur, MALAYSIA.

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Contents

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Editorial

Welcome from The Editors

Welcome to the forty-seventh (47th) issue of Malaysian Construction Research Journal (MCRJ). In this issue, we are pleased to include seven papers that cover a wide range of research areas in the construction industry. The editorial team would like to express our sincere gratitude to all contributing authors and reviewers for their contributions, continuous support and comments.

In this issue:

Mohd Reeza Yusof et al. emphasised that persistent delivery issues, such as cost overruns, delays, and poor coordination, continue to hinder the successful implementation of the Industrialised Building System (IBS) in the construction industry. This study investigates the adoption of Integrated Project Delivery (IPD) as a best practices framework to address these challenges. Grounded in Leavitt's Diamond Theory, the research identifies and categorises 41 critical best practices across four domains: strategy, technology, practice, and people. The study's findings provide a practical reference for policymakers and industry players seeking to optimise IBS implementation through a more collaborative, integrated delivery approach aligned with Malaysia's construction transformation agenda.

Noor Aisyah Asyikin Mahat and Mohamed Hafiz Md Isa developed environmental specifications for a sustainable construction industry, as the construction industry significantly impacts global resources and the environment, highlighting the need for sustainable development practices. In Malaysia, environmental specifications essentially reference the SIRIM Eco Label, but a more tailored framework is required to address local challenges and regulatory needs. This study focuses on integrating the SIRIM Eco Label and international standards into Malaysia's Government Green Procurement (GGP) Guideline for three key products: paint, fibre cement, and masonry units. Through extensive desktop research and stakeholder interviews, the study identifies critical elements essential for developing a robust environmental specification for the construction sector. The findings propose a comprehensive framework that strengthens sustainable construction practices, enhances regulatory clarity, and bridges policy gaps. By aligning with international sustainability goals, this framework aims to support Malaysia's transition toward more eco-friendly construction practices, ensuring long-term environmental and industry benefits.

Syafizal Shahruddin and Nurhidayah Rosely develop an interpretive phenomenological framework to examine architects' evolving identities in digital construction environments, shaped by building information modelling (BIM), artificial intelligence (AI), and cloud computing. By integrating Smith's interpretive phenomenology analysis (IPA), van Manen's hermeneutic phenomenology, and Lindseth and Norberg's hermeneutical method, the study offers a structured approach for analysing identity paradoxes in technologically mediated practice. Reflexive research practices highlight the importance of critically examining assumptions, employing flexible conceptual frameworks, and engaging in a double hermeneutic process. The study makes theoretical and practical contributions by outlining a six-step methodological framework, providing scholars with a comprehensive tool for exploring performance identity and digital collaboration in the field of architectural research.

Lian Huahua et al. present an innovative approach that combines deep learning-based defect detection with the QLASSIC standard to assess housing quality. While numerous studies have explored the application of deep learning for defect detection, there remains a lack of integration with comprehensive systems such as QLASSIC. The proposed approach includes the following key steps: (1) categorisation of visual defects according to QLASSIC; (2) collection of defect-related image datasets; (3) image preprocessing and pixel-level manual annotation; (4) selection and training of deep learning models; and (5) evaluation and refinement of model performance. By integrating these steps, the proposed approach aims to enhance the efficiency and accuracy of building assessments, thereby facilitating more transparent communication and decision-making among all stakeholders involved in the construction process.

Fatima Hanif and Rahimi A. Rahman investigate how to improve sustainable building management by combining Digital Twin (DT) technology with the WELL Building Standard. Real-time monitoring, predictive maintenance, and energy optimisation are made possible by DT, which complements WELL's emphasis on occupant comfort and health. The main conclusions indicate that DT optimises operational efficiency, reduces energy consumption, and enhances air quality to enhance building performance. Nevertheless, there are still issues to be addressed, such as the high cost of implementation, the scarcity of empirical research, and the lack of leadership frameworks for integrating DT and WELL. Research on data-driven decision-making and long-term sustainability consequences is lacking in the scattered literature on this convergence. To close these gaps, additional empirical case studies, digital transformation leadership techniques, and coherent frameworks that strike a balance between technology innovation and human-centred design are needed. By transforming WELL-certified buildings into intelligent, efficient, and health-focused spaces, this case study showcases DT's potential to pave the way for more intelligent and sustainable building management techniques.

Moetaz Elhawary et al. compared the performance and durability of geopolymer concrete produced using locally available materials with those of conventional concrete to determine whether geopolymer concrete has the potential to be a suitable replacement in hot climate countries such as Kuwait. To formulate the geopolymer concrete, ground granulated blast furnace slag (GGBS), sodium hydroxide and sodium meta-silicate solutions were utilized. After curing, the mechanical properties of the mixes, including tensile strength, modulus of elasticity and compression strength, were tested. The durability of the concrete samples was determined by testing the resistance to freezing and thawing, sulfuric acid, seawater, heat, water penetration and absorption. The shrinkage behaviour of the concrete was also studied through restrained ring test. Results showed that geopolymer concrete had high early strength development, better tensile strength, and increased compressive strength up to 95% when exposed to temperatures of 100, 300, and 500 ºC. It also had lower water penetration, suggesting better durability. Geopolymer concrete also showed better resistance to acids, showing its potential as a suitable replacement for cement-based concrete.

Alias Abdul Rashid et al. highlight that iconic buildings are architectural landmarks that possess distinctive design, large scale, and strong symbolic value, contributing to city identity, economic growth, and urban development. However, their complex forms, advanced materials, and sophisticated engineering systems pose significant challenges for long-term maintenance and facilities management. As architectural trends evolve, effective management strategies are essential to ensure the sustainability and performance of these buildings. This study aims to identify critical success factors (CSFs) that enhance facilities management practices for iconic buildings in Malaysia. A qualitative Delphi Method was employed, involving three rounds of consultation with local experts from facilities management, architecture, construction, consultancy, and professional associations. The findings revealed five key CSFs influencing effective management: adoption of FM technologies, life-cycle cost analysis, skilled staffing, logistical and locational considerations, and proactive maintenance planning. Additional factors such as user interaction, physical attributes, symbolic meaning, sustainability, community impact, and tourism were also identified. The study provides practical insights for improving the long-term value and performance of iconic buildings in Malaysia.

Editorial Committee

AN INTEGRATED PROJECT DELIVERY (IPD) BEST PRACTICES APPROACH FOR INDUSTRIALISED BUILDING SYSTEM (IBS)

Mohd Reeza Yusof[1*], Izatul Laili Jabar[1], Abdul Hadi Nawawi[1], Mohd Nasrun Mohd Nawi[2], Mohamad Faiz Musa[3] and Nurulhuda Mat Kilau[4]
[1]*College of Built Environment, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor, Malaysia*
[2]*School of Management of Technology and Logistic, Universiti Utara Malaysia (UUM), Sintok, Kedah, Malaysia*
[3]*Construction Industry Development Board (CIDB) Malaysia, Kuala Lumpur, Malaysia*
[4]*Construction Research Institute of Malaysia (CREAM), Kuala Lumpur, Malaysia*

**Corresponding Author: mohdreeza@uitm.edu.my*

Abstracts
The Industrialised Building System (IBS) is a transformative approach in Malaysia's construction sector, offering significant advantages in productivity, efficiency, and sustainability. However, persistent delivery issues such as cost overruns, delays, and poor coordination continue to hinder its success. This study investigates the adoption of Integrated Project Delivery (IPD) as a best practices framework to address these challenges. Grounded in Leavitt's Diamond Theory, the research identifies and categorises 41 critical best practices across four domains: strategy, technology, practice, and people. A two-stage methodology was employed, comprising expert validation and a pilot survey involving 31 multidisciplinary IBS stakeholders. The findings highlight essential practices such as project trend awareness, computer-aided design (CAD) usage, teamwork, and customer-centric planning. This study provides a practical reference for policymakers and industry players seeking to optimise IBS implementation through a more collaborative, integrated delivery approach aligned with Malaysia's construction transformation agenda.

Keywords: *Integrated Project Delivery (IPD), Industrialised Building System (IBS), Collaborative Construction, Project Efficiency, Stakeholder Integration, Leavitt's Diamond Theory*

INTRODUCTION

IBS is the term used by the government and industry players to represent the concept of prefabrication of building components and the adoption of industrialisation in the Malaysian construction industry. IBS is defined as a construction method in which components are manufactured in a controlled environment (on or off-site), transported, placed and assembled into a structure with minimal additional works (Construction Industry Development Board (CIDB), 2003; Musa et al., 2016; Tajul Ariffin et al., 2019). The construction industry implementation of IBS is still deficient compared to conventional methods (A. A. Rahim & Qureshi, 2018). Several issues hinder the performance of IBS during construction projects, including a preference for conventional methods, a lack of integration, delays, poor quality, cost overruns, and others (Khalil et al., 2016). This poor performance highlights the need for the IBS project to explore alternative management practices that can improve performance (S. A. A. Rahim et al., 2020). According to Jaffar & Lee (2020), the integration factor is one of six (6) critical factors that significantly impact IBS project performance. This statement is also in line with a study done by Viana et al. (2020), Hu & Chong (2020), Liyana et al. (2018) and Nawi et al. (2014) that recommends increasing integration by changing from traditional procurement to innovative procurement, which can enhance the delivery of IBS projects.

Over the last several years, several studies have been conducted on innovative procurement, particularly IPD using IBS in Malaysia. Moreover, there is a lack of studies on IPD in IBS procurement since most of the studies focus on IPD in IBS readiness (Osman et al., 2017), literature review (Zuber et al., 2019) and design team communication (Nawi, 2012). Several researchers (Ahamad et al., 2020; Dzulkalnine et al., 2016; Jalil et al., 2015) had already focused on IBS procurement, but not on IPD in IBS.

Nevertheless, this paper argues for the importance of IPD-IBS best practices, as they have rarely been discussed in previous studies. Therefore, this study aims to identify the best IPD best practices for IBS implementation to fill this gap. This paper reviews several past studies that discuss IPD-IBS best practices and involve IBS construction experts to evaluate and suggest additional best practice factors. The outcomes of this paper will represent comprehensive IPD-IBS best practices that impact IBS implementation and will serve as a helpful reference for IBS stakeholders.

INTEGRATED PROJECT DELIVERY (IPD)

A project delivery method that integrates people, systems, business structures, and practices into a collaborative process that harnesses the talents and insights of all participants to reduce waste and optimise efficiency through all phases of design, fabrication, and construction (AIA et al., 2007).

This technique was developed to improve traditional methods of project implementation. IPD was introduced by the American Institute of Architects (AIA) in 2007. IPD involves significant collaboration among the owner, the prime designer, and the prime contractor (AIA et al., 2007). This collaboration begins early in the design phase and continues through to the project's completion and handover. The IPD team fosters collaborative project design, construction, and commissioning (Lichtig, 2010). All members of the IPD team are required to collaborate individually to ensure the transparent and cooperative provision of project information.

IPD PRINCIPLES AND BENEFITS

The IPD method promotes teamwork and emphasises the project's objectives rather than the participants' gains (AIA et al., 2014). While IPD has the potential for improved results, it is essential to recognise that these results can only materialise if the individuals accountable for achieving them transform. Therefore, to obtain the advantages of IPD, all individuals involved in the project must adopt the Principles of IPD fully (AIA et al., 2007; Kent et al., 2010; Ling et al., 2020; Nawi, 2012):

- Mutual Respect and Trust
- Mutual Benefit and Reward
- Collaborative Innovation and Decision Making
- Early Involvement
- Early Goal Definition
- Intensified Planning
- Open Communication
- Appropriate Technology
- Organisation and Leadership

The IPD approach delivers numerous benefits to a project. The authors have identified the subsequent advantages of IPD based on the reviewed literature and prior research done by (AIA et al., 2007; Khandi et al., 2020; Kent et al., 2010; Pal & Nassarudin, 2020; Rodrigues & Lindhard, 2023; Sherif & Abotaleb, 2023; Simonsen et al., 2019; Viana et al., 2020).

Table 1. IPD Benefits

Benefit Characteristics	Description
Shared Risk and Reward	All project stakeholders are bound by a single contract, which entails shared rewards and risks.
Minimum Variation Orders	All parties participating in the project are involved in the early stages, sharing information and progress.
Lower Cost	Less variation orders and requests for information (RFI) lead to lower costs and a more optimal schedule.
Improved Project Profit	A singular contract has the potential to maximise profits for all parties involved.
Better Communication	All project parties can communicate more effectively due to their shared objective.
Optimise Materials' Use and Time	As the project's overall success directly impacts everyone's profit, there is strong motivation for all individuals to discover the most effective approaches to accomplishing the task.
Quality	It enhanced construction quality as a result of improved coordination and collaboration.
Planning	Shorter and optimised work schedules result from thorough early planning at the initial stage of projects.
Integration	Decisions are made throughout every stage of the construction process as a team. IPD has played a role in reducing the culture of blame and fostering a more positive work environment.
Respect &Trust	IPD achieves its goals by encouraging desired behaviours such as respect and trust, teamwork, and open communication.
Contract	The contract facilitates effective collaboration by promoting problem resolution and the mutual identification of optimal solutions.
Technology	Technological advancements, such as BIM, have enhanced communication and facilitated the exchange of information in IPD projects.

Source: Author (2025)

The AIA established IPD in 2007 as a project delivery approach that combines design, engineering, architecture, and construction. IPD aims to synchronise the goals and methods of stakeholders to leverage their perspectives for enhancing project efficiency (Lu et al., 2021). IPD emphasises the necessity of early involvement in parallel processes to integrate people, systems, business structures, and practices, thereby minimising waste and maximising efficiency throughout all stages of design, fabrication, and construction (Nawi, 2012). According to Allison et al. (2018) and Lopez et al. (2022), IPD is suitable for IBS because it enables early alignment of the project team, allowing them to plan the project scope and budget before the design phase begins. Collaborating with IPD team members during the early design stage results in the availability of more specific information sooner than in the conventional design process. Thus, collaboration can assist in recognising and managing potential risks during the manufacturing and construction phases using IBS concepts (Lu et al., 2021). Therefore, IBS projects can be executed more efficiently by supporting new project management and delivery methodologies through IPD, addressing the need for greater integration in the current IBS industry.

The AIA established IPD in 2007 as a methodology that combines design, engineering, architecture, and construction processes. IPD aims to synchronise the objectives and strategies of stakeholders to leverage their insights for enhancing project efficiency (Lu et al., 2021).

IPD emphasises the importance of early engagement in concurrent processes to integrate personnel, systems, organisational structures, and methodologies, thereby minimising waste and improving efficiency across all stages of design, manufacturing, and construction (Nawi, 2012). Allison et al. (2018) and Lopez et al. (2022), claim that IPD is suitable for IBS as it promotes early alignment of the project team, allowing for the planning of the project scope and budget before the design phase begins. Involving IPD team members during the initial design phase provides access to more accurate information sooner than the conventional design method. Cooperation can facilitate the identification and mitigation of potential hazards during the production and construction phases through the application of IBS concepts (Lu et al., 2021). Therefore, IBS projects can be conducted more effectively by adopting innovative project management and delivery approaches through IPD to address the need for greater integration within the current IBS sector.

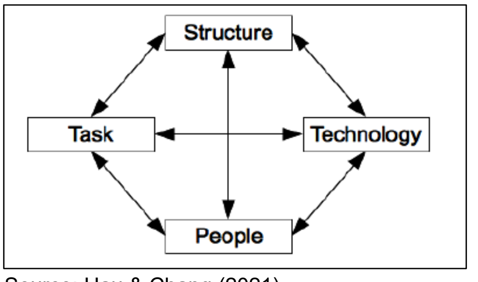
IPD IN IBS

The IBS is increasingly recognised in IPD for its capacity to enhance project timelines, minimise on-site disruptions, and elevate construction quality (Raj, 2024), while also facilitating collaboration and coordination among IBS project stakeholders (Lens, 2023). IPD integrates IBS prefabrication into project planning and execution, enabling expedited project delivery while maintaining design flexibility and quality standards (Raj, 2024). IPD incorporates the advantageous aspects of design-build, such as speed, information sharing, and performance contracts, focusing on outcomes through shared risk and incentives (Smith, 2011). IPD facilitates collaboration among clients, consultants, and constructors to deliver pre-construction services such as cost estimating and constructability reviews, effectively integrating the efforts of all project team members (Smith, 2011). The AIA developed the IPD from product design and production methodologies, mainly drawing from the automotive industry, which is closely aligned with modular approaches. Thus, IPD facilitates IBS construction by promoting early contractor engagement and integrating modular processes during the design phase.

UNDERPINNING THEORY

This research is grounded in Leavitt's Diamond Theory, with numerous prior studies employing the diamond model as the foundational framework for their investigations into IBS. IPD is a project delivery method that integrates practices, systems, business structures, and individuals across all phases of design, fabrication, and construction. This aligns with the four essential components of Leavitt's diamond model: task, structure, people, and technology. The researcher found that Leavitt's diamond model acts as a foundational framework for several prominent models and theories of change management, including the Congruence Model, McKinsey 7S Model, and the Burke-Litwin Model. This model posits that any change in one component induces a ripple effect on all other components, thereby requiring balance among all essential elements within the model.

The Leavitt diamond model (Figure 1) was developed by Harold J. Leavitt in 1965 to analyse the widespread consequences that changes in organisational structure have (Liao & Teo, 2019). Leavitt's Alignment Model, often referred to as Leavitt's System Model, emphasises the interdependent interaction among its components. It proposes that any modification will inevitably generate changes in the other components (Aristovnik et al., 2024). According to Hau & Chang (2021), the diamond model developed by Leavitt is a theoretical framework often used to study the effect of organisational change. This analysis determines how the adjustment will affect the interrelationships between the four main components of the organisation: tasks, structure, staff, and technology. The structure, tasks, technology, and people are the four components that make up Leavitt's diamond model. Hupperz et al. (2021) and Liao & Teo (2019) indicate that structure refers to the authority system, communication systems, and task composition. Tasks encompass all functions that generate value, while technology includes hardware and applications. People refer to human resources within an organisation who perform tasks.



Source: Hau & Chang (2021)

Figure 1. Leavitt's Diamond Model by Leavitt (1965)

THE DEVELOPMENT OF ELEMENTS OF IPD IN IBS

Lyytinen & Newman (2008) asserted that Leavitt's model's four-element categorisation is commendable due to its simplicity, comprehensiveness, and clear definition. This model embodies a comprehensive approach to accomplishing systematic or organisational shifts spanning many different areas (Yousefzadeh et al., 2023). For example, Ivanov (2024) improved the theory with the management, scope and modelling element; while other studies have also included cost and factory element (Musa et al., 2016). Over time, Leavitt's Diamond Theory has been widely recognised and applied in previous studies on IBS (Abd Rashid, 2022; Hamid et al., 2011; Haron, 2013; Kamar, 2011; Musa et al., 2016, 2017; Nawi, 2012; Ruikar et al., 2006) in novel and critical ways. The alterations to the terminology of key elements (refer to Table 2) were seen as revisions to Leavitt's theory, incorporating modern concepts, rather than as modifications to the original theory's meaning.

Table 2. Terminology of Key Elements for Leavitt's Diamond, Modified Leavitt's Diamond and IPD

Leavitt's Diamond Model	Modified Leavitt's Diamond Model	Integrated Project Delivery
People	People	People
Task	Practice	Practice
Structure	Strategy	Business Structure
Technology	Technology	System

Consequently, this study used the terminology of key elements: people, practice, strategy, and technology. This study is supported by a model of Leavitt's Diamond Theory, as numerous prior studies have utilised the diamond model as the foundational framework for their investigations on IBS. Additionally, IPD is a project delivery method that integrates peoples, practices, business structures, and systems throughout the entirety of the design, fabrication, and construction processes. This is comparable to the four key elements of Leavitt's diamond model: people, task, structure, and technology.

Table 3. IPD-IBS Best Practices

No.	Author / Best Practice	(Yusof et al., 2015)	(Yunus et al., 2017)	(Nduka et al., 2019)	(El-Abidi et al., 2019)	(Baharuddin et al., 2019)	(Kasim et al., 2019)	(Wuni & Shen, 2020a)	(Rashid et al., 2019)	(Mohsen Alawag et al., 2022)	(Saad et al., 2022)	(Al-Aidrous et al., 2022)	(Nawi, 2012)	(Yu et al., 2019)	(Whang et al., 2019)	(Hamzeh et al., 2019)	(Franz & Roberts, 2022)	Total (√)
1	Effective communication	√	√	√	√		√	√	√	√		√	√	√		√	√	13
2	Key decision	√	√	√			√	√			√			√	√	√		9
3	Extension planning and schedule	√	√	√	√		√	√	√	√		√		√				10
4	Supply chain	√		√	√		√		√									5
5	Top-down management	√	√	√	√		√	√	√	√			√	√				10
6	Strategies on business and finance approach Financial	√	√	√	√	√		√		√		√						8
7	Close relationship with suppliers and sub-contractors	√		√					√	√			√					5
8	Information and communication technology (ICT)	√	√	√				√	√	√		√	√	√		√		11
9	Procurement systems	√	√	√	√	√	√		√		√	√	√	√	√		√	12
10	Efficient and experienced workforce	√	√	√	√	√	√	√	√		√	√					√	11
11	Teamwork	√	√	√	√	√	√			√	√	√	√		√	√	√	13
12	Standardisation	√		√	√		√		√		√	√						7
13	Good time management for the site, transportation, and machinery	√	√		√					√								4
14	Continuous improvement and learning	√	√	√			√		√	√	√				√			8
15	Education and training	√	√		√	√			√	√		√			√			8
16	Personal working attitude		√										√					2
17	Government policy				√	√				√		√	√					5
18	Collaboration		√				√	√	√	√	√	√			√	√		7

Table 3. IPD-IBS Best Practices (Continued)

No.	Author / Best Practice	(Yusof et al., 2015)	(Yunus et al., 2017)	(Nduka et al., 2019)	(El-Abidi et al., 2019)	(Baharuddin et al., 2019)	(Kasim et al., 2019)	(Wuni & Shen, 2020a)	(Rashid et al., 2019)	(Mohsen Alawag et al., 2022)	(Saad et al., 2022)	(Al-Aidrous et al., 2022)	(Nawi, 2012)	(Yu et al., 2019)	(Whang et al., 2019)	(Hamzeh et al., 2019)	(Franz & Roberts, 2022)	Total (√)
19	Risk management			√	√		√		√							√		5
20	Government support				√	√			√		√	√						5
21	Quality management									√	√			√				2
22	Project trend knowledge				√	√						√						3
23	Adaptability		√	√					√									3
24	Roles of Agencies					√						√	√					2
25	Shared risk and reward												√	√	√	√	√	5
26	Customer focus		√							√							√	3
27	Better coordination		√	√	√				√	√							√	6
28	Early involvement			√	√			√	√		√	√			√			7
29	Demand & supply			√					√									2
30	IoT											√						1
31	Robotic & Automation								√			√						2
32	Share objective and goal													√			√	2
33	Adequate staff																√	1
34	PM leadership and commitment																√	1
35	Mutual respect & trust		√										√	√				3
36	Speed of construction								√									1
37	Availability of plant								√									1
38	Owner competent																√	1
39	BIM								√	√		√	√	√	√	√		7
40	CAD												√		√	√		3
41	CAM												√					1

BEST PRACTICES FOR IPD IN IBS

Developing a formalised procedure to leverage beneficial experiences is key to best practice. This process facilitates the internal transfer of knowledge within an organisation through process improvements and the external exchange of information between organisations via models for quality enhancements, standardised information technology systems, and professional networks (Axelsson et al., 2011). Upon reviewing the literature authored by various scholars, it was concluded that the 41 best practices enumerated in Table 3 represent the critical criteria for the successful application of IPD in IBS.

RESEARCH METHODOLOGY

To achieve the aim of this research, a comprehensive literature review, a questionnaire survey, and a pre-testing questionnaire will be conducted prior to the pilot test. A thorough thematic analysis of the literature was undertaken to determine and verify the best practices of IPD-IBS, as described in the previous section. The best practices in Table 2 have been categorised into four elements, which are strategy, technology, practice, and people. Previous research findings on best practices served as a guide for this study, helping to categorise best practices within each element, and were validated by an expert panel. The preliminary data for this research paper were based on scientific and technical sources, including scientific journal articles, industry reports, websites, government technical reports, and university theses. A description of the leading research steps is provided below.

Stage 1 – Questionnaire Development and Pre-Test

This research used a questionnaire survey as the primary data collection technique. A mixture of digital and printed questionnaires was sent to participants. The survey used the Likert scale for all its questions. The finalised questionnaire comprises four sections: Part A, which provides basic information; Part B, which highlights IPD best practices in IBS; Part C, which focuses on IBS project performance; and Part D, which concludes the questionnaire. This research uses Leavitt's diamond model (1965) as a framework and, with modifications for IPD, categorises best practices into four sections in part B of the questionnaire. This model provides a foundational notion for the development of the conceptual framework. After the development of the questionnaire, a pre-testing questionnaire enabled the researcher to refine the questions developed before the pilot test (Bryman, 2012; Mahbub, 2015). The pre-test featured interviews with five experts who have accumulated expertise ranging from ten to twenty-five years, representing various organisations such as IBS contractors, IBS manufacturers, IBS consultants, and government agencies within the CIDB-IBS Sector. Creswell (2009) indicates that the appropriate number of experts for content verification of an instrument range from five to twenty-five. Consequently, the number utilised in this study is adequate. The survey was conducted from March to April 2023. Following the pre-test, the questionnaire was refined based on the feedback received to ensure that the final questions were as clear and understandable as possible.

Stage 2 – Pilot Survey

A pilot study involving a small sample of thirty-one respondents was conducted in May 2023. This study employed the methodology proposed by Hair et al. (2003) and Iram et al. (2016). A pilot study with fewer than thirty respondents would yield insufficient supplemental information for refining the instrument. The primary objective of the pilot test was to identify ambiguous questions and to conduct an initial evaluation of the data collection method (Chua, 2011; Creswell, 2005). The questionnaire was piloted with 31 respondents to assess its reliability. The questionnaires were sent to randomly selected companies from the CIDB list of IBS contractors with a grade G7 specialised in B01-Precast Concrete System. According to the Construction Industry Development Board (2021), most IBS systems use a precast concrete system. Furthermore, the circular issued by the government mandates the utilisation of IBS in government projects valued at RM10 million or more to attain a minimum IBS score of 70. Specifically, IBS contractors classified as G7 must handle projects exceeding RM10 million, which automatically requires them to use IBS. Besides that, the sample also consists of IBS consultants, IBS precast system clients, IBS precast manufacturers, and suppliers registered with CIDB. However, since this research is still ongoing as this paper is being written, the data presented here are only the findings from the pilot study. The "Cronbach Alpha" method quantifies reliability on a scale from 0, indicating no internal reliability, to 1, signifying perfect internal reliability. Bryman (2012) stated that a reliability reading of 0.6 is the minimum acceptable level, 0.7 is considered satisfactory, and 0.8 represents a good standard. Table 4 below shows the results of the reliability test for the questionnaires.

Table 4. Results of the Reliability Test Conducted in the Pilot Study Conducted

No	Element	Variable	No of Items Measures	Cronbach's Alpha
1	Strategy	IV	12	0.934
2	Technology	IV	9	0.927
3	Practice	IV	11	0.977
4	People	IV	11	0.961

FINDINGS AND DISCUSSION

Demographic Profile

Table 5 shows the background of the 31 respondents. The highest proportion of respondents who answered the survey was from Selangor, accounting for 58.0% of the total. In comparison, the second-highest is Sarawak with 19%, followed by Kuala Lumpur with 6.0%, and the remaining states, including Terengganu, Pahang, Kedah, Perak, and Johor, with 3% each. Besides that, only 48.0% of respondents are from contractor organisations, 26.0% from consultants, 13.0% from government agencies, and 3.0% each from manufacturers, suppliers/installers, developers/clients/project owners, and the education sector. Regarding job designation, 19.0% are civil/structural engineers, 16.0% are quantity surveyors, 13.0% are owner/CEO/directors and site supervisors, 6.0% are project managers and lecturers, 3.0% are architects, sales & marketing, site manager, QAQC engineer, planner, and senior executive business development. For educational qualification, 55% hold a degree, 42.0% possess a master's degree, and 3.0% have a Ph.D.

Table 5. Demographic Profile of The Respondents

Item	Description	Frequency	%
Location	Selangor	18	58%
	Kuala Lumpur	2	6%
	Terengganu	1	3%
	Sarawak	6	19%
	Pahang	1	3%
	Kedah	1	3%
	Perak	1	3%
	Johor	1	3%
Business Organisation	Contractor	15	48%
	Manufacturer	1	3%
	Supplier/ Installer	1	3%
	Consultant	8	26%
	Developer/Client/ Project Owner	1	3%
	Government Agency	4	13%
	Education	1	3%
Designation	Quantity Surveyor	5	16%
	Project Engineer	2	6%
	Civil / Structural Engineer	6	19%
	Owner / CEO / Director	4	13%
	Project Manager	2	6%
	Architect	1	3%
	Lecturer	2	6%
	Sales & Marketing	1	3%
	Site Manager	1	3%
	QAQC Engineer	1	3%
	Planner	1	3%
	Site Supervisor	4	13%
	Sr. Executive Business Development	1	3%
Education Qualification	Degree	17	55%
	Master	13	42%
	Ph.D.	1	3%
Working Experience	Less than five years	23	74%
	6 to 10 years	4	13%
	11 to 15 years	3	10%
	16 to 20 years	0	0%
	more than 20 years	1	3%
Types of Stakeholders	Government	9	30%
	Private	11	35%
	Both	11	35%
Types of IBS Project	Residential Projects	11	35%
	Non- residential projects	11	35%
	Both	9	29%
Location of IBS Projects	Urban	17	55%
	Sub-urban	4	13%
	Rural	5	16%
	All above	5	16%

In addition, most respondents have been involved in IBS projects for less than five years, which is 74.0%. Only 13.0% of the respondents have been in the construction industry for 6 to 10 years. However, the respondents have been in the construction industry for 11 to 15 years, which accounts for 10.0%, and the rest have been in the industry for more than 20 years, comprising 3.0% of the total. Regarding the type of stakeholders, only 30.0% of the project types were clients from the government. At the same time, most clients are of the private kind, with a combination of both, accounting for 35.0% of the total. Additionally, most respondents have been in the construction industry for 7-15 years, accounting for 56.6%. While the respondents have been using IBS in residential projects only, non-residential projects also account for 35.0% each, and a balance of 30.0% is allocated to both types of IBS projects. Finally, in terms of the location of IBS projects, the majority are located in urban areas (55.0%), followed by rural areas (16.0%), all locations, including urban, suburban, and rural areas (16.0%), and lastly, suburban areas (13.0%).

IPD-IBS Best Practices

The results of the data analysis are presented in Tables 6 to 9, ranking the current best practices of IPD in the implementation of the IBS from the highest to the lowest mean value within each element. For conciseness, only the three most effective best practices from each element are addressed.

Table 6. Best Practices of Strategy Element for IPD in IBS

Item	Strategy	Mean	Standard Deviation	Ranking
1	Project trend knowledge	4.677	0.979	1
2	Quality management	4.613	1.086	2
3	Roles and responsibilities	4.581	1.057	3
4	Business and financial	4.581	0.958	3
5	Government support	4.452	1.150	5
6	Share the objective and goal	4.452	1.028	5
7	Top-down commitment	4.452	0.961	5
8	The shared risk and reward	4.387	1.086	8
9	Government policies	4.355	1.170	9
10	Demand & supply	4.355	1.018	9
11	Risk assessment	4.290	1.039	11
12	Adaptability to IBS	4.226	1.023	12

Table 6 shows the ranking from number one (1) to twelve (12) from the highest to the lowest mean value for best practices under the strategies element. The highest ranking of best practices in the strategies element is project trend and knowledge (M = 4.6777, SD = 0.979) on IPD in IBS. This finding suggests that Malaysian contractors are well-versed in adopting IBS in the construction industry. According to (Al-Aidrous et al., 2022)With sufficient knowledge of the IBS of parties involved in construction, IBS would become more competitive and strengthen its industry position. Saad et al. (2022) identified that a failure to understand the categories of the IBS system in a Malaysian context deters parties involved from adopting the IBS system and alters the IBS adoption rate in Malaysia. The application of IBS addresses the problem of the conventional approach in Malaysia. Besides that, current project trends impose the need to adopt innovative technologies (IBS) and IPD business models to remain competitive and achieve a competitive cost advantage (Wuni & Shen, 2020a).

Quality management best practices rank second, with a mean score of M = 4.613 and a standard deviation of SD = 1.086. Quality management in IBS can refer to design codes and standards that directly influence the quality of industrialised buildings (Luo et al., 2015). In IBS implementation, construction components are produced and manufactured in a standardised line at the factory. CIDB Malaysia introduced Construction Industry Standard (CIS) 24: 2023 Industrialised Building System (IBS) Assessment & Certification. CIS 24 ensures that the IBS products and systems assessed meet quality assurance standards and outlines the rules that applicants must follow to qualify for CIS 24 certification. Using IPD in IBS improves quality by decreasing the number of technical, architectural, scheduling, and organisational modifications during the execution of the project (De Marco & Karzouna, 2018).

Roles and responsibilities (M = 4.581, SD = 1.057) and business and financial practices (M = 4.581, SD = 0.958) shared the third position in the strategy element. A clear understanding of roles and responsibilities in IPD for IBS is crucial as they influence the business strategies that support IBS. According to (Nawi, 2012), to become an effective IPD team in IBS projects, all the members must have a sense of ownership, clearly understand their roles, and be responsible for the project from beginning to end. These roles are of critical significance because they influence relational capability. The roles played by firms can reflect the industry's maturity and relational richness (Steinhardt et al., 2020). For business and finances, updating business strategies to suit IBS and have a competitive advantage is crucial for survival. This is in line with research done by Baharuddin et al. (2019); Yunus et al. (2017); Nduka et al. (2019); and Whang et al. (2019), where they identify business and financial practices as best practices because it can help to manage IPD in IBS projects with a collaborative business model in target project performance. Business and financial models also help parties to remain competitive and achieve a competitive cost advantage in the construction industry (Wuni & Shen, 2020a).

Table 7. Best Practices of Technology Element for IPD in IBS

Item	Technology	Mean	Standard Deviation	Ranking
1	Computer-Aided Design (CAD)	4.839	1.098	1
2	Speed of IBS construction	4.710	1.243	2
3	Information and communication technology (ICT)	4.581	1.409	3
4	Availability of plant	4.419	1.205	4
5	Computer Aided Manufacturing (CAM)	4.323	1.107	5
6	Internet of Things (IoT)	4.226	1.431	6
7	Building Information Modelling (BIM)	4.161	1.267	7
8	Virtual Reality (VR) and Augmented Reality (AR)	3.742	1.290	8
9	Robotic and automation	3.677	1.376	9

Many technology applications and tools have recently become available to the construction industry. Table 7 shows that CAD (M = 4.839, SD = 1.098) ranks first in the technology element. According to Johnston et al. (1999), CAD systems create graphical representations of objects, such as building locations and layout configurations. CAD also helps ensure the high productivity of IBS components (Akinradewo et al., 2021). Kiani et al. (2013) note that CAD can facilitate collaboration among all parties involved throughout the project, helping to avoid design and construction conflicts during the various phases. This ultimately leads to a project that is both on budget and on time, virtually unheard of in the building industry.

IBS reduces the construction project period compared to the conventional construction method. This time reduction is achieved due to overlapping work (Construction et al. (CIDB), 2018). For an IBS project, the components are produced concurrently with the site works, such as the earthwork or substructure work (Musa et al., 2017). The statement has been supported by Alinezhad et al. (2020), which concluded that in a comparison between the efficiency and productivity of IPD in IBS projects and non-IPD in IBS projects, the indicators of efficiency and productivity of IPD projects, including the speed of project delivery, achieved higher values. Thus, in the IPD-IBS based projects, changes have been fewer, the performance speed has been higher, and project delivery time has also improved significantly.

Information and Communication Technology (ICT) is a vital and reliable support tool to improve tendering, planning, monitoring, distribution, logistics, and cost comparison processes by establishing integration, accurate data, and effective management of project documents (Yusof et al., 2015). Using ICT management tools, IPD can integrate different types of information, work processes, and activities into IBS projects (Whang et al., 2019). Communication and information sharing among logistics companies, manufacturers, and assembly contractors are crucial to ensuring that every participant is informed about the progress at every stage of the supply chain. Thus, using ICT communication during all project phases, especially when dealing with specific problems, helps speed up the problem-solving process and help it converge to a better solution.

Table 8. Best Practices of Practice Element for IPD in IBS

Item	Practices	Mean	Standard Deviation	Ranking
1	Teamwork	4.742	1.182	1
2	Early involvement of team members	4.710	1.243	2
3	Standardisation	4.677	1.077	3
4	Supply chain	4.581	1.259	4
5	Better coordination	4.581	1.148	4
6	Design, manufacture, transportation, and installation	4.548	1.234	6
7	Mass production	4.516	1.061	7
8	Appropriate procurement method	4.484	1.387	8
9	Good working collaboration	4.452	1.207	9
10	Communication channels	4.355	1.199	10
11	Planning and scheduling	3.968	0.912	11

The highest mean score for the best practices item in the practice's element (Table 8) is for teamwork (M = 4.742, SD = 1.182). According to Mohsen Alawag et al. (2022), teamwork is another essential part of establishing a successful IBS organisation. The primary objective of the team strategy is to incorporate everybody in IBS, which comprises developers, consultants, contractors, vendors, subcontractors, and shareholders. Teams are an essential aspect of any IBS project because they allow different firm segments to collaborate to satisfy customer demands in a manner that individual work performance cannot. To carry out a project successfully, all participants must cooperate as a team, including clients, design teams, quantity surveyors, contractors, and specialists (Whang et al., 2019). With IPD contracts between IBS project team members, relationships can become more reliable, cooperative, and respectful (AIA et al., 2014).

The second highest best practice in the practice element is the early involvement of team members (M = 4.710, SD = 1.243). Managing the early stages of the IBS project life cycle is crucial, as empirical evidence shows that the ultimate success or failure of IBS projects often depends on decisions made during these initial phases (Wuni & Shen, 2020b). In an integrated project, the key participants are involved from the earliest practical moment. Decision-making is improved by the influx of knowledge and expertise from all key participants. Their combined knowledge and expertise are most potent during the project's early stages, where informed decisions have the most significant effect (AIA et al., 2007). Thus, an IPD contract based on early involvement and a concurrent approach should be considered during the development of the IBS project.

Standardisation (M = 4.677, SD = 1.077) is ranked number three for best practices for IPD in IBS for the practices element, and standardisation in IBS projects is significant in improving project productivity and the team integration process through IPD and facilitates cooperation between various parties in construction (Nawi, 2012). This statement aligns with research done by Jabar et al. (2013) and Al-Aidrous et al. (2022), where the authors identified that one of the success factors in IBS usage is the standardisation of components. Jamalluddin et al. (2022), stated that IBS is more complex and challenging when standardisation of the IBS components is not adopted in the manufacturing process. It demonstrates that standardisation is an essential and unavoidable stage in the manufacturing process to achieve full industrialisation in the IBS process.

Table 9. Best Practices of People Element for IPD in IBS

Item	Peoples	Mean	Standard Deviation	Ranking
1	Focusing on customer	4.935	1.209	1
2	Continuous improvements	4.903	1.136	2
3	Good personal working attitude	4.806	1.327	3
4	Mutual respect & trust	4.806	1.276	3
5	Close relationship	4.774	1.230	5
6	Key decision	4.742	1.210	6
7	Project Manager leadership & attitude	4.677	1.107	7
8	Training & Education	4.516	1.363	8
9	Staff qualification adequate	4.419	1.232	9
10	Efficient and experience	4.387	1.430	10
11	Owner competent in IBS knowledge	4.323	1.301	11

The customer has a significant role in enabling industry transformation, e.g., through collaborative models or by setting new requirements for projects and products (Peltokorpi et al., 2021). This indicates that focusing on customers (M = 4.935, SD = 1.276) is the best practice in the people element (Table 9) for IPD in IBS implementation. According to a study by Mohsen Alawag et al. (2022), IBS companies must develop updated or current consumer expectations and adjust organisational operations based on these expectations. Evans & Farrell (2023), mention that four main points need to be built for strong customer relationships and delivering customer-centric solutions: 1) ask questions to identify customer needs accurately, 2) prioritize work based on customer requests, 3) follow up with customers to ensure problems are solved and 4) benchmark customer feedback and satisfaction and provide innovative ideas to meet their future needs.

The second highest best practice in the people's element is continuous improvement (M = 4.903, SD = 1.136), where continuous improvement in managerial and technological personnel creates a balance in IBS implementation (Nduka et al., 2019; El-Abidi et al., 2019). All parties in IBS projects also need to participate in continuous improvement by practising many small changes in their working area and enhancing the construction site conditions with the instructions of applying IPD in IBS (Le & Nguyen, 2022). Capuyan and Jocson (2024), stated that continuous improvement and scaling, refining the framework, and expanding its application to other projects are necessary. Thus, the organisation's best practices and lessons learned are documented and shared to promote continuous improvement.

According to the AIA California Council (2014), integration also requires respect where the project team mutually commits to treating each other respectfully and valuing each professional's input. For trust, meaningful integration cannot occur without trust, and trust is fostered through experience together, as well as purposeful decisions (AIA et al., 2014). The focus of such integration is empowering the IPD, while IPD is the main component of building mutual respect and trust in the project team (Alinezhad et al., 2020). Therefore, there is a need for mutual respect and trust (M = 4.806, SD = 1.276) among critical stakeholders of the IPD-IBS project.

A positive personal working attitude (M = 4.806, SD = 1.327) is ranked number three, and it is vital in decision-making and strategy formation to achieve high project performance and influences the project-task-related characteristics and response to risk (Akmam et al., 2018). Research done by Nasrun et al. (2017), shows that personal working attitudes are essential for successful IPD in Malaysian IBS projects. As a result, all team members must prioritise maintaining a positive personal working attitude to mitigate the risk of project failure and avoid disputes among team members.

CONCLUSION

The implementation of IPD offers a viable and structured approach to overcoming longstanding challenges in IBS project execution in Malaysia. Through the identification of 41 key best practices across strategic, technological, procedural, and human resource elements, this study demonstrates the potential for enhanced collaboration, improved efficiency, and improved project performance. The findings underscore the importance of early stakeholder involvement, clear contractual structures, digital design tools, and continuous communication. By aligning these best practices with the principles of IPD, industry stakeholders can move towards a more integrated and sustainable construction environment. The study serves as a foundational reference for construction professionals, government agencies, and project managers aiming to optimise IBS outcomes and support national goals for construction innovation.

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DEVELOPING ENVIRONMENTAL SPECIFICATIONS FOR A SUSTAINABLE CONSTRUCTION INDUSTRY

Noor Aisyah Asyikin Mahat[1] and Mohamed Hafiz Md Isa[2]
[1]School of Construction Management & Quantity Surveying, College of Built Environment, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia
[2]Fakulti Teknologi dan Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia

Abstract
The construction industry is a major contributor to global resource consumption and ecological impact, highlighting the urgent need for sustainable development practices. Environmental specifications have emerged as a critical tool in promoting eco-friendly construction methods and materials in response to increasing sustainable concerns. In Malaysia, the environmental specification for construction projects often refers to the SIRIM Eco Label while also incorporating elements from other global eco-standards. However, there is a growing need to establish a more comprehensive and tailored framework to address the unique environmental challenges and regulatory requirements within the local construction sector. This necessity arises from increasing demands for sustainable practices and the need to align with international sustainability goals. To address this, the study focuses on developing environmental specifications tailored to Malaysia's construction sector, integrating the SIRIM Eco Label and international standards into the Malaysian Government Green Procurement (GGP) Guideline for three key products: paint, fibre cement, and masonry units. In this context, the research aims to identify and determine the key elements essential for creating an environmental specification specifically designed for the construction industry. The methodology adopted for this study includes extensive desktop research and a series of interviews with relevant stakeholders from the construction and regulatory sectors. By synthesising local and international eco-labelling frameworks, this study proposes a comprehensive set of elements to be incorporated into Malaysia's construction environmental specification. The findings propose a comprehensive framework to enhance sustainable construction practices, bridging gaps in policy and practice while aligning with global sustainability trends.

Keywords: *Environmental Specification; Green Procurement; Green Material; Sustainable Construction*

INTRODUCTION

The construction industry is a significant contributor to global resource consumption and environmental degradation, responsible for approximately 40% of total energy usage and a substantial portion of greenhouse gas emissions (IEA, 2020; United Nations Environment Programme, 2021). As awareness of climate change and environmental sustainability has grown, there has been an increasing push for sustainable construction practices that minimise ecological impact while promoting social and economic benefits (Zuo & Zhao, 2014). In Malaysia, where rapid urbanisation and industrial growth present unique challenges, the need for effective strategies that support sustainable development in the construction sector is more pressing than ever (Shafiei & Dola, 2015). Countries such as Sweden, renowned for their robust environmental policies and stringent eco-labelling systems, and broader European Union nations, with their well-established green procurement frameworks under directives like the EU Green Public Procurement (GPP), offer valuable benchmarks. These systems emphasise criteria such as lifecycle analysis, carbon footprint reduction, and circular economy practices. For Malaysia, understanding how its eco-labelling efforts and green procurement initiatives align with or diverge from these advanced practices can provide crucial insights into potential improvements and adaptations.

Environmental specifications have emerged as a critical tool to guide construction projects toward more sustainable outcomes. By defining the materials, processes, and standards that promote eco-friendliness, these specifications serve as a framework for decision-making at every stage of a project (Ding, 2008). In Malaysia, the SIRIM Eco Label is often referenced in developing environmental specifications, yet it is essential to recognise that sustainability is a multifaceted concept that can benefit from integrating various international eco-standards and frameworks (Khan et al., 2020). This research focuses specifically on developing environmental specifications limited to three construction products identified in Malaysian Government Green Procurement (GGP) Guideline 3.0, which are 1) Paint (PG-02), 2) Fiber cement (PG-03), and 3) Masonry unit (PG-30). The selection of these products is justified by their significant impact on both environmental performance and resource efficiency in construction. Paint contributes to indoor air quality and energy efficiency, with eco-friendly options reducing volatile organic compounds (VOCs) and enhancing energy performance (Sullivan & Seagren, 2019). Fibre cement is favoured for its durability and resistance to moisture, making it a sustainable alternative to traditional materials, while masonry is a staple in construction known for its longevity and thermal mass properties, which can lead to energy savings in buildings (Häupl et al., 2020). This research aims to fill the gap in knowledge regarding the key elements necessary for creating a comprehensive environmental specification tailored to the Malaysian construction industry. The findings are expected to provide valuable contributions to the advancement of sustainable construction practices in the region, supporting the ongoing efforts to mitigate environmental impacts and promote a sustainable future.

LITERATURE REVIEW

The rise in market demand for "green" products has led to an increase in standards aimed at promoting sustainability. As global awareness of environmental issues grows, the importance of green procurement practices in the construction sector has become evident. Green procurement focuses on acquiring goods and services that minimise environmental impacts throughout their life cycle, from production to disposal (Wang et al., 2018). This approach seeks to promote sustainable development by reducing resource consumption, minimising waste, and encouraging the use of eco-friendly materials. Oguntona and Aigbavboa (2017) highlight that the selection of products with unfavourable environmental impacts poses a significant challenge to the construction industry's transition toward sustainability. Construction, operation, and maintenance materials contribute to environmental degradation, hindering the industry's sustainability objectives (Ahn et al., 2010).

In recent years, Malaysia has made progress in formalising green procurement within its construction sector, integrating environmental considerations into procurement practices to achieve sustainable construction goals. The Malaysian Government Green Procurement (GGP) initiative aligns public sector purchasing with environmental sustainability, prioritising green products and services to facilitate a transition toward sustainable construction (Hassan et al., 2018).

Table 1. Environment Criteria Selection (Parameter)

Parameter	Description
1. Material Selection	Material selection in the product life cycle is a crucial aspect of sustainable design and manufacturing. The criteria mapping process involves extracting requirements on organic and/or recycled content from the GGP Guideline 3.0 to identify the minimum required recycled content and/or organic content for each product group.
2. Hazardous Substance Content	Hazardous content in products can have significant implications throughout the product life cycle, impacting human health, environmental quality, and regulatory compliance. Eliminating or minimising hazardous content throughout a product life cycle shall reduce health and safety risks as well as environmental risks associated with the product.
3. Design for End-of-Life	Design for end-of-life refers to a set of principles and strategies aimed at ensuring that products are designed with consideration for their eventual disposal, recycling, or reuse. The goal is to minimise environmental impact and resource consumption during the end-of-life phase by facilitating the recovery of materials, components, and resources for subsequent use. Design for end-of-life shall also include designing products that are reusable, recyclable, biodegradable, and modular (easily disassembled for repair, replacement, refurbishment and recycling).
4. Product Longevity/ Life Cycle Extension	Products with life cycle extensions are designed with a focus on extending their usable life by taking into consideration aspects such as durability, easy maintenance, repair-ability, and upgrade-ability, thus reducing the need for disposal.
5. Packaging	Packaging plays a significant role in environmental impact. The criterion focuses on reducing excess packaging materials and promoting reusable, recyclable and compostable packaging solutions. The mapping process focuses on identifying eco-friendly packaging options such as utilisation of recycled or biodegradable plastics, biomass packaging or recycled paper packaging materials.
6. End-of-Life Management	End-of-life management of a product refers to the processes and strategies employed to handle and manage the disposal, recycling, or reuse of products at the end of their useful life. A product take-back policy may be implemented by manufacturers or retailers to manage the collection and disposal of end-of-life products in a responsible and sustainable manner
7. Environmental Management	Management criteria encompass eco-conscious practices throughout the product's life cycle. This involves assessing the manufacturer's environmental policies, energy and waste management, and recycling programs. Environmental management requirements extracted from the GGP Guideline are compliance with the Environmental Management System and/or the Energy Management System.

Roles of Government Green Procurement (GGP)

Malaysian GGP initiatives play a crucial role in promoting sustainable practices by encouraging government agencies to prioritise environmentally friendly products in procurement decisions. By establishing guidelines and criteria for green procurement, these initiatives can influence market demand, encouraging suppliers to adopt greener practices. The Construction Industry Development Board (CIDB) has significantly advanced green procurement through its Green Technology initiative launched in 2009, which supports the GGP by urging stakeholders to use sustainable materials and providing related regulations and awareness tools. The government's commitment to promoting sustainable practices positions Malaysia as a regional leader in sustainable construction (Zhang et al., 2020). The MyHijau initiative further supports this by offering a comprehensive database of certified eco-friendly products, streamlining procurement processes. Additionally, the SIRIM Eco Label provides reliable environmental certification, encouraging the demand for sustainable products and motivating manufacturers to adopt eco-friendly practices. Together, these initiatives foster a culture of sustainability within Malaysia’s construction sector.

Despite positive trends and increased public awareness of eco-labelling, challenges remain in the collaboration between government and non-governmental institutions to promote sustainable materials. Greater cooperation and communication are essential to maximise the effectiveness of these initiatives.

Environment Specification in The Construction Industry

Establishing environmental specifications for products in the construction industry requires comprehensive selection criteria to ensure alignment with sustainability goals. This systematic approach aids decision-makers in selecting materials that minimise environmental impact while maximising performance and durability (Zhang et al., 2020). Selection criteria (see Table 1) encompass various aspects, such as material choice and hazardous substance content, which are vital for assessing the sustainability of construction practices (Wang et al., 2018). Additionally, these criteria promote principles like "design for end-of-life," encouraging the use of reusable or recyclable materials to reduce waste and foster a circular economy (González et al., 2019). By systematically selecting environmentally preferable products, stakeholders can stimulate innovation, support sustainable material sourcing, and enhance the viability of construction projects (Ahn et al., 2010). Ultimately, these criteria advance sustainable practices and align with broader environmental initiatives aimed at conserving natural resources and safeguarding human health (Oguntona & Aigbavboa, 2017).

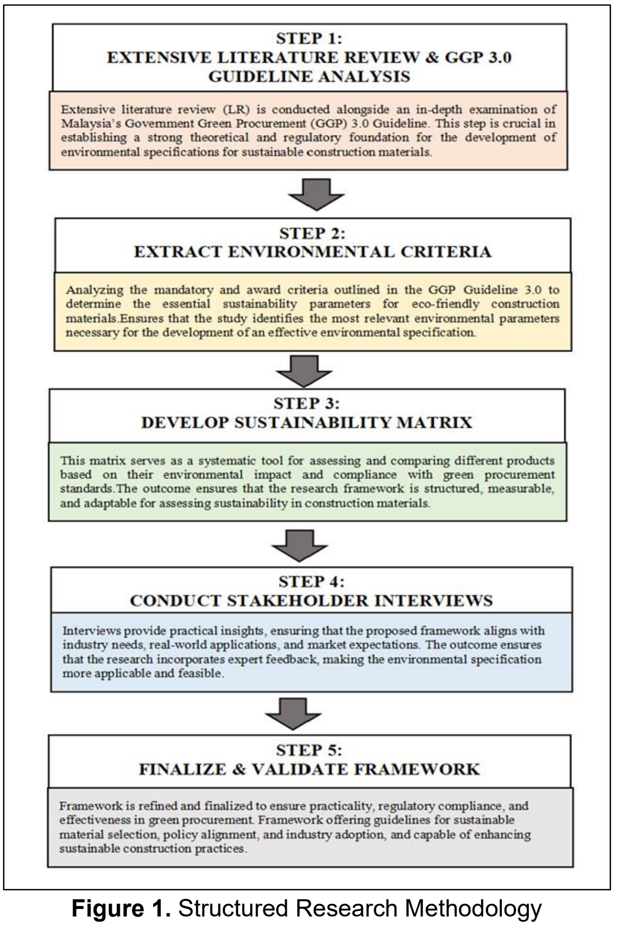

Figure 1. Structured Research Methodology

RESEARCH METHODOLOGY

The research methodology is designed to establish a structured framework that is essential for ensuring the effective execution of data collection and analysis. This systematic approach facilitates the smooth progression of the research process and is crucial for consistently achieving the defined research objectives. To accomplish this, the GGP Guideline 3.0 was thoroughly examined, and the relevant environmental requirements (from the mandatory and award criteria sections) for each product group were meticulously extracted. This information serves as primary data for the proposed Sustainable Matrix Checklist. To further enrich the finding's, semi-structured interviews were conducted with six relevant stakeholders from the construction and regulatory sectors. This qualitative approach aims to deepen the understanding of sustainability concepts and the adaptability of eco-labelling specifications for construction materials. The structured research methodology, illustrated in Figure 1, outlines the key steps undertaken, from data extraction to framework validation. The flowchart provides a clear visualisation of the systematic research approach, demonstrating the logical sequence of data collection, analysis, and integration. Details regarding the profiles of the participants are summarised in Table 2. Following the interview sessions, feedback will be compiled and integrated into the research findings, ensuring that the overall objectives are met.

Table 2. Profile of The Stakeholder Agreed to Interview

No.	ID	Participant Position	Participant Organisation	Experience in Construction	Experience in Green Product
1.	E1	General Manager	CIDB	25 years	20 years
2.	E2	Director	Manufacturer	20 years	15 years
3.	E3	Procurer	Government Agency	15 years	15 years
4.	E4	Procurer	Government Agency	18 years	10 years
5.	E5	Executive	SIRIM	20 years	20 years
6.	E6	Director	Manufacturer & Supplier	20 years	20 years

FINDING & DISCUSSION

The GGP Criteria Matrix (Product) in Table 3 provides a visual of the environmental requirements stipulated in GGP Guideline 3.0 for 1) PG-02 - Product Group "Paint", 2) PG03 - Product Group "Fibre Cement" and PG-30 - Product Group "Masonry Unit". The criteria in the matrix are used to identify the relevant parameters associated with the product.

Table 3. Criteria Matrix: GGP Product Requirement

Criteria	PG-02	PG-03	PG-30
	(Paint)	(Fibre Cement)	(Masonry Unit)
1. Material Selection *SIRIM eco-label requirement*	X	X	X
2. Hazardous substance content *Hazardous content (SIRIM eco-label)*	X	X	X
3. End of life management *Take back policy*	X		
4. Environmental management			
ISO 14001	X	X	X
ISO ISO 5001	X	X	X

Based on the criteria matrix, the detailed environment specification requirements are developed based on the standard compliance required in the GGP 3.0 guideline. The developed specification was then validated by selected stakeholders during the interview session to verify the confirmed relevancy of the criteria. The findings of all products are discussed below:

a) Table 4: Environmental Specification for Green Product: PG-02 “Paint”
b) Table 5: Environmental Specification for Green Product: PG-03 “Fibre Cement”
c) Table 6: Environmental Specification for Green Product: PG-30 “Masonry Unit”

The specification criteria for Product PG02 - Paint was presented to stakeholders during the interview session to confirm and validate the compliance of the developed specifications with the stipulated requirements in the GGP Guideline 3.0. While the criteria were generally accepted by all respondents, there was a notable concern raised by Respondent E4 regarding the requirement for "Packaging." E4 emphasised that the "Buy-Back Policy" should be excluded and not listed as an award criterion in the GGP Guideline 3.0. This recommendation is based on compliance with the Environmental Quality Act 1974 and the Environmental Quality (Scheduled Wastes) Regulations 2005, which classify paint materials as scheduled waste, necessitating their disposal rather than buy-back. Consequently, E4 suggested that the term "Buy-Back Policy" be clearly redefined to specify its appropriate scope and applicability.

Table 4. Environmental Specification for Green Product: PG-02 “Paint”

Product Criteria	Description
1. Material Selection	*a) Volatile Organic Compounds (VOCs)* In the material selection process for sustainable construction, limiting VOCs in paints is crucial for environmental and health benefits. According to SIRIM ECO 019:2019, emulsion paints must not exceed 50g/l of VOCs, water-based varnishes 100g/l, solvent-based paints and varnishes 300g/l, and industrial coatings 340g/l. These limits ensure that products meet both environmental and performance standards, contributing to better indoor air quality and reducing pollution. Compliance with these eco-label criteria aligns with green procurement strategies, promoting sustainability in construction projects.
	b) Environmental Feature/Solvent Type The type of solvent used in paints greatly impacts their environmental features, service provider must specify the solvent type for their products. Water-based paints are eco-friendly, with low VOC emissions, while solvent-based paints, using petrochemical solvents, have higher VOC levels but are more durable. Natural-based and plant-based paints use solvents from renewable sources, offering a greener option with low environmental impact. Recycled paints, made from leftover paint, reduce waste and resource use. Choosing paints with water, plant-based, or recycled solvents supports sustainability by lowering pollution and promoting healthier indoor air quality.
2. Hazardous Substance Content	Paint products must comply with SIRIM ECO 019:2019- Paint by limiting hazardous substances such as heavy metals (lead, mercury, cadmium, and chromium), aromatic hydrocarbons (e.g., toluene, xylene), halogenated hydrocarbons (e.g., chlorinated solvents), and formaldehyde. The standard restricts heavy metals to a maximum of 0.1% ppm and imposes strict limits on VOCs, including aromatic hydrocarbons, to reduce air pollution. Halogenated hydrocarbons are prohibited, and formaldehyde content must be below 0.01 to ensure minimal health risks. Compliance with these limits ensures safer products, reducing harm to human health and the environment.

Product Criteria	Description
3. Design for End-of-Life	a) *Shelf Life* The paint product must specify its estimated shelf life, indicating how many years the paint remains usable when stored in a sealed container from the date of manufacture. This helps users plan usage and prevent waste from expired products.
	b) *Unused Paint* Service providers are required to track and report the amount of paint sent for disposal compared to the total used. To reduce waste, they must aim to limit unused paint to 5%, presenting the data in either volume or weight, ensuring minimal environmental impact from excess materials.
	c) *Unused Paint Disposal:* Service providers must dispose of unwanted paint responsibly, following established procedures. They must show evidence of proper disposal at government-approved or private waste treatment facilities, ensuring compliance with environmental safety standards.
4. Packaging	a) *Metal Packaging Requirement* Metal containers used for paint packaging must contain no more than 0.01% (100 ppm) lead (Pb) by weight. The packaging must either be certified or undergo testing as specified by relevant industrial standards to ensure compliance and reduce environmental and health risks.
	b) *Plastic or PVC Packaging* Plastic or PVC packaging must be clearly marked with symbols identifying the type of plastic material used in accordance with Malaysian Standards. This ensures proper sorting, recycling, and disposal, contributing to environmental sustainability.
5. End of Life Management	Buy-back policy: Manufacturers or suppliers should offer a buy-back service for paint products that are no longer usable to reduce waste. Through this policy, they are responsible for maximising the reuse or recycling of unused paint and ensuring that any remaining product is handled in an environmentally safe manner. The buy-back initiative promotes waste reduction and supports the safe disposal of paint, preventing environmental harm.
6. Environmental Management	Paint products shall comply with ISO 14001, which requires the product to minimise environmental impact and meet environmental regulations, while ISO 50001 ensures the product is made with energy efficiency and reduced energy use in mind. Both aim for continuous improvement in these areas.

The specification criteria listed for Product PG-03 were thoroughly reviewed during the stakeholder interview, and all stakeholders unanimously agreed and accepted the proposed specifications. The criteria were found to be clear, comprehensive, and well-structured, effectively addressing the necessary requirements. Stakeholders confirmed that the specifications not only met the relevant guidelines but also aligned with the expectations for quality and environmental performance, ensuring a robust framework for product evaluation and compliance.

Table 5. Environmental Specification for Green Product: PG-03 "Fibre Cement"

Product Criteria	Description
1. Material Selection	a) *Product Quality* The fibre cement product must comply with Malaysian Standards (MS) for quality and adhere to local environmental regulations that prevent air pollution, water contamination, and improper waste disposal. It should be made from materials that minimise harmful emissions and environmental impact. Compliance with these requirements is based on SIRIM ECO 021:2017, which ensures that the product is both effective and environmentally friendly.
	b) *Source of Fibre* The organic fibres used in the production of natural and synthetic fibre cement composites must be sourced from sustainable, renewable, and recycled resources. This ensures that the materials contribute to environmental sustainability and reduce the depletion of natural resources. Using responsibly sourced fibres, the product supports eco-friendly practices and promotes a circular economy.
	c) *Percentage of Recycled Materials* The fibre cement product must contain at least 15% recycled material by weight in any of its parts or components. This recycled content helps reduce the demand for virgin materials, supports resource conservation, and minimises environmental impact.
2. Hazardous Substance Content	The fibre cement product must comply with the SIRIM Eco label (SIRIM ECO 021:2017) by ensuring it is free from prohibited chemicals such as asbestos, asbestos-containing minerals, and glass fibres. It should not contain toxic substances that could harm health or the environment. Additionally, any surface coatings or paints used on the product must meet relevant safety standards. Heavy metals composition must not exceed the limits specified in the eco-label, and to verify compliance, the product must undergo the Toxicity Characteristics Leaching Procedure (TCLP) Test according to USEPA Method 1311, ensuring that the maximum concentration of heavy metals leaching does not exceed 100 mg/L. This specification ensures the product is safe and environmentally friendly.
3. Design for End-of-Life	Instructions for the storage, transport, installation, and disposal of the fibre cement product must be clearly provided to ensure safe and responsible management at the end of its life cycle.
4. End of Life Management	The fibre cement product must be designed to be easily separable into recyclable or reusable units. It should be possible to disassemble the product without the need for specialised tools, allowing for straightforward separation of components. Each part of the product should be clearly identifiable to facilitate efficient sorting and recycling.
5. Environmental Management	Fibre cement products shall comply with ISO 14001, which requires the product to minimise environmental impact and meet environmental regulations, while ISO 50001 ensures the product is made with energy efficiency and reduced energy use in mind. Both aim for continuous improvement in these areas.

All the specification criteria listed for Product PG-30 (Masonry Unit) were agreed upon and accepted by the stakeholders. However, Respondents E1 and E2 suggested that the scope of the GGP 3.0 document should explicitly specify requirements for green procurement related to the supply of brick-and-block products, with particular emphasis on promoting the use of IBS Blockwork Systems. This approach is aimed at encouraging eco-friendly construction practices and enhancing overall project sustainability. They also recommended that the scope should include any hybrid materials used for masonry construction to ensure comprehensive sustainability coverage.

Table 6. Environmental Specification for Green Product: PG-30 "Masonry Unit"

Product Criteria	Description
1. Material Selection	a) *Recycled Materials* Masonry unit products must incorporate recycled materials such as quarry dust, pulverised fuel ash, incinerated industrial waste ashes, waste laterite, and sludge from water treatment plants. These materials must be approved by relevant authorities, such as the Department of Environment (JAS), to ensure they meet environmental and safety standards. This promotes the use of sustainable resources, reducing reliance on virgin materials and minimising environmental impact.
	b) *Percentage of Recycled Materials* The recycled content material shall not be less than 20 - 30%.
2. Hazardous Substance Content	The masonry unit product must comply with SIRIM ECO 023:2016 by ensuring that the maximum concentration of toxic substances does not exceed the specified limits. Toxic substances present in the product on a dry basis must be at concentrations equal to or lower than the values set in the standard. This ensures that hazardous content is minimised, protecting human health and the environment during production, use, and disposal.
3. End of Life Management	Masonry units should be designed for reuse or recycling. When properly managed, the product can be crushed and reused in new construction projects, promoting resource efficiency and minimising waste.
4. Environmental Management	Masonry unit's product shall comply with ISO 14001, which requires the product to minimise environmental impact and meet environmental regulations, while ISO 50001 ensures the product is made with energy efficiency and reduced energy use in mind. Both aim for continuous improvement in these areas.

CONCLUSION

The environmental design criteria for PG-02 (Paint), PG-03 (Fibre Cement), and PG-30 (Masonry Units) were found to be well-structured, clear, and compliant with the GGP Guideline 3.0. However, stakeholder consultations revealed significant concerns regarding the Buy-Back Policy for PG-02, which appears to conflict with Malaysia's Environmental Quality Act 1974 and the Scheduled Wastes Regulations 2005. To resolve these inconsistencies, it is recommended that alternative policy mechanisms be explored. These may include the adoption of Extended Producer Responsibility (EPR) frameworks, the establishment of regulated paint recycling systems, and the facilitation of industry-wide collaboration. Such measures would not only ensure regulatory compliance but also advance sustainability objectives within the construction sector. To further strengthen the implementation of the proposed specifications, a multi-faceted approach is recommended. This includes refining existing policies, initiating pilot programs to test feasibility, developing targeted training initiatives for industry stakeholders, and introducing incentives to encourage the adoption of green procurement practices. These steps are essential for creating a clear and enforceable regulatory framework, fostering greater uptake of sustainable practices, and driving innovation in the production and use of environmentally friendly construction materials.

The findings of this study provide a structured framework that can serve as a reference for improving eco-labelling initiatives and sustainable construction practices in other regions with similar environmental and regulatory challenges. Future studies can expand on this work by benchmarking international sustainability standards, exploring cross-border green procurement policies, and enhancing eco-labelling systems. Furthermore, capacity-building efforts, such as training for contractors, curriculum integration in universities, and professional certification programs, will be crucial in bridging the gap between theory and practice. By addressing regulatory concerns, fostering stakeholder engagement, and aligning sustainability with industry practices, this study contributes to the advancement of sustainable construction, ensuring long-term environmental and economic benefits for the sector.

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INNOVATING AN INTERPRETIVE PHENOMENOLOGICAL FRAMEWORK TOWARDS INVESTIGATING CONFLICTING ARCHITECT IDENTITIES IN THE DIGITAL CONSTRUCTION ENVIRONMENT

Syafizal Shahruddin[1] and Nurhidayah Rosely[2]
[1]School of Housing, Building and Planning, Universiti Sains Malaysia, Pulau Pinang, Malaysia
[2]Faculty of Business and Management, Universiti Teknologi MARA, Cawangan Kelantan, Kelantan, Malaysia

Abstract
The digital transformation of the construction industry, particularly through Building Information Modelling (BIM), is reshaping architects' professional identities. While interpretive phenomenology has been extensively applied in fields such as psychology, nursing, and healthcare to explore experiences like psychological distress, patient illness, and child development, its potential to illuminate the complexities of professional identity in architecture remains underexplored. This study, therefore, addresses this gap by formulating a novel interpretive phenomenological framework that integrates Smith's Interpretive Phenomenological Analysis (IPA), van Manen's hermeneutic phenomenology, and Lindseth and Norberg's hermeneutical method to capture the shifting identities shaped by technological advancements. Drawing on reflexive research practices, the study reveals four key insights: (1) reflexive engagement requires scholars to critically examine their ontological and epistemological assumptions to ensure the authenticity in capturing architects' dynamic identities shaped by technological, social, and personal influences; (2) inductive reasoning supported by a flexible conceptual framework uncovers identity paradoxes while maintaining analytical depth; (3) naive understanding, refined through a double hermeneutic process preserves the complexity of individual experiences; and (4) thematic structural analysis highlights tensions between traditional roles and digital expectations by offering layered insights into identity conflicts. This framework advances methodological approaches to studying professional identity in technologically mediated environments by offering a structured yet flexible tool for researchers. It also contributes to broader discussions on human-technology interaction and identity evolution, with implications for architectural practice, education, and policy in the digital age.

Keywords: *Interpretive Phenomenology; Methodological Framework; Professional Identity; Digital Construction; Building Information Modelling*

INTRODUCTION

The traditional image of architects as creative designers, prime decision-makers, and lone geniuses has long dominated the profession. Architects were seen as singular visionaries, blending aesthetics with functionality while independently crafting innovative solutions (Cole, 2019). As artists, they were regarded as possessing unique creative insight, capable of making decisive design choices and leading projects from concept to completion, often dictating the overall vision and guiding a team of specialists (Deutsch, 2020). However, this long-held notion is increasingly being challenged by the rise of digital construction practices. With the integration of digital tools such as Building Information Modelling (BIM), artificial intelligence (AI), cloud computing, 3D printing, and robotics, architects' design leadership status has been diluted (Kołata & Zierke, 2021; Kong & Jie, 2024). As projects grow more complex, architects must now adapt to new job patterns that emphasise collaboration over individual leadership (Shahruddin & Husain, 2024). Decision-making authority is shared with a wider range of stakeholders (e.g., engineers, sustainability consultants, data analysts, and digital managers), diminishing the architect's previous role at the helm of the design process (Ahuja, 2023). Simultaneously, the rise of new professional roles, such as BIM managers and digital engineers, has further fragmented the architect's traditional authority. Architects are increasingly becoming facilitators rather than sole decision-makers, collaborating with specialists whose technical expertise reshapes project outcomes (Shahruddin et al., 2022). This shift has eroded the "lone genius" archetype while presenting opportunities for architects to redefine their roles within a rapidly evolving construction landscape.

Given these changes, it is essential for architects to detach from the traditional notion of their identity to remain relevant in today's dynamic construction environment. Architects must navigate the paradox of rejecting the idealised identity that once granted them status in order to reclaim their place in a digitally driven and collaborative ecosystem (Shahruddin & Husain, 2024; Shahruddin et al., 2022) By embracing new identities, demonstrating adaptability, and integrating their creative expertise with digital and interdisciplinary processes, architects may not only retain their relevance but also lead the way in shaping the future of construction. In light of the complexity surrounding the evolving identity of architects in the digital construction environment, an interpretive phenomenology research design (Lindseth & Norberg, 2004; Manen, 2016; Smith, 2004) is deemed well-suited to explore this phenomenon. This approach enables an in-depth investigation into the lived experiences of architects as they navigate the conflicting and shifting aspects of their professional identity. Unlike quantitative or purely descriptive methods, interpretive phenomenology seeks to uncover the underlying meaning and subjective realities of individuals, which is crucial for examining the emotional and psychological dimensions tied to the transformation of architects' professional identities.

While interpretive phenomenology has traditionally found prominence in fields such as children's development, patient illness experiences, psychological distress, and nursing (Cuthbertson et al., 2020; Farr & Nizza, 2019; Firouzkouhi et al., 2022; Frechette et al., 2020; MacLeod, 2019; Stolz, 2020; Zahavi & Martiny, 2019), its application within the architectural field, particularly in BIM environments, remains underexplored. The dynamic interaction between humans and technology in BIM environments necessitates methodological innovations specifically tailored to investigate this evolving experiential landscape. Although phenomenology has been instrumental in exploring subjective experiences across various contexts, its adaptation to the intricacies of architectural experiences within BIM-based settings is still largely untapped. Therefore, the present study seeks to develop a methodological framework to study human experiences within technologically mediated environments, innovating upon the interpretive phenomenology tradition. This research aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities). By exploring architects' shifting identities in digital construction environments, the study supports innovation in sustainable construction and resilient urban design, emphasising human-centred approaches to technological adoption. The methodological innovation created in this exploration could serve as a valuable reference for fellow scholars, particularly those researching performance identity, BIM environment, and competence demonstration.

The first part of the article addresses the strengths and limitations of three prominent scholars in interpretive phenomenology (including that of Smith, van Manen, and Lindseth and Norberg) before proposing a novel methodological framework to meet the needs of the study. The second part clearly outlines the six core activities that constitute the innovated interpretive phenomenology framework to understand architects' experiences. The third part reflects the lessons learned from this adaptation. Finally, the paper concludes with a discussion of the research implications, limitations, and suggestions for future research directions.

THE POINT OF DEPARTURE TOWARDS INNOVATIVE METHODOLOGICAL FRAMEWORK

The ground-breaking approach of interpretive phenomenological analysis developed by Smith (2004) is fundamentally characterised by the following three features: idiographic, inductive, and interrogative. The first feature (idiographic) focuses on providing detailed descriptions of individual cases. Failing to do so may likely lead to the risk of losing the depth of individual experience. The second feature (inductive) concerns the essential themes of the phenomenon, which are grounded in the informants' experiential claims. The ideographic and inductive procedures are not sequential but rather iterative in nature. Technically, such a process cycle is termed "double hermeneutic." Finally, despite the tenets of interpretive phenomenology revolving around the depth of the phenomenon, the elicited experiences are not viewed as a separate discourse but rather are interpreted holistically in relation to the existing scholarship. Hence, the interrogative feature of interpretive phenomenological analysis.

It is worth noting that the interpretive phenomenological procedures are not rigid, specified, and prescriptive as in traditional descriptive phenomenology but rather auditable and flexible in nature to suit the needs of individual research studies (Pringle et al., 2011). The works of Lindseth and Norberg (2004), for example, propose the following three methodological steps based on the fundamental principles of "double hermeneutic": naive understanding, thematic structural analysis, and comprehensive understanding. The process of naive understanding is very similar to the concept of idiographics advocated by Smith (2004). In naive understanding, the phenomenologist would reflect and capture his/her immediate thoughts, perceptions, and reactions to each of the individual narrations. It has to be further validated and invalidated iteratively via thematic structural analysis, which is in accordance with the concept of "double hermeneutics." Also, Lindseth and Norberg's (2004) final series of steps (comprehensive understanding) appears to be consistent with the interrogative feature of Smith's (2004) version, considering that the researchers' naive understanding and the constructed themes via structural analysis are interpreted comprehensively in relation to the relevant literature. To summarise, whichever set of steps the researcher decides to commit to, the steps should warrant him or her to undergo a two-staged interpretive process.

With the flexibility of the nature of IPA in mind, the researcher altered Lindseth and Norberg (2004) interpretive phenomenological methodologies, making several improvisations, particularly on thematic structural analysis. The deployment of thematic structural analysis is considered appropriate for a research study that is purely governed by an inductive approach and has a limited theoretical background. That is to say, the codes are grounded in the informants' narratives via a "bottom-up" approach. The researcher, nevertheless, perceives himself as a co-interpreter by performing an active role in making sense of the phenomenon (refer to the following section for detailed clarification).

A question arose as to how the mentioned "analytical approaches" (techniques used to elicit and interpret experiences) advocated by Lindseth and Norberg (2004) and Smith (2004) fit within the broader framework of interpretive phenomenological "methodology" (the plan of action)? Van Manen (2016), for example, who is widely recognised and has worked intensively with hermeneutic (interpretive) phenomenology framework, proposes the following six main research activities with a specific focus on educational research: (1) turning to a phenomenon of particular interest to the researcher; (2) investigating experience as individuals live it rather than as they conceptualise it; (3) reflecting on the essential themes that characterise the phenomenon; (4) describing the phenomenon through the art of writing and rewriting; (5) maintaining a strong and oriented relation to the phenomenon; and (6) balancing the research context by considering parts and whole.

The methodological framework proposed by Van Manen (2016) differs in key areas from the interpretive phenomenological analysis of Smith (2004) and the phenomenological hermeneutical method of Lindseth and Norberg (2004). Van Manen's (2016) first step, which involves reflecting on the ontological and epistemological position of the researcher regarding the phenomenon, is not explicitly discussed by Smith (2004) or Lindseth and Norberg (2004). Van Manen (2016) emphasises the importance of understanding the researcher's assumptions and beliefs about the phenomenon before engaging with the data. This reflective stance is essential in phenomenological research as it shapes the entire inquiry. In contrast, Smith (2004) or Lindseth and Norberg (2004) place greater emphasis on reflecting and interpreting the meaning of the phenomenon from the participants' perspectives (data analysis) rather than foregrounding the researcher's preconceptions. While this reflection is implicit in their approaches, it is not formalised as a distinct step.

Next, Van Manen's (2016) second step emphasises investigating the experience as individuals live it, rather than as they conceptualise it. This step closely aligns with the data collection phase, focusing on capturing the immediacy of lived experience in its raw form. However, both Smith (2004) and Lindseth and Norberg (2004) tend to place greater emphasis on the analytical reflection and interpretation of the data, rather than on the lived experience itself during collection. This difference highlights a methodological gap in terms of capturing the pre-reflective nature of experience.

The third step of van Manen's process, reflecting on the essential themes that characterise the phenomenon, is a major concern from our perspective. While van Manen encourages the researcher to explore the existential significance of phenomena, such as identity, meaning, and temporality, this approach can be loosely defined, as pointed out by Govindarju (2017). This lack of specificity can present challenges when interpreting complex, individual lived experiences, making it difficult to systematically extract and present themes in a structured way.

To address this concern, the study opted for thematic structural analysis, following Lindseth and Norberg's (2004) approach, which offers a more rigorous and systematic method to derive and validate themes. This method is highly iterative, aligning with the double hermeneutic process of IPA (Smith, 2004), where initial interpretations (naive understanding) are continually tested and refined through further analysis. By combining the idiographic focus of Smith (2004) with the thematic structural analysis of Lindseth and Norberg's (2004), the study has ensured that each informant's experience is considered in depth, while also identifying broader patterns across cases.

In Van Manen's (2016) fourth step, the focus shifts to the presentation of data, which is essential to any phenomenological inquiry. Here, the goal is to represent the informants' experiences in a way that captures both their depth and complexity. Similarly, Smith (2004) and Lindseth and Norberg's (2004) emphasise the importance of presenting individual narratives while maintaining analytical clarity.

Lastly, van Manen's final step, balancing the research context by considering parts and whole, bears a strong resemblance to the comprehensive understanding stage described by Lindseth and Norberg and the interrogative feature of Smith's IPA. Both approaches emphasise the need to integrate individual narratives into a broader and holistic understanding of the phenomenon while also interrogating these findings against existing scholarship. This balance is crucial for developing a well-rounded analysis that respects both the individual depth and the theoretical context in which the research operates.

Building on the strengths and limitations of the interpretive phenomenological approaches proposed by Smith, van Manen, and Lindseth and Norberg, this study seeks to address a critical gap in the literature by exploring identity conflicts among architects in the context of a digital construction environment. Recent studies have applied interpretive phenomenology to investigate these issues within the Malaysian architectural context. For instance, Shahruddin and Husain (2024) examined the paradoxes of identity and leadership within the Malaysian construction industry, focusing on tensions between the roles of designer and technologist, as well as collaboration versus independence. Similarly, Shahruddin et al. (2022) investigated the performance-based identity of architects in a BIM environment, identifying key roles such as design strategist, facilitator, coordinator, and innovator. Asif et al. (2020) addressed challenges in defining a Malaysian architectural identity, particularly in relation to Western influences and client preferences for aesthetics over cultural representation. Nevertheless, while these studies contribute valuable insights, the application of interpretive phenomenology in examining identity conflicts in the context of a digital construction environment is not well documented or reflected upon for use by other scholars. Therefore, there is a clear need for further methodological development in interpretive phenomenology to deepen the understanding of these identity conflicts and provide a more robust framework for investigating the psychosocial dimensions of architecture in the digital era. This innovative methodological framework is further elaborated in the following section.

METHODOLOGICAL CONSIDERATIONS

Assessing the strengths and limitations of Manen (2016), Lindseth and Norberg (2004), and King (2012) in interpretive phenomenology methodologies in relation to the nature problem of the study, the authors have adapted and innovated them into six core research activities. These activities encompass (1) the phenomenological orientation of the researcher, (2) sampling strategy and procedures, (3) lived experience investigation, (4) essential themes of reflection and isolation, (5) validation of interpretations, and (6) presentation of phenomenological findings. To illustrate the implementation of these activities within qualitative research, this study draws on examples from the author's own research, reflecting Malaysian architects' experiences in navigating, behaving, and assuming various conflicting identities within a BIM environment.

The Phenomenological Orientation of the Researcher

The phenomenological orientation of the researcher emerged from personal experiences with the phenomenon. This orientation significantly influenced the formulation of specific research questions and shaped the conceptual framework of the study, as detailed in the following sections.

Experience of The Researcher

The ontological and epistemological presuppositions of the researcher are closely related to their phenomenological orientation. The researcher's perception and conceptualisation of phenomena are shaped by their ontological beliefs, which also influence their assessment of whether the phenomenon represents a single reality or several realities. Simultaneously, epistemological assumptions revolve around how experiences are formulated and unearthed, including the researcher's relationship with the phenomenon under investigation.

The research trajectory has been significantly shaped by the first author's academic pursuits and industry engagements. After completing architectural degrees, the first author spent three years actively involved in a BIM-based architectural practice in Kuala Lumpur, Malaysia. Subsequently, advanced studies focused on integrated design and BIM were pursued at Salford University. Following this, industrial placements were undertaken within major construction firms heavily involved in BIM-driven projects. This practical experience prompted critical reflections on the limitations of using positivist epistemology to understand phenomena in this environment.

Such exposure within such environments reshaped the first author's perception of an architect's identity. It became evident that addressing issues related to BIM tasks during construction should ideally commence during the design phase, utilising BIM methodology. However, the architectural consultants lacked sufficient digital proficiency at that time. Consequently, design leadership gradually shifted to a third party, the BIM consultant, challenging the traditional perception of architects as inherent leaders. This transformation highlighted the need for architects to not only modify their work processes but also adapt to various personalities, characteristics, and traits to stay relevant in the digital age. That is to say, embodying various identities that challenge the norm of architects' professional identity as a natural leader.

In attempting to understand how architects manifest their identity within a BIM environment, it was found that fitting social norms into a broader context was inadequate. The conventional view of architects as natural leaders and prime decision-makers in a singular reality lost relevance in the digital landscape. Consequently, the traditional positivist approach was not suited to this study. Each architect had unique experiences and motivations. Drawing from the first author's firsthand experiences, architects' experiences were shaped by diverse factors like interactions and perspectives. This realisation guided us toward an interpretive phenomenological orientation, aiming to collaboratively understand the multifaceted and context-driven nature of architects' experiences.

Formulation of Specific Research Questions

Studies are not done in isolation; they are inherently linked to the existing knowledge within a field. Thus, upon gaining clarity about presupposition and experiences regarding the phenomenon, a critical review of pertinent scientific literature was undertaken. The intention was to explore how previous scholars have addressed a practical problem within a real-life setting. Such exploration guided the process of formulating a specific research question for this study. There are significant population and methodological limitations in the literature on identity construction, development, and manifestation in a BIM environment.

Considering the first limitation, previous studies have tended to focus on the sustainability of BIM specialist roles and construction professionals working in contractor, engineering, and management consultancy practices, with less attention given to those in architectural-based practices (Akintola et al., 2017; Azzouz & Papadonikolaki, 2020; Ernstsen et al., 2021; Olugboyega, 2022). Nevertheless, the manifestation of architects' identity has always been associated with the following ethos that distinguishes them from other construction and creative professionals: their design signature, their aesthetic originality, their work philosophy, and their creativity. Considering that this ethos remains significant, it was argued that architecturally trained individuals, particularly those serving an architectural consultancy practice, may perceive their identity differently from other construction professionals in a BIM environment. Secondly, previous studies have not explored how construction practitioners, particularly architects, adopt and express conflicting identities within the context of a BIM environment, largely due to the quantitative nature of their research inquiries (MacManus & O'Donnell, 2024; Olasunkanmi et al., 2023; Omer et al., 2022; Zhang et al., 2018).

To fill the gaps in the literature, this study sought to investigate the contradictory identities that architects face in reaction to the challenges of working in a BIM environment within architectural consulting practices. As a result, the following research question was formulated: What specific types of conflicting identities do architects experience in response to the challenges posed by the BIM environment within architectural consultancy practices? (Shahruddin & Husain, 2024). To sum up, the formulation of specific research questions in the phenomenology study was derived from the researchers' prior experiences and the identified research gaps within the scholarly world.

Conceptual Framework Formulation

The study acknowledged that qualitative research, especially in phenomenological research design, often relies on inductive reasoning, where researchers explore phenomena to develop explanations or theories. In this approach, constructed experiences stem directly from individuals' narratives. However, we align with Maxwell's (2013) perspective, which suggests that a researcher's interpretation of participants' experiences is subtly influenced by their pre-existing understanding of the phenomenon and existing theories. This raises the question of how to balance the use of inductive reasoning and a theoretical or conceptual framework in eliciting participants' experiences. Therefore, determining the use of a theoretical or conceptual framework becomes essential to address this concern.

In this study, the conceptual framework served as both a "decipherer" and a "gap spotter" (Larsen & Adu, 2022; Maxwell, 2013). Firstly, as a decipherer, it helped me make sense of my pre-existing understanding by connecting to the relevant information. This facilitated the identification of the most effective approach to address the identified problem. For instance, concepts like identity paradox and performance-based identity were adapted after a thorough evaluation of various theoretical concepts (such as identity work, identity regulation, and social identity) in relation to the problem under study.

However, the conceptual framework also revealed certain gaps, as discussed in previous sections, such as methodological inadequacies and unexplored perspectives from individuals trained in architecture. This role as a "gap spotter" highlighted areas requiring further exploration or refinement. These limitations guided the refinement of the research question, thus contributing to the body of knowledge in this area. The following methodological research activity focuses on the sampling strategy to recruit potential informants for the study.

Sampling Strategy and Procedures

The informants in this study represent a subset of the architectural professional community within the Malaysian construction industry. Specifically, the study targeted architecturally trained individuals engaged in architectural consultancy practices (ACPs) rather than those employed by main contractors or client organisations. To identify suitable informants, the "key informant technique" (Marshall, 1996) was predominantly employed, supplemented by the snowball technique (Moser & Korstjens, 2018). Given the limited number of individuals who have experienced the phenomenon being studied, the key informant technique helped in purposefully identifying informants who not merely meet specific criteria but also possess extensive knowledge, expertise, and experience within a specific phenomenon. The predetermined criteria included (1) position and responsibilities, (2) knowledge and personal skills, (3) willingness, (4) communicability, and (5) impartiality. Once ethical approval was obtained from the Research and Innovation Office, potential informants were identified through several steps: (1) seeking recommendations from BIM-based public and private organisations; (2) collaborating with the Malaysian Institute of Architects (PAM) BIM committee; (3) obtaining recommendations from informants' employer and co-workers; (4) conducting informal discussions to evaluate potential informants' communication and articulation abilities; and (5) evaluating each informant against the predetermined criteria.

The study selected a small group of architects for this study based on four key justifications. First, the focus of this research is on an in-depth exploration of individual experiences using interpretive phenomenology, which seeks to provide rich insights into how architects navigate multiple identities in a digitally mediated environment. This approach emphasises depth rather than the breadth typically associated with descriptive phenomenology. Second, it is common in phenomenological studies to work with small samples, typically ranging from 3 to 25 participants, to achieve data saturation (Larsen & Adu, 2022). Third, informal discussions with members of the PAM Research and Futures Committee and the Council of Architectural Accreditation of Education Malaysia (CAAEM) revealed a lack of agreement among institutional players on how architects' identities may develop in the context of digital transformation. This led us to focus on individuals at the grassroots level to capture personal, lived experiences. Fourth, to compensate for the small sample size, we conducted multiple rounds of interviews and utilised a range of data collection methods to ensure comprehensive insights into the phenomenon. Finally, based on the understanding that six to seven participants typically capture around 80% of the key themes (Guest et al., 2020), we concluded the recruitment of 14 informants, as no new data or themes emerged during the thematic structural analysis phase. This decision aligns with Guest et al. (2020), who suggest that an initial saturation assessment should be conducted after six interviews and that achieving a higher degree of saturation typically requires 11 to 12 informants. With 14 participants, the study exceeds this threshold, hence justifying the small sample size in the present study.

Live Experience Investigation

To capture the lived experiences of the informants, a combination of written accounts (Langdridge, 2007) and in-depth, semi-structured interviews (Patton, 2015) was employed. Initially, informants were invited to express their thoughts, reactions, and feelings in writing about any experiences they wished to share. This approach aimed to prevent their disclosures from being unduly influenced by the study's agenda, the researcher's predispositions towards the phenomenon, or the professional relationships established during the study. The written account exercises offered informants the opportunity to thoughtfully organise their experiences, bridging past occurrences and potential future events into their present experiences at a time of their choosing (Handy & Ross, 2005). However, it is acknowledged that such exercises may impose demands on informants, requiring time, effort, and commitment (Langdridge, 2007). Recognising this potential challenge, the authors provided specific guidance to informants, including (1) a recent and specific event within the BIM environment considered crucial for challenging their inherent identity; (2) details regarding the occurrence, including what happened and when; (3) information about the other actors involved in the situation; (4) insights into cognitive thought processes, reactions, feelings, and actions taken while navigating conflicting demands; and (5) a suggested length of an A4 paper for each written account. This structured approach aimed to balance the need for rich, detailed data with an awareness of potential time and effort constraints on the informants.

The subsequent phase involved conducting in-depth, semi-structured interviews to capture the lived experiences of the informants (Langdridge, 2007; Patton, 2015). The interview schedule and guiding questions were crafted in alignment with the conceptual framework and customised based on the written accounts provided by each informant. Instead of being strictly governed by the researchers' agenda, the structure of the interview sessions was intended to be more discursive by allowing for a free-flowing interchange of experiences. Informants signed a consent form provided by the institution to indicate their willingness to participate in the study. Follow-up interviews were carried out in order to improve rapport with the informants and obtain a better knowledge of experiences that could have been less obvious (Elliott, 2005). Every conversation was painstakingly captured on tape and accurately transcribed. This comprehensive method is intended to capture the subtleties of the informants' narratives and ensure a detailed analysis of their lived experiences.

Essential Themes Reflection and Isolation

The reflection and interpretation of themes that emerged were guided by the following three analytical approaches: naive understanding, thematic structural analysis and comprehensive understanding (Lindseth & Norberg, 2004). It is worth noting that the aforementioned three analytical approaches in interpretive phenomenology are not rigid, specified, and sequential as in traditional descriptive phenomenology but rather iterative and flexible in nature to suit the needs of individual research studies.

Naive Understanding

To comprehend the entirety of the informants' experiences, the authors initiated a preliminary understanding by engaging in a naive reading (Lindseth & Norberg, 2004). This involved freely reflecting on immediate reactions and thoughts in response to individual interview transcripts and written accounts provided by the informants before producing the essence of the phenomenon. Neglecting this step might pose the risk of overlooking the depth of individual experiences. The depth of idiographic engagement at this stage was crucial to uncovering the richness of lived experiences, which might be diluted if the analysis proceeded too quickly to converge the experiences. Drawing from personal experiences and theoretical orientation of the phenomenon, this initial interpretation sought to capture the holistic meaning of individual perspectives from informants in their unique contexts. Members of the research team meticulously revisited each transcription over five times, actively listening to audio recordings and paying attention to natural elements of speech, including intonation, pitch, and stress. The overarching question guiding this process was: What specific types of conflicting identities do architects experience in response to the challenges posed by the BIM environment within architectural consultancy practices? A naive understanding was documented for each informant to avoid the risk of overlooking the depth of individual experiences, as in descriptive phenomenology. Below is an excerpt from the first author's naive understanding of the seventh informant (K7):

> *"I was very inspired by the seventh informant's (K7) conviction, courage, and desire to advocate his novel ways of working in design management practices to a more experienced member within the organisation. Despite being less experienced in the field, K7 has been actively involved in facilitating and coaching the organisational team members in their digital delivery process due to his technical proficiency in presenting BIM solutions. K7 seemed to mostly act as a translator or mediator in bridging the gap between the idealistic expectations of the senior project architects and the practical views of BIM implementation experienced by the technical BIM team members."* (Shahruddin, 2022)

The naive understanding above highlighted a commitment to understanding specific individual experiences by giving due attention to that informant's unique context, motivations, and challenges in manifesting his/her identity. By focusing on K7's distinct role as a mediator in BIM implementation, for example, the study managed to capture the divergence within the data, highlighting how K7's experience might differ from others in terms of his technical proficiency, advocacy, and leadership role despite being less experienced.

Thematic Structural Analysis

As the initial naive understanding was developed, the thematic structural analysis was initiated to validate and challenge these preliminary insights (Lindseth & Norberg, 2004). In the first phase of thematic structural analysis, the data (consisting of interview transcripts and written accounts) were decontextualised into meaning units or segments of text perceived as relevant to contributing to the understanding of conflicting identities experienced by the informants within the phenomenon. The meaning units could range from parts of sentences to several sentences or even entire paragraphs related to the formulation of themes.

The second phase involved condensing the meaning units into everyday language. These were expressed in layman's terms and phrases, providing a literal description of the written and disclosed experiences encapsulated in labelled codes. These codes were associated with actions, personality traits, characteristics, values, beliefs, or emotions of the informants, reflecting their identity in a BIM environment. Additionally, the meaning units were condensed as quickly and spontaneously as possible to explore potential directions for future research.

In the third phase, codes with similar characteristics were grouped to form broader categories. At this stage, the analysis transcended surface-level, literal meanings from the second phase, transitioning into deeper connotations and latent meanings within the data. An iterative process was employed, shifting between semantic (literal) and latent (underlying) levels to refine the codes and categories as new insights emerged. This phase also marked the beginning of the member validation process, during which informants were regularly consulted through informal interviews to clarify the emerging categories, particularly those related to conflicting identities. If the validated categories contradicted the initial naive understanding, a thorough re-examination of the entire text ensued. This iterative step led to the development of a new understanding, subsequently validated through a fresh round of thematic structural analysis. This process is technically referred to as a "double hermeneutic," indicating a dual interpretation wherein the experiences are interpreted from the informants' perspectives while concurrently refining the evolving understanding (Pietkiewicz et al., 2014). An example of validating and challenging the naive understanding against the emergent experiences induced by the phenomenon is provided below:

> *"During my time practising BIM with architectural practices in Kuala Lumpur, I experienced a hard time changing the team members' mindset, especially for those at the middle and top-level people, towards working digitally. They argued that the use of Revit has robbed the creative mind of exploring design naturally as individuals tend to invest their time more towards developing a workaround due to the capability's limitations of certain software. Such a phenomenon is very much relatable to the ninth informant's (K9) experience, as he explained: "Whenever the topic of the workflow was brought up in a meeting, the conversation always ends up with the old-timer saying they did not need 3d back in their days and end up becoming a generation debate instead of moving forward. Honestly, this issue can only improve in time as the new generation takes over slowly, bit by bit, at the top management". From my perspective, this may be avoided once individuals cognitively understood the concept of digital workflows in the design process. Such personal claim was further illuminated by the first informant (K1): "I think it is important for the lead*

designed. When I say this, it is either myself or any designer in the team to be in the model, so when I say in the model, it is not only being able to open the PDFs or CAD drawings, but it is able to manipulate the model or adjust it accordingly. This is where the generation of architects, especially like me, are still able to understand the process, be in the BIM model, adjust it accordingly and make the required changes." (Shahruddin, 2022)

The example provided illustrates the double hermeneutic process by showcasing the iterative nature of interpretation and validation within the research context. Initially, personal experience working with BIM in architectural practices prompts an interpretation regarding resistance to digital workflows among middle and top-level personnel. This interpretation is then validated through the experiences shared by informants, particularly informant K9, who articulate similar experiences within their own professional setting. Subsequently, informant K1's perspective further validates our initial interpretation, emphasising the importance of lead designers being actively engaged in the BIM model to facilitate understanding and adaptation to digital workflows. Through this process of interpretation, validation, and refinement, deeper insights were gained into the phenomenon of resistance to digital transformation within architectural practices, demonstrating the application of the double hermeneutic approach in understanding and analysing lived experiences.

Table 1. Example of Thematic Structural Analysis

Semantic Level of Analysis		**Latent Level of Analysis**	
Meaning Unit	**Codes**	**Category**	**Final Theme**
"It happened when I was working with a client with a very specific design vision. I disagreed with some of their ideas because they were impractical and not in line with our design principles and style. The client was insistent on their vision, so I had to find a way to work with them while upholding our design principles (K9)"	Disagreement with client's design vision, upholding design principles.	Balancing client vision and design principles.	Harmonising technical proficiency and social adaptability. Description: This central theme encapsulates the overarching struggle experienced by architects in a BIM environment as they navigate the conflicting demands of technical expertise and social interactions.
"Let me give you a few examples. For our American project, I had to deal with a very picky structural engineer. Every design decision we made was met with challenges, but in the interest of serving the client well and keeping the project on schedule, I made adjustments and presented several options that met our aesthetic standards (K6)"	Dealing with picky structural engineers, adjustments for client satisfaction.	Navigating interdisciplinary collaboration.	
"Our team was adept in using BIM tools and handling the technical parts of the design process, but there were communication gaps and misconceptions within the disciplines, notably regarding the specialised needs of a healthcare institution. By holding monthly interdisciplinary workshops on healthcare-specific design issues such as patient flow, infection control, and medical equipment integration (K9)"	Addressing communication challenges and disciplinary misunderstandings through monthly interdisciplinary workshop.		

In the final phase, all labelled codes and categories were systematically converged to reflect the conflicting identities experienced by architects, culminating in the development of the final themes of the informants' experiences. These themes captured the informants' real-life experiences and were refined through multiple rounds of member validation to ensure that the constructed themes and categories accurately represented the informants' perspectives. This process helped directly address the central research question of the study. A sample illustrating the semantic and latent levels of the thematic structural analysis is presented in Table 1. The constructed codes, categories, and final themes were organised into a thematic analysis matrix (TAM) (Zairul, 2021).

Comprehensive Understanding

As previously debated, despite the principle of interpretive phenomenology revolving around the depth of the phenomenon, the elicited experiences are not viewed as a separate discourse but rather are interpreted holistically in relation to the existing scholarship. Hence, it justified the employment of a comprehensive understanding method to elucidate the informants' experiences in relation to the researchers' pre-existing knowledge and relevant literature. The following example demonstrates a thorough integration of existing literature with the informants' experiences in navigating the duality of technical and social identities in BIM environments, drawing on insights from various sources such as Shahruddin et al. (2021), Azzouz and Papadonikolaki (2020), Omer et al. (2022), and Papadonikolaki et al. (2022). This measure is necessary to demonstrate how the essential meanings of the phenomenon have enlightened, challenged, and contributed to the identified gaps within the existing literature.

> *"The informants' experiences underscore the crucial role of soft skills—such as communication, collaboration, and relationship-building—alongside technical expertise during the ongoing process of digital transformation. Their insights affirm existing literature that highlights the need for professionals to balance their technical and social roles iteratively. Shahruddin et al. (2021) emphasise that architects must possess a blend of personal competencies, including analytical thinking, communication, leadership, and management skills, to successfully engage in collaborative environments. Similarly, Azzouz and Papadonikolaki (2020) stress the value of soft skills, such as fostering a mindset of sharing and transitioning between technical and non-technical roles, especially in digital innovation contexts. Supporting this, Omer et al. (2022) and Morgan and Papadonikolaki (2022) highlight that digital transformation in construction is inherently socio-technical, requiring leadership qualities like communication, openness, responsibility, and multicultural awareness to foster effective collaboration in BIM-driven projects. However, much of the existing literature has predominantly focused on other construction professionals and how they navigate the duality of technical and social identities. This study, by focusing on architects, provides fresh insights into how they specifically approach digital transformation, balancing their technical expertise with essential interpersonal skills like teamwork and relationship-building. This analysis brings into focus the unique context within which architects operate, shaped by their professional culture, ideology, history, and belief system, and how these factors influence their adaptation to evolving digital environments."* (Shahruddin & Husain, 2024, p. 603).

The passage reflects the hermeneutic circle as the experiences of the informants are not viewed in isolation but are interpreted in relation to the broader scholarship on soft skills and digital transformation in the construction industry. The study discussed the informants' shared experiences with studies by Shahruddin et al. (2021), Azzouz and Papadonikolaki (2020), Omer et al. (2022), and Morgan and Papadonikolaki (2022). This exemplifies the hermeneutic circle by showing how these findings inform the interpretation of the data while also allowing the informants' insights to contribute to and potentially challenge existing theories. The three analytical approaches discussed (including of naive understanding, thematic structural analysis, and comprehensive understanding) are summarised in Figure 1.

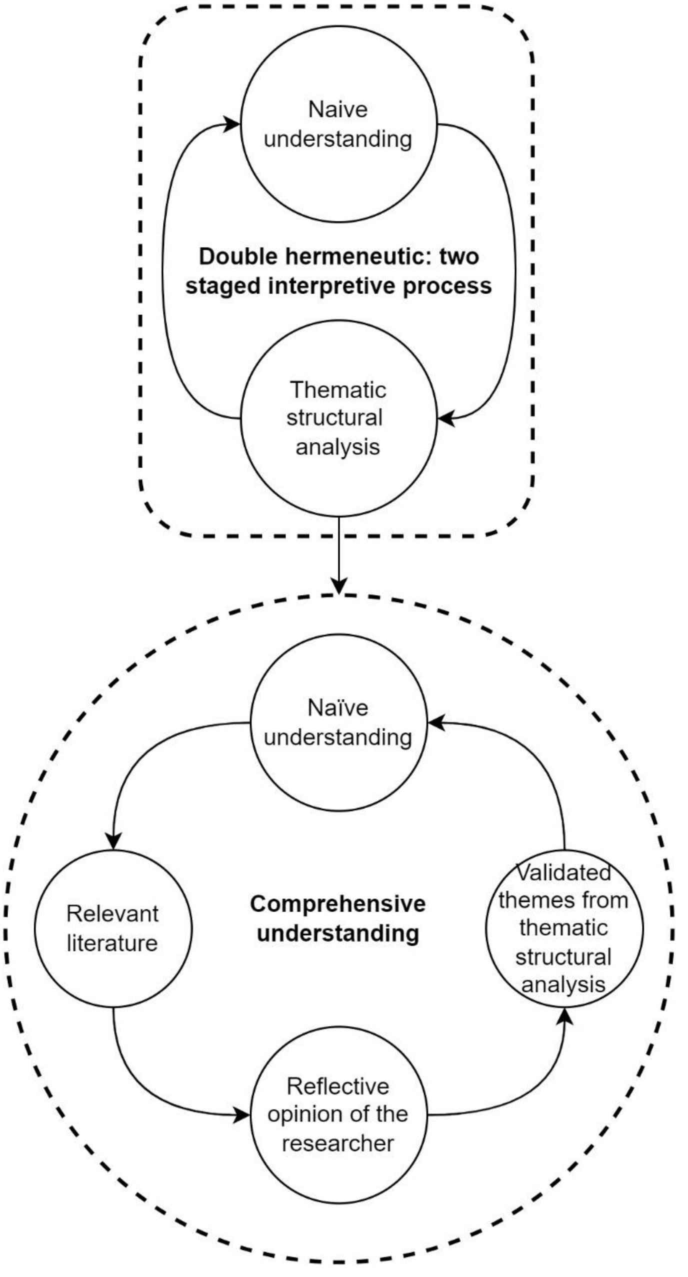

Figure 1. Naive Understanding, Thematic Structural Analysis, and Comprehensive Understanding

Validation of Interpretations

Several questions arose about the level of confidence placed on the accuracy of the meanings of the interpreted data (credibility), the impartiality by which the interpretation should be clearly derived from the informants' narratives (confirmability), the applicability of validated experiences in other contexts (transferability), the stability and consistency of the findings (dependability), and the implication of the researcher's prior experiences, and the relationship he/she develops with the informants towards data interpretation (reflexivity). The validation strategies, therefore, were not deployed sequentially but rather occurred concurrently throughout the lived experience investigation and reflection processes to validate the interpretations (refer to Table 2).

Table 2. Validation of Interpretation Strategies

Criteria	Stage	Strategy employed
Credibility	Lived experienced investigation and essential themes reflection and isolation.	Member check (Harvey, 2015) The sessions were conducted in a more interactive way whereby both the researcher and the informants could co-construct the experiences throughout the analysis process rather than merely returning the individual transcripts to the informants at the later stages. Triangulation (Denzin, 2009) Space (data) triangulation: We collected information on the same phenomena from a variety of ACPs, including sole proprietorships, partnerships, and architectural corporations. Person (data) triangulation: We captured lived experiences from those in various hierarchical positions, such as an architectural director, a senior architect, an architectural design technology specialist, a design architect, and an assistant architect. Method triangulation: Various types of data collection techniques were employed, including written accounts and in-depth semi-structured interviews. The triangulation method managed to render the richest and most detailed aspects of the data. Prolonged engagement (Lincoln & Guba, 1985) We performed repeat interviews as we uncovered some lines of inquiry that were overlooked during the first interview.
Transferability	Sampling stage	The transferability judgment by the potential users was facilitated not only through the thick description of the key informant criteria but also through their disposition towards BIM alongside the organisational and industry context in which they are practising. Describing such a context may facilitate outsiders to make sense of the experiences collectively (Lincoln & Guba, 1985).
Dependability and Confirmability	Throughout the research process	Audit Trail As for the present study, an audit trail was developed to deal with the threats of dependability and confirmability of the research findings. The predispositions, cognitive thought processes and changing perceptions of the researcher throughout the stage of phenomenological orientation lived experience investigation, essential themes reflection, themes validation and presentation were reflected transparently in an audit trail (Carcary, 2009).

Criteria	Stage	Strategy employed
Reflexivity	The phenomenological orientation of the researcher. Essential themes reflection. Validation of interpretations.	Hermeneutic circle approach (Lindseth & Norberg, 2004) We disclosed his prior experience practising in a BIM-based environment for both the architectural consultancy practice and contractor company. We consistently underwent a continuous iterative process between examining the reflected themes from the thematic structural analysis and the researcher's naive understanding of the text. If the thematic structural analysis invalidated the naive understanding, we reread the whole text, and a new naive understanding was developed and validated through a new thematic structural analysis.

Presentation of Phenomenological Findings

The findings were organised around a main theme with various categories and subcategories overarching the meanings of lived experience, a structure akin to the vignettes approach (Reay et al., 2019). The data from diverse informants were connected with critical situations into a single scene. The contextual descriptions, in-text citations, and images were presented to facilitate immersion into the informants' lived experiences. Finally, the thematic analysis process of each research question, ranging from the deductive code to initial coding, categories, final themes, and emerging themes, was summarised in a thematic analysis matrix (TAM). Figure 2 illustrates the overall six core activities innovated and adapted by assessing the strengths and limitations of Manen (2016), and Lindseth and Norberg (2004). These six core activities, nevertheless, are not sequential but iterative in nature. The section that follows reflects on the lessons learned from the innovation of this methodological framework.

FINDINGS AND DISCUSSION

The study reveals four key insights: (1) reflexive engagement requires scholars to critically examine their ontological and epistemological assumptions to ensure the authenticity in capturing architects' dynamic identities shaped by technological, social, and personal influences; (2) inductive reasoning supported by a flexible conceptual framework uncovers identity paradoxes while maintaining analytical depth; (3) naive understanding, refined through a double hermeneutic process preserves the complexity of individual experiences; and (4) thematic structural analysis highlights tensions between traditional roles and digital expectations by offering layered insights into identity conflicts. The first and second key insights emerged during the initial stage of the research (refer to Figure 2), which involved reflecting on personal forestructures, developing research questions, and employing a flexible conceptual framework. As the study progressed to stages 4, 5, and 6 (refer to Figure 2), the third and fourth key insights became evident.

Critical Reflection on Researcher Assumptions

Adopting an interpretive phenomenological framework requires the authors to move beyond the traditional role of objective observer. Instead, they must engage in critical self-reflection on their beliefs about the phenomenon and their role within the research process. Goldspink and Engward (2019) argue that researchers must acknowledge their own beliefs and experiences, as these resonate with those of participants, emphasising the importance of reflexivity in ensuring authentic interpretations. Furthermore, Engward and Goldspink (2020) suggest that IPA researchers must continuously "live with the data," meaning that they should engage with their findings reflexively to ensure alignment with phenomenological inquiry. This process echoes the present study in understanding evolving identities, such as those of architects in BIM environments, where identities are not static but shaped by technological, social, and personal influences. The necessity of this reflexive approach is further reinforced by studies in other fields, such as autism research, where researchers must balance their interpretations with participants' lived experiences (Howard et al., 2019). Thus, researchers must recognise themselves as active participants in the interpretative process to ensure authenticity in their phenomenological inquiries.

Flexibility in Conceptual Frameworks

Building on this reflective foundation, the balance between inductive reasoning and the use of a conceptual framework was another critical aspect of this research. In phenomenological studies, there is often a risk of imposing pre-existing theories onto informants' experiences, thus distorting the authentic voices of those being studied. Sibeoni et al. (2020) emphasise that inductive methods like “Inductive Process to analyse the Structure of lived Experience” (IPSE) are designed to capture lived experiences as they naturally unfold, allowing researchers to derive insights without imposing rigid frameworks. In the context of BIM, Shahruddin et al. (2022) found that an inductive approach enabled architects to reveal new hybrid identities that were not captured in traditional professional identity frameworks. This aligns with Gyollai (2020), who emphasises the necessity of an iterative process in IPA, balancing inductive insights with structured interpretation. Additionally, Soltani and Kirci (2019) argue that in architectural phenomenology, an open-ended approach is necessary to allow themes to emerge from participants' lived experiences rather than from a pre-imposed framework. By treating the conceptual framework as a flexible tool rather than a rigid structure, this study ensures a deeper understanding of the identity paradoxes within architectural practice.

Double Hermeneutic Process for Deeper Understanding

Following this, the naive understanding stage offers important lessons for future researchers engaged in interpretive phenomenological studies. This step is crucial because it provides a holistic and idiographic perspective, focusing on the individual context and motivations of each participant. Correspondingly, Lindseth and Norberg (2022) emphasise that naive understanding is the first step in interpretive phenomenology research, allowing researchers to capture an initial and holistic grasp of participants' experiences before engaging in structured analysis. Without this preliminary engagement, there is a risk that the depth and complexity of individual experiences could be overlooked or diluted when the analysis proceeds to thematic convergence. However, it is important to note that these preliminary understandings were not treated as definitive. Instead, they were continuously challenged and validated through the double hermeneutic process. Montague et al. (2020) highlight that the double hermeneutic process requires researchers to iteratively refine their interpretations by actively engaging with participant narratives. SmithBattle et al. (2024) further argue that researchers' assumptions inevitably shape their interpretations, making continuous reflection essential to maintaining analytical rigour. This process of co-interpretation ensured that our findings were grounded in both participant narratives and our evolving understanding, as discussed next.

Thematic Structural Analysis of Identity Tensions

Finally, the thematic structural analysis and the double hermeneutic process phase represent a critical juncture in the research process, where the initial naive understanding is challenged, refined, and validated through a deeper engagement with the data. This iterative process, referred to as double hermeneutics, involves two layers of interpretation: the first being the informants' interpretation of their experiences and the second being the researcher's interpretation of these accounts. Montague et al. (2020) argue that double hermeneutics allows researchers to refine informant insights by continuously engaging with multiple perspectives, particularly in cases where experiences are shaped by complex social dynamics. This dual interpretation allows for a more in-depth understanding of the phenomenon, as the researcher's evolving insights are continuously validated against the informants' lived experiences. Dabengwa et al. (2020) reinforce that IPA research must be conducted as a dynamic process where themes are refined through iterative engagement, ensuring that researcher interpretations remain aligned with participant narratives. An example of this process can be seen with the ninth informant, whose experience of resistance to digital workflows among senior personnel aligned with the first author's initial interpretation that this resistance stemmed from a lack of understanding of BIM's potential at higher levels. This validation process aligns with Monaro et al. (2022), who emphasise that phenomenological research requires a structured thematic analysis process where data is repeatedly deconstructed and reconstructed to ensure findings remain grounded in participant experiences.

CONCLUSIONS

The study was motivated by the evolving challenges faced by architects in the digital construction environment, where the integration of tools like BIM, AI, and cloud computing has fundamentally altered traditional professional identities. This shift has diluted architects' status as singular decision-makers, requiring them to adapt to new collaborative job patterns and embrace diverse identities. Recognising the lack of existing research on the impact of digital transformation on architects' identities, particularly through a phenomenological lens, this study aimed to develop a novel interpretive phenomenological framework that integrates Smith's IPA, van Manen's hermeneutic phenomenology, and Lindseth and Norberg's hermeneutical method, drawing on reflexive research practices from previous studies. Reflexive research practices revealed four key insights: (1) scholars must critically examine their assumptions to authentically capture architects' evolving identities; (2) a flexible conceptual framework enhances analytical depth in uncovering identity paradoxes; (3) naive understanding, refined through a double hermeneutic process, preserves experiential complexity; and (4) thematic structural analysis exposes tensions between traditional roles and digital expectations. These insights offer a deeper understanding of human-technology interactions in BIM environments and provide a structured approach for future research on performance identity and digital collaboration in architectural practice.

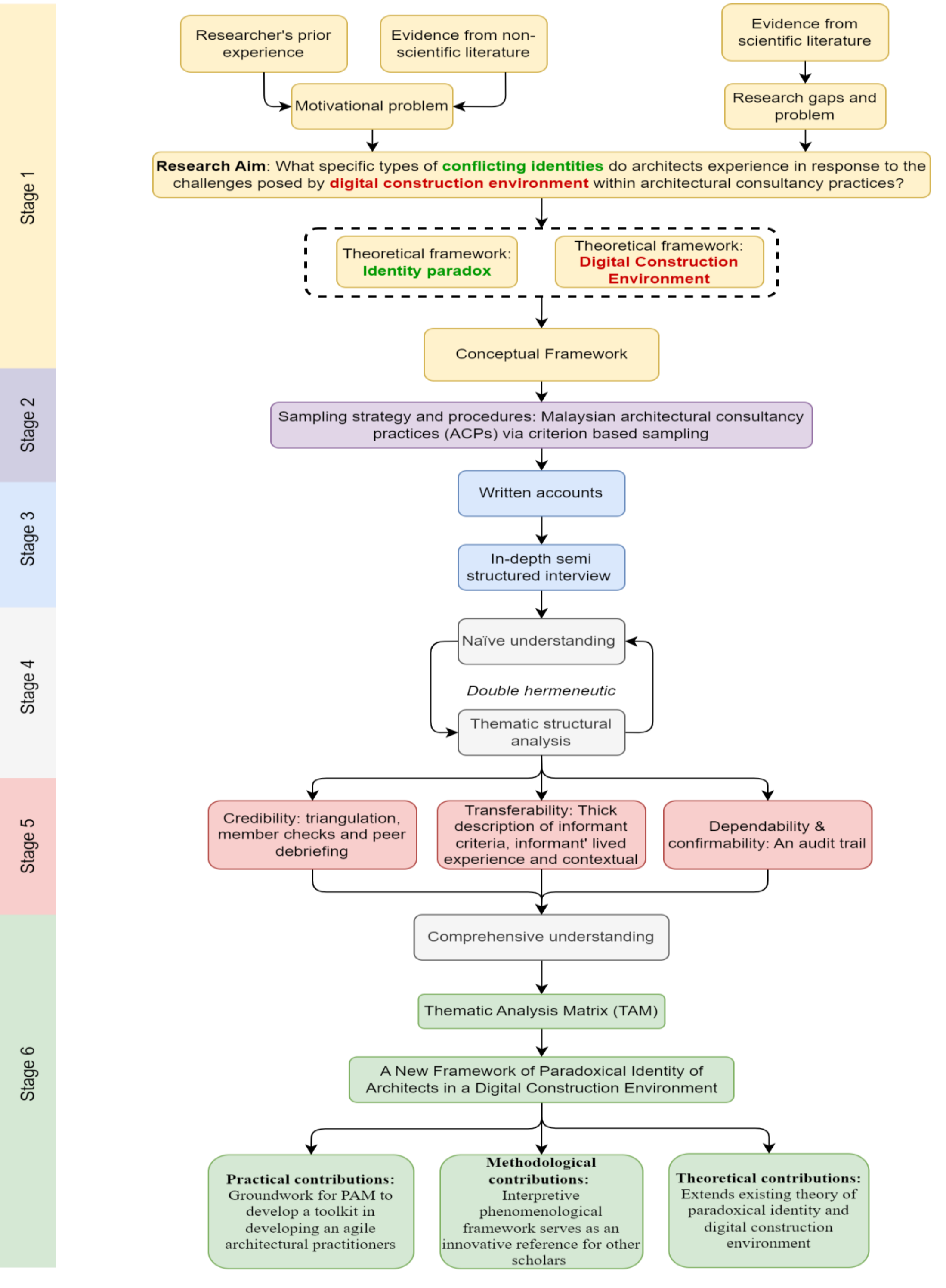

Figure 2. Interpretive Phenomenological Framework Towards Investigating Conflicting Architect Identities in The Digital Construction Environment

This research offers important theoretical contributions through the development of a newly innovated methodological framework (refer to Figure 2) by integrating three prominent interpretive phenomenological frameworks: Smith's IPA, van Manen's hermeneutic phenomenology, and Lindseth and Norberg's hermeneutical method. Together, these approaches offer a robust and holistic framework for investigating the evolving identities of architects in digitally mediated environments. The strength of this integration lies in its ability to balance idiographic depth with the systematic analysis of shared experiences, ensuring that individual narratives are both preserved and contextualised within broader themes. By engaging in a double hermeneutic process, this approach allows for the validation and refinement of initial naive understandings, ensuring a deeper, more in-depth interpretation of complex phenomena like digital transformation. The study also addressed the limitations of each framework: van Manen's reflective approach can be loosely defined, while Smith's IPA and Lindseth and Norberg's method require structured engagement with informants' experiences. By integrating these methodologies, the study provides a comprehensive and innovative approach to understanding the human-technology interaction in BIM environments, offering valuable insights for future research on performance identity and digital collaboration in architecture.

This study also offers practical contributions to scholars, especially those seeking to apply interpretive phenomenology within the architectural research field. The newly developed methodological framework outlines a clear path for conducting in-depth investigations of lived experiences in technologically mediated environments. It covers six core activities: (1) the phenomenological orientation of the researcher, which involves reflecting on personal forestructures and developing research questions and a conceptual framework; (2) a sampling strategy that identifies suitable informants based on their direct engagement with the phenomenon; (3) the investigation of lived experiences through a combination of written accounts and semi-structured interviews; (4) the reflective process of naive understanding, thematic structural analysis, and comprehensive understanding; (5) the validation of interpretations through a structured process that refines findings and (6) presents them in a way that honours the depth of the informants' experiences. This structured framework provides architectural researchers with a comprehensive tool for exploring complex phenomena like the digital construction environment while maintaining a focus on the human experience behind the data.

Despite the contributions of this study, several limitations should be acknowledged. First, the research primarily draws on the experiences of architects engaged in architectural consultancy practices, leaving out those in other construction professionals' roles, whose perspectives might offer additional insights into the evolving professional identities in construction. Future studies could expand by exploring how digital transformation affects other construction professionals and their roles. Moreover, this study focused on the adaptation of interpretive phenomenology to investigate identity shifts, but further refinement of this methodology could be applied to different architectural challenges, such as sustainability or the use of AI in design.

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INNOVATIVE DEEP LEARNING METHODS FOR IMPROVING QLASSIC ASSESSMENT OUTCOMES

Lian Huahua[1,2], Liew Siau Chuin[3], Lu Yang[1] and Lim Kar Sing[1]
[1]Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Kuantan, Malaysia
[2]School of Ningxia College of Finance and Economics, Yinchuan, China
[3]Faculty of Computing, Universiti Malaysia Pahang Al-Sultan Abdulla, Pekan, Malaysia

Abstract
As societal demands shift toward higher-quality living environments, construction defects have become a significant concern for homeowners. To address this, the Construction Industry Development Board Malaysia (CIDB) introduced the Quality Assessment System in Construction (QLASSIC), a system designed to evaluate construction quality based on defect quantification. However, traditional manual inspections are labour-intensive, costly, time-consuming, and subjective. Recent advancements in machine vision, particularly deep learning, have significantly improved automated defect detection. Convolutional Neural Networks (CNNs) are especially favoured for their ability to autonomously identify key features without human intervention. While numerous studies have explored the application of deep learning for defect detection, there remains a lack of integration with comprehensive systems such as QLASSIC. This paper presents an innovative approach that combines deep learning with the QLASSIC standard to assess housing quality. The proposed approach includes the following key steps: (1) categorisation of visual defects according to QLASSIC; (2) collection of defect-related image datasets; (3) image preprocessing and manual pixel-level annotation; (4) selection and training of deep learning models; and (5) evaluation and refinement of model performance. With the proposed approach, it is expected to improve the efficiency and accuracy of building assessments and subsequently foster clearer communication among all parties involved in the construction process.

Keywords: *QLASSIC; Deep Learning; CNN; Housing Quality; Defect Detection; Image Processing*

INTRODUCTION

Housing is one of the fundamental needs for every individual (Maliene & Malys, 2009). While the United Nations Sustainable Development Goals (SDGs) Goal 11 underscores the importance of providing safe, affordable housing and fostering sustainable urbanisation for all (United Nations, 2023), the purchase of a home remains the most significant investment for the majority of people throughout their lives. This decision entails careful consideration of multiple factors, including the living environment, property prices, and the credibility of developers. More critically, a comprehensive and meticulous assessment of housing quality is essential. Alarmingly, over 80% of construction projects exhibit quality-related issues (Olanrewaju & Lee, 2022). In response to this challenge, the Malaysian government has introduced the ISO 9001 standard, aimed at fulfilling the mission of the Construction Industry Development Board Malaysia (CIDB) to deliver quality products within the construction sector (Tang & Ogunlana, 2003).

Despite its global recognition and widespread application across industries, the adoption of ISO 9001 within the construction sector remains limited due to its diversity and the unique challenges posed by this field. To address these issues, CIDB has developed the Quality Assessment System in Construction (QLASSIC), drawing insights from Singapore's construction quality assessment framework to cater to the specific needs of the Malaysian construction industry (Al-Tmeemy, Abdul-Rahman & Harun, 2011).

QLASSIC is an independent and objective method to measure and evaluate the workmanship quality of construction works based on the relevant approved standards (CIDB, 2021). It allows for the relative and quantitative comparison of workmanship quality across various construction projects, offering a standardised evaluation system that ensures quality while providing an objective means to assess contractors' performance. Additionally, aggregating and analysing data collected through QLASSIC aids in identifying trends, common issues, and best practices within the construction industry, thereby offering valuable statistical insights.

The QLASSIC assessment process involves evaluators using sampling methods to inspect the quality of the architectural works, basic mechanical and electrical fittings, and external components of construction projects (CIDB, 2021). However, the implementation of QLASSIC presents challenges: the training, examination, and certification of assessors are time-consuming and costly. Moreover, the detailed manual evaluations and handwritten records not only require considerable effort but also result in a high margin of error. Variability in assessors' expertise and experience further complicates the uniformity of evaluations (Hoang, Nguyen & Tien Bui, 2018). Post-assessment, evaluators generate computer-generated reports that merely list inspection results, necessitating careful analysis by stakeholders to derive corrective measures, as the technical terminology and complexity of QLASSIC documentation can be overwhelming for homeowners (Kariya, Abas, Mohammad & Siti Khalijah, 2022). The traditional inspection protocols involve extensive manual checks and cumbersome paperwork, leading to time and cost overruns, as well as potential errors (Radopoulou & Brilakis, 2017).

Therefore, there is a pressing need for technological applications and enhanced skills and knowledge as foundational elements to address these challenges and ensure the effective operation of the QLASSIC certification system (CIDB, 2023). The construction industry is undergoing a technological transformation, with 81% of construction firms adopting mobile platforms, 43% implementing robotic process automation, and 40% integrating artificial intelligence technologies (KPMG, 2023). Despite significant advancements in the application of deep learning methodologies for defect detection, existing research often focuses on specific defect types, thereby limiting applicability and comprehensiveness (Mostafa & Hegazy, 2021). Given the diverse categories of visual defects outlined in QLASSIC standard, conventional models often struggle to identify and accurately classify these defects comprehensively. Therefore, the combined use of models tailored to different defect characteristics becomes crucial. This paper explores a deep learning defect detection method based on QLASSIC standard.

LITERATURE REVIEW

The construction industry is increasingly recognised as a cornerstone of global economic growth (Lima, Trindade, Alencar, Alencar & Silva, 2021). A reality check on the progress towards SDGs for mid-2030 indicates that only about 10% of the targets, particularly Goal 11, are on track or have been achieved (United Nations, 2023). This assessment highlights that globalisation presents numerous prospects for the expansion of the construction sector. Within this context, Malaysia's construction industry contributes approximately 10% to the country's gross domestic product (GDP) and employs over 10% of the workforce in many economies (Olanrewaju & Lee, 2022). Given that the construction sector is predominantly labour-intensive (Akmam Syed Zakaria & Amtered El-Abidi, 2021), a shortage of skilled workers often leads to inferior craftsmanship in numerous projects. Additionally, as buyers become increasingly educated, their expectations for high-quality products have risen, resulting in frequent complaints regarding the quality of delivered housing. CIDB is dedicated to identifying effective solutions to these challenges.

To this end, CIDB has actively engaged in research, examining the Construction Quality Assessment System (CONQUAS) developed through collaborations between the Building and Construction Authority Singapore (BCA) and other industry technical leaders. This investigation revealed that the CONQUAS system has achieved significant success in enhancing construction quality and offers valuable insights for the Malaysian construction sector (Subramaniam, 2022). Consequently, in 2007, Malaysia initiated the Construction Industry Master Plan (2006-2015), abbreviated as CIMP (2006-2015), and began the implementation of QLASSIC. Since its inception, QLASSIC has sparked a wave of research within academia regarding the application of quality assessment systems, exploring the motivations for adopting QLASSIC in the construction industry (Hamid, 2012, Kam & Abdul Hamid, 2015), the barriers faced by contractors (Khalid & Tamjehi, 2020, Seman, Esa & Yusof, 2021, Zahrizan, Affendy & Johan, 2023), and potential improvements to the QLASSIC framework (Adnan & Fateh, 2022, Ali, 2014). However, studies focused on improving QLASSIC's inspection methodologies remain limited.

Building quality is synonymous with customer satisfaction and adherence to required standards, as defects impede the functional performance of structures and services. Thus, poor building quality is often represented by the presence of defects (Olanrewaju, Tan & Soh, 2022). According to the CIS 7 defect analysis and QLASSIC acceptable scoring from 2015 to 2018, 77% of the assessed projects were residential (CIDB, 2020). This statistic indicates that housing quality assessments can also be effectively represented through defect detection. To ensure the quality of housing, various technological methods have been employed in quality inspection, including manual defect detection (Katipamula & Brambley, 2005), ultrasonic testing, infrared thermography, and image processing techniques (Gupta, Khan, Butola & Singari, 2022).

With the rapid advancements in computer and AI technologies, numerous deep learning-based defect detection methods have been widely applied across various industrial scenarios. Companies, both domestic and international, have developed commercial software for industrial surface defect detection based on deep learning, such as MVTec's Halcon 17, Cognex's acquisition of VIDI, and Hangzhou Dichuang Technology Co., Ltd.'s AiDitron (Tao, Hou & Xu, 2021). In practical defect detection applications, the significant variability in the shape, size, background, layout, and imaging conditions of the objects being inspected renders defect classification a formidable task in complex environments. Convolutional Neural Network (CNN) has emerged as the preferred method in surface defect detection due to their exceptional performance in feature extraction and object recognition in image and video processing (Dhillon & Verma, 2020, Mostafa & Hegazy, 2021, Yao, Lei & Zhong, 2019). In recent years, CNN has been successfully utilised in various defect detection and classification applications, including pavement condition assessment systems (Majidifard, Adu-Gyamfi & Buttlar, 2020), building safety inspection models (Pham, Rafieizonooz, Han & Lee, 2021), degradation identification and classification in roofs (Mostafa, Hegazy, Hunsperger & Elias, 2023), and visual defect classification in concrete bridges (Amirkhani, Allili, Hebbache, Hammouche & Lapointe, 2024). Furthermore, studies by Mei and Gül have demonstrated the robustness and efficacy of CNN, reinforcing their advantages in handling complex visual tasks (Mei & Gül, 2020). Despite the abundance of research and publications concerning CNN applications, these studies typically focus on singular applications or themes (Alzubaidi, et al., 2021), lacking integration with quality system standards in defect detection research. Thus, integration of these applications is crucially needed to enhance the existing QLASSIC assessment process tailored to the visual inspection aspect.

EXPERIMENTAL SET UP

Design of Experiment

With the continuous emergence of new technologies such as artificial intelligence, big data, and cloud computing, computer algorithms have become essential tools for learning and exploring scientific knowledge. An algorithm is a method or procedure that solves problems through a finite series of steps, each of which must be precisely defined to ensure clear execution for each application (Angius, Primiero & Turner, 2021). The proposed innovative approach in this study is explained in detail in the following sections.

Data Collection and Preparation

Most defects have been previously identified in practical detection scenarios through professional statistical analysis and categorisation (Dongliang et al., 2022). Therefore, this study classifies defects according to the defect groups outlined in the CIS 7 standard. Defects will be detected either directly based on their characteristics or through the collection and annotation of datasets using prior knowledge to train the model. As shown in Table 1, all elements comprise five defect groups: finishes, cracks, materials, functionality, and joints. In Malaysian buildings, defects such as water ingress, cracks, and surface issues are common.

Table 1. Summary of Defect Group Division

Elements	Defect Groups	Descriptions of Defect
Floors & Internal/ External Walls	Finishing	Stain mark, colour tone & paintwork, patchy & rough surface
	Alignment and evenness	Evenness of surface, falls in wet areas, Verticality of wall, walls meet at right angles
	Cracks and damages	Defects & damages
	Hollowness/ delamination	
	Jointing	Gaps between wall and skirting
Ceilings	Finishing	Stain mark, colour tone & patchy surface
	Alignment and evenness	Surface smooth, even & not wavy, straightness of corners
	Cracks and damages	Spalling & leaks
	Roughness/ patchiness	Rough surface
	Jointing	Consistent, align & neat
Doors/ Windows/ Internal Fixtures	Joints and gaps	Joints or gaps too wide, inconsistent, improper seal
	Alignment and evenness	Not aligned, sagging, not flushed, not a right angle, rattling sound
	Materials and damages	Cracks, chipping, dents, scratches, stains, tonality, warping, sagging
	Functionality	Cannot be opened or closed properly, squeaky sound
	Accessories defects	Missing items, improper fixing, stains, corrosion, other damages

(Source: CIDB,2021)

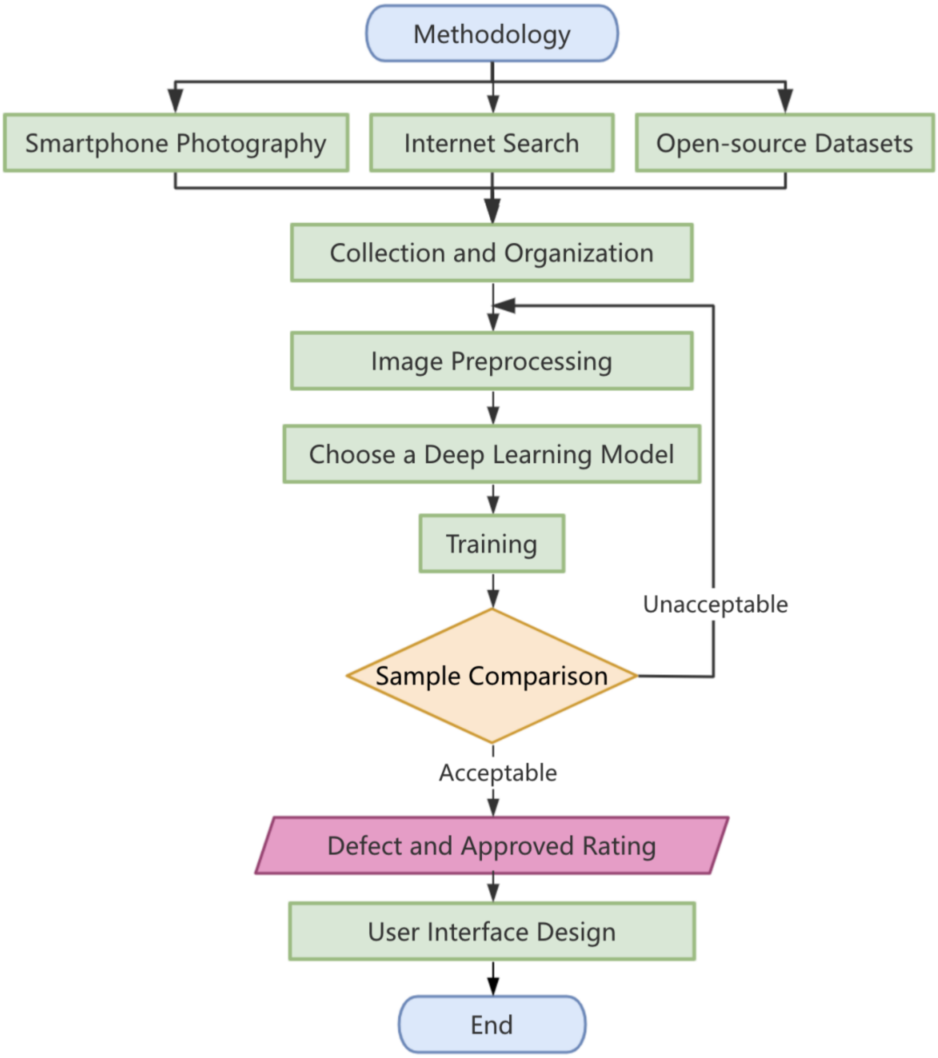


Figure 1. Experimental Flowchart

This study focuses on the aforementioned QLASSIC visual defects and plans to collect data sources from three key approaches: (1) Utilising a 64-megapixel smartphone wide-angle camera, a predetermined path will be followed to capture images of relevant defects under varying angles and lighting conditions. (2) Relevant defect images will be sourced from online platforms such as the Construction Research Institute of Malaysia (CREAM) database, Google Search, Baidu Search, and from assessment agencies. (3) Selected open-source defect detection datasets (Langyue & Yiquan, 2023), including portions of the House Dataset, will also be employed.

As shown in Table 2, the existing datasets encompass a significant portion of the defect data specified by QLASSIC, including defects related to walls, floors, ceilings, and doors and windows, as well as instances of water ingress. These datasets provide a comprehensive foundation for analysing and detecting the various defects identified within the QLASSIC framework.

Table 2. Common Datasets for Defect Inspection

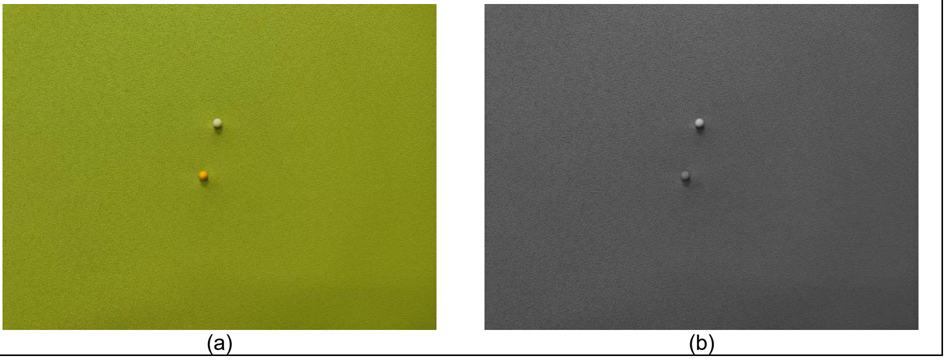
Data Sets	Defect Types	URL Links
CrackDataset_DL_HY	Concrete cracks	https://github.com/juhuyan/CrackDataset_DL_HY
CrackForest	Concrete cracks	https://github.com/cuilimeng/CrackForest-dataset
House Dataset	Concrete cracks	https://aistudio.baidu.com/datasetdetail/2943
Crack500	Concrete cracks	https://github.com/fyangneil/pavement-crack-detection
CODEBRIM	Concrete cracks, peeling, weathering, corrosion	https://paperswithcode.com/dataset/codebrim
GC10-DET	Metal surface pitting, dents, scratches	https://github.com/lvxiaoming2019/GC10-DET-Metallic-Surface-Defect-Datasets
Meic Wood datasets	Wood knots, knots, cracks	https://github.com/Ldhlwh/DFMGAN/issues/42
TianChi	Ceramic tile holes, stains, missing corners	https://tianchi.aliyun.com/dataset/dataDetail?dataId=110088

(Source: Lian, 2024)

Image Preprocessing

During the training of models or execution of algorithms, it is crucial to acknowledge that not all images possess the same quality or yield optimal results. Therefore, it is essential to preprocess the collected housing image datasets using techniques such as image denoising, image enhancement, contrast adjustment, normalisation, and edge detection, facilitating subsequent model training and validation.

This study plans to utilise the Python programming language and the PyTorch machine learning framework for image preprocessing. The OpenCV library's \`imread()\` method will be employed to load images, followed by the \`resize()\` method to standardise the dimensions of all images. To simplify the image data and reduce the computational demands on the algorithm, colour images will be converted to grayscale using the \`cvtColor()\` method. Subsequently, common denoising methods, including \`GaussianBlur()\` and \`medianBlur()\`, will be applied to eliminate undesirable noise from the images.



(a) (b)

Figure 2. (a) Original Image; (b) Grayscale Image

To enhance the images for analysis and enable the deep learning model to learn patterns independently of lighting conditions, histogram equalisation will be performed using the \`equalizeHist()\` method, scaling all pixel values between 0 and 1. Segmentation techniques will be employed to isolate the foreground subjects from the background, utilising the \`threshold()\` and \`Canny()\` methods to obtain clear images that contain only the subjects of interest.

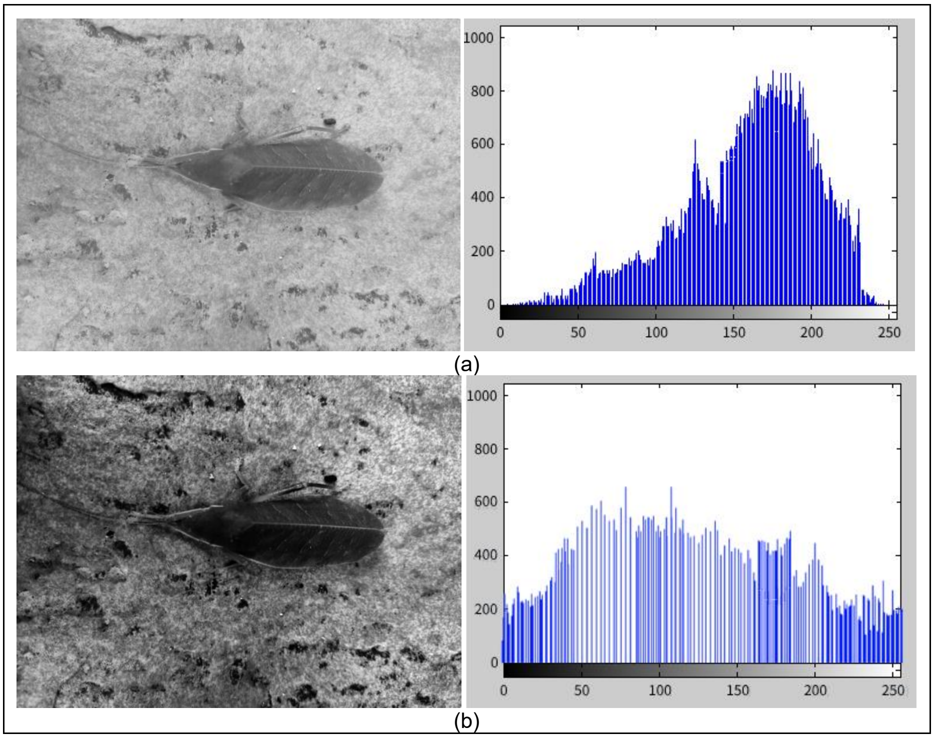


Figure 3. (a) Original Image and Histogram; (b) Equalised Image and Histogram

Based on the types of defects displayed in the retrieved images, manual pixel-level annotations will be conducted. This study will utilise the PixelAnnotationTool software to create ground truth labels for specific information or attributes within the image data. The aim is to annotate pixel points that comprehensively cover all relevant pixels of the marked objects, thereby enhancing the quality of the annotations and, consequently, improving the model's ability to recognise target objects.

In practical scenarios, gathering a sufficient amount of raw image data is necessary. Therefore, data augmentation techniques will be employed to expand the dataset size (Maharana, Mondal & Nemade, 2022). This will involve operations such as horizontal and vertical flips, as well as rotations at various angles to generate new data points. Additionally, the sliding window technique will be applied to crop images to different sizes and aspect ratios, creating new images with varied perspectives. Adjustments to brightness, contrast, hue, and saturation will further generate images with different appearances. It is essential to exercise caution during this process to avoid excessive augmentation, which could lead to image distortion or confusion within the model.

Deep Learning Model Selection and Training

Following data preprocessing, 70% of the total samples will be randomly selected as the training set, consisting of 50% defective images and 50% non-defective images, to estimate model performance. A further 20% will be allocated as the validation set, which will be used to determine network architecture or adjust parameters related to model complexity. The remaining 10% will serve as the test set, allowing for an assessment of the performance of the final selected model.

This study will leverage image processing algorithms to extract features and select an appropriate deep learning model for training. CNN is a type of artificial neural network (ANN) particularly suited for image recognition and processing, demonstrating strong learning capabilities for high-dimensional data (Li, Liu, Yang, Peng & Zhou, 2021). CNN can learn abstract, essential, and higher-order features from input data (i.e., pixel data). CNN can autonomously learn and extract local features from images without the need for human intervention (Haihong, et al., 2019). This capability enables CNN to excel at capturing subtle variations in architectural defects, effectively identifying issues such as cracks and stains regardless of their positional changes within the image. Furthermore, leveraging extensive training datasets, CNN demonstrates remarkable adaptability, allowing for precise detection of different types of buildings and their associated defects, while also exhibiting strong generalisation performance (Wu. In recent years, there has been a growing body of research focusing on CNN applications for building defect detection, facilitated by open-source frameworks such as TensorFlow and PyTorch, which provide a wealth of tools and models that streamline experimental implementation and debugging processes (Novac, et al., 2022; Vasilev, Slater, Spacagna, Roelants & Zocca, 2019; Zafar, Tzanidou, Burton, Patel & Araujo, 2018). Given these unique characteristics of CNN, this study will adopt CNN as the foundational model for training purposes.

This study will employ the Python programming language and the PyTorch machine learning framework to construct a two-stage deep learning method based on Region-based Convolutional Neural Network (R-CNN). In the first stage, a CNN will classify the raw images as either defective or non-defective. The second stage will analyse the images identified as "defective" by the first CNN to determine the type of defects present and quantify their sizes.

The specific experimental approach begins with selecting an individual house for the study. Initially, images will be examined to ascertain whether they contain defects. All images collected from the selected house will serve as input for the first CNN responsible for defect detection. Subsequently, the images classified as "defective" will be used as input for the second CNN, which is tasked with classifying the types of defects. Finally, the classification results from the second CNN will be compared with the outcomes from existing detection methods, allowing for parameter adjustments. Once the CNN is fully developed, it will be applied to all the images collected during this study.

Performance Evaluation and Postprocessing

The performance of the model is determined by various evaluation metrics. Accuracy is one of the fundamental assessment indicators, calculated as follows:

$$\text{Accuracy} = \frac{\text{Number of correct predictions}}{\text{Total number of samples}} \tag{1}$$

Accuracy provides a measure of the model's prediction accuracy across all samples. Given that this model is designed to predict multiple categories of defects, accuracy alone does not fully reflect its performance. Therefore, precision and recall will also be calculated to evaluate the model. The formulas for precision and recall are as follows:

$$\text{Precision} = \frac{\text{True positives}}{\text{True positives + False positives}} \tag{2}$$

$$\text{Recall} = \frac{\text{True positives}}{\text{True positives + False Negatives}} \tag{3}$$

There exists a trade-off between precision and recall, which will be balanced by adjusting the classification threshold. After computing both precision and recall, the F1 score will be utilised for a comprehensive evaluation of the model's performance, calculated using the following formula:

$$\text{F1} = \frac{2\times\text{Precision}\times\text{Recall}}{\text{Precision + Recall}} \tag{4}$$

A higher F1 score indicates better model performance. Once the model is finalised, hyperparameters will be adjusted using the validation set, followed by testing the remaining images with the test set to enhance the model's generalisation capability.

The QLASSIC standard primarily provides weights rather than specific scores. It assesses defects merely based on presence or absence, without evaluating their severity, which can hinder timely repairs by construction personnel and limit the ability of assessors to provide maintenance recommendations. Homeowners may struggle to determine appropriate repair plans. To address this, after finalising the model, this study will utilise the React Native mobile application development framework to design and implement a user interface. Users will be able to upload images of their houses, enabling them to access defect identification results, corresponding scores, and repair suggestions anytime and anywhere. This technology not only enhances the automation of construction quality assessment but also provides a more intuitive and convenient user experience, further facilitating the effective implementation of the QLASSIC standard in practice.

EXPECTED RESULTS

With the continuous advancement of technology, the application of intelligent technologies in the field of building assessment is expected to increase gradually, leveraging these innovations to reduce defects and enhance overall efficiency (Rahimin, Isa, Mohd & Ahmad, 2023). This study proposes the application of deep learning techniques within the QLASSIC assessment framework, anticipating the following outcomes:

(1) High Accuracy in Defect Detection: The QLASSIC assessment methodology traditionally relies on manual inspection; however, this study introduces a deep learning approach, which has demonstrated accuracy levels in many application domains that are comparable to, or even exceed, those of human evaluators in certain contexts.

(2) Streamlined QLASSIC Workflow, Time Savings: Users will not require specialised training or examinations prior to conducting QLASSIC. The evaluation process does not necessitate the use of specialised equipment or tools, nor does it require in-depth knowledge of QLASSIC to complete paper-based forms. Upon completion of the assessment, an electronic report will be automatically generated without the need for human intervention, thereby ensuring data consistency, uniformity and reliability. The entire assessment process

will be automated, encompassing data collection, analysis, and report generation, which will significantly save time.

(3) Automated Reporting and Efficient Communication: The deep learning defect detection method based on the QLASSIC standard will autonomously identify and document various defects within the building. Accompanied by photographs and straightforward annotations outlining the issues and repair recommendations, this method eliminates reliance on manual input and facilitates the automated generation of reports. These reports will present evaluation results in a visual format, using charts and images to enable rapid and effective communication among project stakeholders, ensuring a clear understanding of quality standards, deviations, and corrective actions.

Through these anticipated outcomes, this research aims to not only improve the efficiency and accuracy of building assessments but also to foster clearer communication among all parties involved in the construction process.

CONCLUSION

This study presents a deep learning defect detection method based on the QLASSIC standard, aimed at compiling a dataset of defect images that comply with QLASSIC criteria through manual collection, annotation, and preprocessing. This dataset serves as a robust foundation for training models tailored to the QLASSIC assessment framework, facilitating the integration of advanced technologies into QLASSIC detection methods in the future. Moreover, the research not only seeks to alleviate the workload of evaluators but also aspires to achieve efficient automated detection. This approach provides crucial technical support and theoretical guidance for construction personnel and homeowners during the maintenance and repair of properties. The defect detection discussed in this paper focuses exclusively on visual defects. To enhance the practicality and accuracy of applications, future work could explore the integration of deep learning with other sensor technologies. Additionally, investigating more sophisticated neural network architectures and utilising a broader range of image features could enable the comprehensive automation of QLASSIC, further advancing the field of construction quality evaluation.

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INTEGRATING DIGITAL TWIN WITH WELL BUILDING STANDARD: CURRENT GAPS AND FUTURE RECOMMENDATIONS

Fatima Hanif[1] and Rahimi A. Rahman[2,3]
[1]Civil and Environmental Engineering, University of New Hampshire, Durham, USA
[2]Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Kuantan, Malaysia
[3]Faculty of Graduate Studies, Daffodil International University, Dhaka, Bangladesh

Abstract
The built environment is pivotal in shaping sustainability, serving as a dynamic system that balances energy use, materials, and human well-being. In recent years, sustainable building management has evolved from energy conservation to more holistic approaches integrating ecological integrity, socioeconomic benefits, and technological innovation. Digital leadership and emerging technologies, including digital twin (DT), have become essential to this transformation. DT offers real-time digital replicas of physical structures, enhancing building management by improving predictive maintenance, energy optimisation, and occupant comfort. When integrated with the WELL Building Standard (i.e., WELL), which emphasises health, comfort, and sustainability, DT can enhance building performance further. However, the existing literature on the integration of DT with WELL is fragmented, with limited empirical studies exploring their combined impact on sustainability. Moreover, gaps exist in leadership frameworks necessary for effectively integrating digital technologies to achieve sustainability goals. This study aims to synthesise current knowledge, identify emerging trends, and highlight gaps shaping future research on integrating DT with WELL in sustainable building management.

Keywords: *Sustainable Building Management; Digital Tools, Digital Twin; WELL Building Standard; Maintenance Planning; Energy Savings; Health and Comfort; Intelligent Buildings; Green Practices; AI; IoT*

INTRODUCTION

The built environment, an integral part of human activity, shapes our ecological footprint and landscapes (Alvarado et al., 2021). At the nexus of energy, materials, and human habitation, buildings serve as both symbols and instruments of sustainability (Raihan et al., 2022). The field of sustainable building management has developed from simple energy conservation to comprehensive methods that balance ecological integrity, socioeconomic advantages, and technical advancement (Fiksel, 2003). This change emphasises a general realisation: structures are dynamic systems interacting with their occupants and the surrounding environment rather than merely static objects (Carlucci et al., 2023).

As the role of buildings in sustainability has grown, so has the need for innovative leadership in managing these systems. In the age of digitisation, the blueprint has evolved from paper to pixels. This has led to the development of frameworks such as the WELL Building Standard (hereafter, WELL) (Allen et al., 2015), which focuses on enhancing occupant health and comfort while promoting sustainability. In parallel, the digital age has introduced innovative tools for managing buildings more effectively. The digital twin (DT) concept encapsulates this evolution (Van der Aalst et al., 2018). It connects building management's physical and digital worlds by developing a real-time digital avatar of a physical structure (Raja Santhi & Muthuswamy, 2023).

However, the impact of DT goes beyond simple simulation. With their data-driven insights, DT is revolutionising occupant comfort, predictive maintenance, and energy optimisation (Opoku et al., 2021). They stand for the nexus of architectural science, the Internet of Things, and artificial intelligence, a trio that is poised to reshape the future of building management (Massafra et al., 2022).

This paper explores how digital leadership, supported by DT, can be leveraged to enhance sustainable building management and achieve the goals set by WELL. The integration of sustainable practices, WELL's human-centred approach (Tan Carmen et al., 2022), and the technological capabilities of DT marks a new frontier in building research (Aheleroff et al., 2022). However, the fragmented nature of existing literature necessitates a synthesis. Through a rigorous review, this paper aims to consolidate current knowledge, identify emerging trends, and highlight gaps that will guide the field's future direction over the next decade.

METHODOLOGY

This literature review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis). It provides a reliable framework for systematically selecting, analysing, and synthesising studies relevant to DT, WELL, and digital leadership in sustainable building management. The key steps include searching for databases such as Scopus and Web of Science for studies on DT, WELL, and sustainability, applying inclusion/exclusion criteria to filter relevant studies, evaluating the quality and relevance of selected studies, as well as extracting and synthesising data for analysis. Figure 1 represents the framework followed in this study.

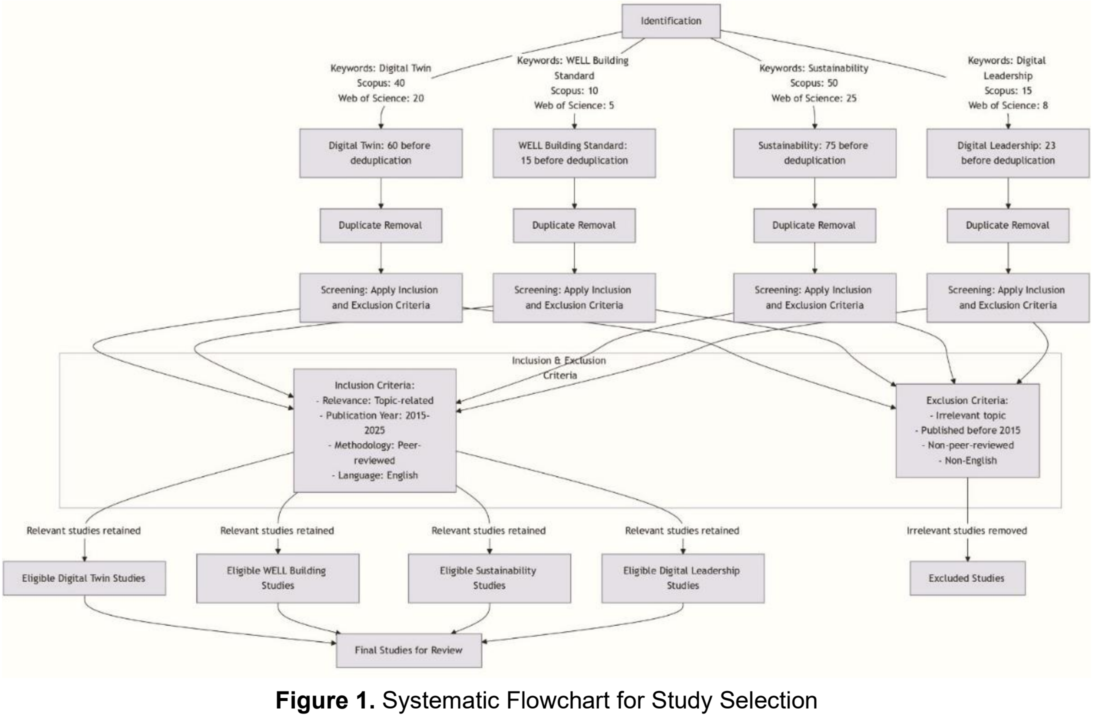

Figure 1. Systematic Flowchart for Study Selection

By following the structured approach, this study investigates the integration of digital leadership, sustainable building practices, and WELL. It focuses on the role of DT in building management and explores research gaps. Figure 2 shows the conceptual framework adopted in this study. Table 1 outlines key themes, sub-themes, significant studies, and areas that need further exploration.

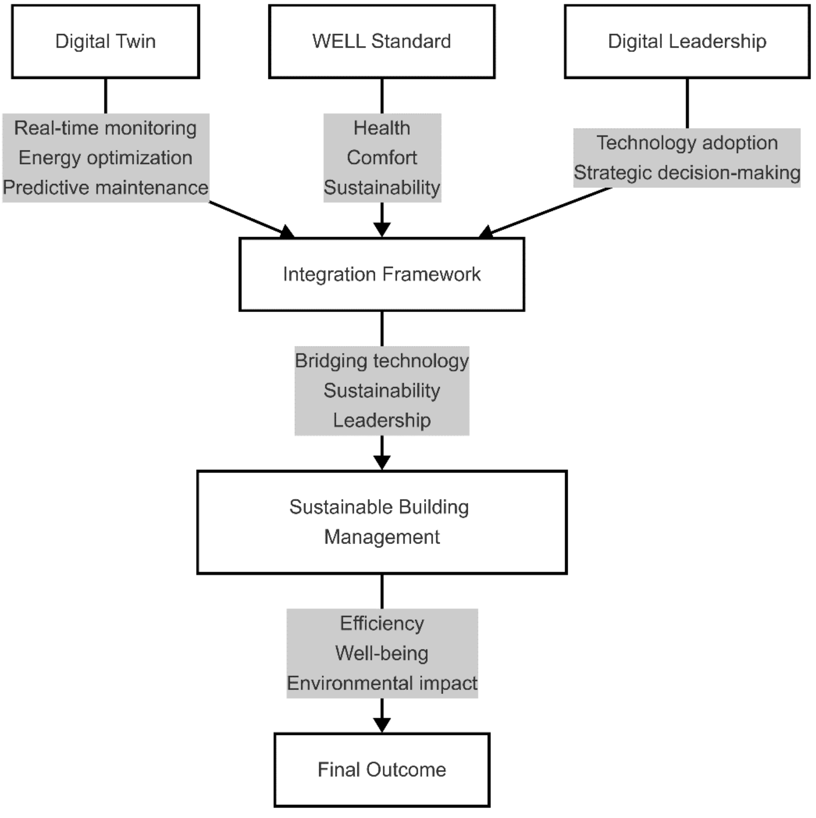

Figure 2. Conceptual Framework

Table 1 examines the combination of ecological, economic, and creative energy-saving approaches, highlighting the important themes in sustainable building management. Despite adopting a human-centred paradigm and emphasising occupant health and comfort, WELL lacks empirical research on its long-term efficacy and integration with new digital technology. DT is showcased for its potential in real-time building management, predictive maintenance, and energy optimisation, with limited research focusing on its application in WELL-certified buildings. Digital leadership underscores the pivotal role of leadership in driving digital transformation, AI, and IoT adoption. Still, research gaps persist in leadership strategies for integrating technologies like DT with WELL. Integrating technologies with standards highlights the synergy of digital tools and sustainability goals, calling for more cohesive frameworks to enhance occupant well-being and operational efficiency while addressing the fragmented literature on their interplay. The explanation of individual components of Table 1 can be seen in further sections.

Table 1. Analytical Framework for Key Themes

Key Themes	Sub-Themes	Key Authors / Studies	Research Gaps
Sustainable building management	Evolution from energy conservation to holistic approaches	Alvarado et al. (2021), Raihan et al. (2022), Baleta et al. (2019), Goh et al. (2021)	Lack of integration of emerging digital technologies
	Ecological integrity, socioeconomic benefits, and innovation	Fiksel (2003), Carlucci et al. (2023), Goge et al. (2024), Said (2022), Amoah & Smith (2024), Garcia et al. (2024)	Insufficient long-term studies on sustainability impacts
WELL building standard	Focus on occupant health and comfort	Allen et al. (2015), McCarthy et al. (2001), Coombs et al. (2016), Colton et al. (2014), Adamkiewicz et al. (2014)	Need for more empirical studies on WELL's long-term effectiveness
	Human-centered approach	International WELL Building Institute (2015), Colton et al. (2014), Heschong et al. (2002), Frumkin (2003), Hammer et al. (2014), Cradock et al. (2009)	Limited research on WELL's integration with digital technologies
DT in building management	Real-time digital replicas	Opoku et al. (2021), Massafra et al. (2022), Zhang et al. (2021), Fernández-León et al. (2024), Teng et al. (2021)	Limited studies on its application in WELL-certified buildings
	Impact on predictive maintenance, energy optimisation	Kan et al. (2021), Tahmasebinia et al. (2023), Ogunsakin et al. (2023), Akinshipe et al. (2024), Keleko et al. (2022), Yu et al. (2021)	Lack of practical case studies in sustainable building management
Digital leadership	Role of leadership in adopting digital transformation	Westerman et al. (2014), Hess et al. (2020), Kane et al. (2015), Fitzgerald et al. (2014), Van der Aalst et al. (2018)	Limited focus on leadership roles in WELL and sustainability efforts
	Influence of AI and IoT on building management	GhaffarianHoseini et al. (2013), Yu et al. (2021), Le et al. (2019), GhaffarianHoseini et al. (2019), Teng et al. (2021)	Research needed on leadership strategies for integrating DT with WELL
Integration of technologies with standards	Integrating DT with WELL for sustainability goals	Zhang et al. (2024), Kan and Anumba (2021), Torres et al. (2024), Byrne et al. (2023), Tahmasebinia et al. (2023), Marberry et al. (2022)	Fragmented literature on the interplay between technology and WELL
	Data-driven insights enhancing occupant well-being and efficiency	Cespedes-Cubides and Jradi (2024), Zhang et al. (2024), Bhandal et al. (2022), De Graaf (2024), Dockery et al. (1993), Brook et al. (2010)	Gaps in practical frameworks for digital leadership in WELL

RESULTS AND DISCUSSION

Figure 3 illustrates the interconnections between DT, WELL, and digital leadership in achieving sustainable building management. It highlights key functions such as real-time monitoring, policy compliance, AI and IoT integration, and strategic leadership adoption. The framework also identifies future research directions, including the need for empirical case studies, leadership strategies, and long-term sustainability studies. The following sections provide a detailed analysis of each component.

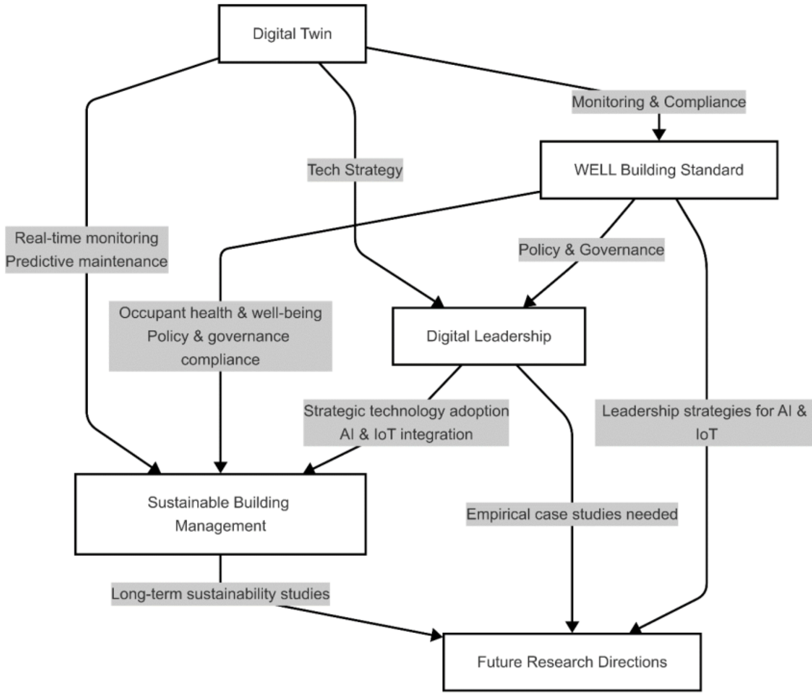

Figure 3. Integrated Findings and Future Directions

Sustainable Building Management

Evolution from Energy Conservation to Holistic Approaches

The field of sustainable building management has progressed from energy conservation to approaches that encompass environmental, economic, and social aspects (Baleta et al., 2019). Baleta et al. (2019) provided a comprehensive review of the latest advancements in integrating energy, water, and environmental systems through the lens of circular economy principles. They highlighted the importance of multidisciplinary approaches and intersectoral scientific cooperation to address global sustainability challenges. The authors showcased various innovative technologies and frameworks that reduce environmental burdens while improving resource efficiency. However, the paper predominantly emphasises technical and economic feasibility, often overlooking the social dimensions of sustainability. Additionally, while the examples cited demonstrate significant progress, these solutions' practical applicability and scalability in diverse real-world contexts require further exploration. Future research should focus on creating holistic metrics and composite indices better to quantify the overall impact of these integrated systems, ensuring a balance across all three pillars of sustainable development: environmental, economic, and social. This critical gap underscores the need for inclusive strategies to advance sustainable development objectives globally.

Early efforts focused on reducing energy consumption through energy-efficient technologies and better insulation (Goge et al., 2024). In contrast, modern approaches integrate smart energy systems, demand-side control initiatives, and renewable energy sources (Said, 2022). Said (2022) provided an in-depth exploration of the role of information communication technologies (ICT) in advancing demand-side management (DSM) for smart grids. The authors offered a comprehensive review of current methodologies, highlighting their potential for energy efficiency, grid stability, and the integration of renewable energy. While the paper effectively categorises DSM techniques and addresses emerging challenges such as cyber security and privacy, it leans heavily on theoretical insights, lacking real-world case studies to substantiate its claims. The discussion on ICT-driven DSM strategies for decentralised microgrids and energy storage systems is commendable but remains fragmented without offering cohesive frameworks for implementation. Future research should prioritise empirical validation and the development of integrated models to enhance the scalability and reliability of ICT solutions in diverse energy markets and geographic contexts.

Prominent scholars such as Kibert, Yudelson, and Cole have underscored the significance of an all-encompassing methodology encompassing lifecycle assessment, occupant well-being, and resistance to natural hazards (Goge et al., 2024; Goh et al., 2021). Kibert's paper (2003) provides a foundational analysis of advancements in green building practices and their alignment with environmental sustainability goals. The author effectively traces the evolution of green building principles, emphasising their potential to minimise ecological impacts, improve resource efficiency, and enhance occupant well-being. However, the paper primarily focuses on conceptual frameworks and regulatory advancements, with limited empirical evidence supporting the proposed strategies' effectiveness. Additionally, while addressing green buildings' environmental and economic aspects, it overlooks the social dimensions and challenges of equitable access to sustainable infrastructure. Future research could benefit from a multidisciplinary approach integrating technological innovations, policy frameworks, and real-world applications to create more comprehensive and inclusive green building solutions.

Yudelson (2012) offers a comprehensive guide to navigating the green building industry through effective marketing strategies. It addresses critical aspects such as identifying target markets, building client relationships, and leveraging green certifications to enhance market positioning. The author's insights, drawn from extensive experience, provide practical advice on differentiating green building services in a competitive market. However, the book predominantly focuses on marketing tactics and less on the technical challenges or innovations driving the green building sector. Additionally, while it emphasises the importance of sustainability as a value proposition, it could further explore the integration of emerging trends like digital technologies and data-driven marketing. The absence of case studies reflecting diverse geographic and cultural contexts limits its global applicability. Future editions might benefit from incorporating these elements to offer a more balanced perspective for professionals aiming to thrive in the evolving green building landscape.

Despite the significant advancements, big data analytics, artificial intelligence, and other new digital technologies are still poorly integrated into sustainable building management (Himeur et al., 2023). The possibility for predictive maintenance, real-time monitoring, and improved energy efficiency is hampered by this gap (Keleko et al., 2022). Building management techniques must actively integrate these technologies to address this problem and create truly sustainable and intelligent buildings (Teng et al., 2021).

Ecological Integrity, Socioeconomic Benefits & Innovation

Sustainable building management emphasises ecological integrity, innovation, and economic benefits (Amoah & Smith, 2024). Cole (2019) has provided a well-structured framework for fostering green building literacy (GBL) through K-12 education. Their research highlights the intersection of green building themes with STEM education, emphasising the integration of factual, conceptual, and procedural knowledge. The author effectively addresses the necessity of equipping future generations with the skills and values to understand and advocate for sustainable practices. The proposed framework aligns with the Next Generation Science Standards (NGSS), offering a robust pathway for curriculum development. However, the paper's reliance on U.S.-centric educational frameworks and focus groups limits its applicability to global contexts. The study would benefit from incorporating more diverse geographic and cultural perspectives to ensure broader relevance. Additionally, while the framework identifies key knowledge categories and skills, there is a need for empirical validation of its effectiveness in diverse educational settings. Future research could expand on the role of green building literacy in shaping behavioural changes and its long-term impacts on sustainability practices, addressing the gap between knowledge acquisition and actionable outcomes.

Research has shown that incorporating sustainable methods into building management can improve social and economic results while reducing environmental impact (Cole, 2019). For instance, the adoption of green construction standards and technologies has been proven to improve energy efficiency (Lee & Jim, 2019), minimise waste (García et al., 2024), and create better living environments (Kent & Thompson, 2019). Innovations such as DT (Zhang et al., 2021) and smart building systems (Le et al., 2019) give real-time data and predictive analytics (Hernandez & Roberts, 2020) and play a crucial role in enhancing building performance and sustainability. These technologies could further complement the findings of (García et al., 2024), which provided a valuable examination of how specific characteristics of European companies influence the disclosure levels and quality of sustainability reports in the waste management sector. The study effectively uses statistical techniques, such as Chi-square analysis and logistic regression, to explore the relationships between company size, location, type, and stock market status with sustainability reporting adherence to global reporting initiative (GRI) standards. The results reveal notable dependencies, such as larger companies and listed firms having higher reporting standards and external verification rates. However, the paper's reliance on GRI reports as the primary data source limits the inclusion of more diverse sustainability frameworks, which could provide a broader perspective. Additionally, the study predominantly focuses on European contexts, which may restrict its applicability to other regions with differing regulatory and cultural landscapes. Future research could enhance these findings by integrating other sustainability metrics and exploring sector-specific challenges in non-European contexts. This would provide a more holistic view of the role of waste management in advancing global sustainability objectives.

Nevertheless, few long-term studies thoroughly evaluate these technologies' long-term effects on sustainability (Raouf & Al-Ghamdi, 2019). This disparity emphasises the necessity of continued study to properly comprehend the long-term advantages and potential drawbacks of sustainable building management techniques (Cao et al., 2022).

The WELL Building Standard: A Framework for Health and Sustainability

In the field of environmental health, it is commonly acknowledged and reiterated that humans spend 90% of their time indoors (American Lung, 1994). Indoor settings logically impact our health because this is the majority of our exposure time and because concentrations of many indoor contaminants are substantially higher indoors than outdoors (Coombs et al., 2016). The purpose of this manuscript is not to provide an exhaustive assessment of these issues; instead, we highlight some of the more significant ones here to demonstrate the scope of the problem: Risks associated with the environment (physical, chemical, biological, and radioactive) (McCarthy et al., 2001), building design, including lighting, acoustics, ventilation, pressurisation, and filtration (Bakó-Biró et al., 2012; McCarthy et al., 2001), social elements (safety, place) (Kim, 2015), behavioural elements (lesson plans, job duties, and wellness initiatives) (Higgins et al., 2005), surrounding land use (green spaces, walkability, noise sources, chemical discharges) (Hammer et al., 2014; Cradock et al., 2009), architectural design (access to natural lighting, dining areas, material choices, Biophilic design, and promotion of physical activity) (Heschong et al., 2002; Frumkin, 2003) and operations and upkeep (integrated pest management, cleaning, preventative maintenance) (Rosenfeld et al., 2011; Adamkiewicz et al., 2014; Colton et al., 2014). Environmental health research usually emphasises the potentially harmful health effects of indoor exposures, like radon lung cancer (Samet and Eradze, 2000), asthma, and phthalates (Bornehag & Nanberg, 2010; Bornehag et al., 2010), the link between second-hand smoke and a higher chance of dying young (Bornehag et al., 2010). It is less common to debate the corollary, which states that when we optimise physical surroundings for human health, the indoor environment may also help health (Fisk, 2000).

The realisation that buildings can have both positive and harmful effects on people and the environment, as well as the desire to reduce adverse effects while boosting positive features, gave rise to the green building movement (Yudelson, 2010). Green buildings minimise local effects at the construction site and save energy and water, which are the main ways to lessen their negative environmental impact. However, improving human health is just one of the objectives of green building design. Green buildings have a significant impact on human health on two fronts: first, directly, by optimising indoor settings for individuals, and second, indirectly, by reducing energy use and, consequently, air pollution, which contributes to early death in the population (Dockery et al., 1993; Laden et al., 2006), heart conditions (Burnett et al., 2014; Brook et al., 2010), aggravating asthmatic conditions (Habre et al., 2014), and contribute to climate change, which is linked to several detrimental effects on human health (Board on Population et al., 2011; Change, 2014).

The green building revolution has certified over 3.6 billion square feet, according to the top green building certification organisation [30]. Since the introduction of the Leadership in Energy and Environment Design (LEED®) certification in August 1998, more than 69,000 LEED-certified buildings have been completed in more than 150 countries (Zhang et al., 2017). Apart from LEED, there have been other recent initiatives to create health-focused building standards. For instance, the International WELL Building Institute spent seven years developing the 2014 standard, which primarily addresses occupant health and does not offer credits for energy or water reduction (2015). The standard adopts a biological systems perspective and includes air, water, food, light, fitness, comfort, and thinking as components of health. Just like in LEED, there are credits for lighting, acoustics, ventilation, air quality, and thermal comfort (Figure 4).

Figure 4 illustrates the key components of WELL, including credits for lighting, acoustics, ventilation, air quality, and thermal comfort, which overlap with LEED standards. However, WELL goes beyond LEED by emphasising human health and well-being through additional criteria such as drinking water quality, ergonomics, and sleep quality. Combined with DT, these standards can be continuously monitored and optimised in real time. For instance, DT can track indoor air quality and dynamically adjust ventilation systems to comply with WELL requirements, ensuring energy efficiency and occupant well-being. WELL also specifies standards for drinking water quality, ergonomics, sleep quality, and carbon filters (air and water). WELL restricts phthalates, polyfluorinated chemicals, and halogenated flame retardants while broadening the chemical focus to include environmentally persistent organohalogen and semi-volatile substances (Standard, 2018).

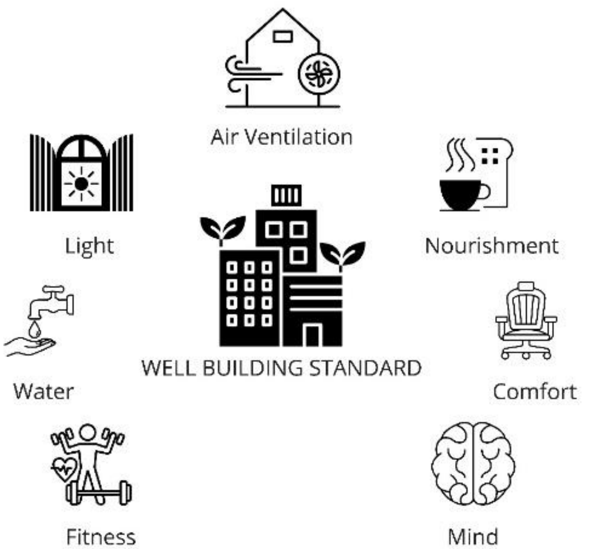

Figure 4. Key Components of WELL Building Standard

Despite the benefits, additional empirical research is desperately needed to assess the long-term effects of WELL on productivity and occupant health (Marberry et al., 2022). Additionally, while the integration of DT with WELL principles shows potential for further boosting building performance, research in this area remains restricted (Byrne et al., 2023). This disparity emphasises the need for more research into how to match digital advancements with WELL's human-centred objectives and optimise their potential advantages.

Digital Twin in Building Management

Real-Time Digital Replicas

DT has emerged as a transformative tool in building management, offering real-time digital replicas of physical assets that enable enhanced monitoring, analysis, and optimisation. By creating a virtual counterpart of a building, managers can track performance metrics, identify inefficiencies, and simulate various scenarios to predict future outcomes. Recent studies by Zhang et al. (2024b) and Tahmasebinia et al. (2023a) highlight the significant potential of DT to improve operational efficiency and sustainability in the built environment through real-time data monitoring and decision-making capabilities. (Zhang et al., 2024b) provided a comprehensive analysis of the applications and potential of DT across the building life cycle, emphasising its role in reducing carbon emissions and enhancing sustainability. The study excels in presenting a conceptual framework for implementing DT, including preparation, deployment, and operational phases, while showcasing real-world proof-of-concept examples to demonstrate feasibility. However, this study reveals significant challenges in integrating DT with WELL, such as high implementation costs, data integration complexities, and the absence of standardised practices. While the research identifies key opportunities for enhancing energy efficiency and life cycle sustainability, its heavy focus on technical aspects limits discussion on broader industry adoption strategies and socio-economic impacts. Furthermore, the study predominantly explores case examples from developed regions, leaving a gap in understanding its applicability in diverse global contexts.

Future research should address these limitations by exploring cost-reduction strategies, scalable models for small- and medium-sized enterprises (SMEs) and developing universal standards to streamline implementation. Additionally, integrating socio-economic considerations and expanding regional diversity in case studies would strengthen the relevance and applicability of DT technologies in achieving global sustainability goals. (Tahmasebinia et al., 2023a) highlighted its comprehensive exploration of DT in enhancing building energy efficiency and sustainability. The paper effectively emphasises the integration of DT with Building Information Modelling (BIM) and machine learning to optimise energy management and achieve sustainability goals. By addressing real-time monitoring, predictive maintenance, and energy optimisation, the study outlines the transformative potential of DT in reducing carbon emissions and improving building performance. However, the paper primarily focuses on theoretical advancements and case studies, with limited discussion on practical challenges such as cost, scalability, and cross-industry implementation. Additionally, while the study highlights the potential of DT, it does not fully address the complexities of integrating this technology with existing infrastructure or regulatory frameworks. Future research could benefit from exploring cost-effective deployment strategies and broader applications in diverse geographic and socio-economic contexts, making the findings more globally relevant.

DT has been instrumental in optimising energy usage, reducing maintenance costs, and improving occupant comfort. A notable example of the application of DT in building management can be seen in the construction of the Smart Campus at the University of Birmingham. Here, the DT created a virtual model of the entire campus, allowing managers to optimise energy use and predict maintenance needs in real time. This practical implementation highlights how DT can improve energy efficiency by tracking building performance and occupant behaviour (Global., 2022). However, despite these advancements, there is a limited body of research exploring the application of DT, specifically within WELL-certified buildings. WELL emphasises health, well-being, and sustainability. Still, few studies have examined how DT can be leveraged to enhance WELL criteria like indoor air quality, lighting control, and thermal comfort. (Fernández-León et al., 2024) suggested that more research is needed to explore the integration of DT with WELL to fully realise their potential in advancing human-centred building design. This gap offers an exciting opportunity for future research to bridge the two fields, enabling more efficient, healthier, and sustainable buildings.

Impact on Predictive Maintenance and Energy Optimisation

One of the most significant benefits of DT is its application in predictive maintenance and energy optimisation. DT enables building operators to predict equipment failures before they occur, reducing downtime and maintenance costs. Additionally, they help optimise energy consumption by simulating various operational strategies and selecting the most efficient one. Studies by Ogunsakin et al. (2023) and Kan (2021) illustrate how DT can be used to forecast maintenance needs and fine-tune energy systems to achieve optimal performance in building management (Akinshipe et al., 2024; Tahmasebinia et al., 2023b). Ogunsakin et al. (2023) presented an innovative approach to developing Adaptive DT (ADT) for dynamic manufacturing systems. The authors address the persistent challenge of synchronising DT with continuously changing physical systems by proposing a novel architecture that enables real-time simulation, online optimisation, and adaptivity (RSO2A). Digital Sub-Twins (DSTs) and Digital Shadows (DSs) offer a robust framework for balancing real-time and non-real-time data flows, ensuring flexibility and adaptability in complex environments like mass personalisation manufacturing. While the study successfully demonstrates the feasibility of the ADT architecture through simulation, it is primarily conceptual, with limited practical validation in real-world manufacturing settings. The reliance on in silico scenarios, such as shoe personalisation, restricts broader applicability and raises questions about scalability and integration with existing industry standards. Additionally, the focus on technical aspects leaves gaps in exploring the socio-economic and organisational implications of adopting ADTs. Future research should expand on these dimensions and include empirical studies to validate the architecture's performance under diverse operational conditions. The study is a significant step forward but requires further refinement to bridge the gap between theoretical advancements and industrial application.

Akinshipe et al. (2024) effectively highlighted the transformative potential of DT in enhancing facility management by making systems more proactive and predictive. By conceptualising the DT-Based Smart Management Plan (DTSMP), the research provides a structured framework that integrates process, people, place, and device, fostering a holistic approach to facility management. The strategic classification into initiation, modelling, utilisation, and reuse phases demonstrates a clear, actionable methodology that aligns with contemporary demands for efficiency and sustainability in the building sector. However, the study predominantly relies on a methodical literature review, with limited empirical validation or real-world case studies to substantiate the proposed framework's applicability and effectiveness. Additionally, while the DTSMP framework emphasises interaction among stakeholders and systems, the practical implementation challenges, such as data interoperability, cost implications, and user adoption, are not addressed sufficiently. The focus on theoretical aspects also leaves gaps in understanding the framework's scalability across diverse building types and operational contexts.

Despite these promising developments, there remains a lack of practical case studies demonstrating the application of DT in sustainable building management. Most existing studies focus on theoretical frameworks or controlled simulations rather than real-world implementations in diverse building types, especially those that aim to meet WELL. (De Graaf, 2024) have called for more comprehensive case studies that explore the practical challenges and opportunities of deploying DT in real-world WELL-certified buildings. The scarcity of empirical data limits our understanding of how DT can be effectively integrated into the operational phases of sustainable buildings, leaving room for further exploration in future research.

Digital Leadership

Role of Leadership in Digital Transformation

While DT provides the foundation for smart and sustainable building management, effective leadership is essential for successfully integrating such technologies. Digital leadership is critical in aligning technological advancements like DT with sustainability and occupant well-being goals, ensuring that these innovations are implemented and scaled efficiently within organisations. To ensure that digital efforts align with the company's overall goals, leaders must have a clear vision. They are essential in creating a change-embracing culture, getting needed funding, and increasing commitment among C-suite executives (Westerman et al., 2014).

The authors present a well-structured framework for achieving digital mastery, categorising organisations into four archetypes: Beginners, Fashionistas, Conservatives, and Digital Masters, based on their digital capabilities and leadership (Westerman et al., 2014). The book combines case studies and theoretical insights to demonstrate how successful digital leaders integrate technology into their strategy, culture, and operations. While the book excels in providing actionable guidance and inspiration for executives, it leans heavily on examples from large, resource-rich organisations, limiting their applicability to small- to medium-sized enterprises (SMEs). Additionally, the rapid evolution of digital technologies since its publication in 2014 means some of its insights may feel dated, particularly regarding advancements in artificial intelligence, machine learning, and cloud computing. The authors also focus on Western business contexts, offering limited perspectives on digital transformation in emerging markets.

Researchers (Kane et al., 2015) have emphasised the critical role of digital leadership and organisational culture in adapting to technological changes, presenting practical recommendations for fostering digital maturity. Their analysis highlights the interplay between digital technology and strategic decision-making, offering a framework for companies to assess their readiness and navigate digital transformation effectively. One of the article's strengths lies in its focus on digital transformation's human and cultural aspects, moving beyond a purely technological point of view. Addressing the importance of leadership, employee engagement, and cross-functional collaboration provides a holistic approach to digital readiness. However, the article's recommendations could be critiqued for their generality, as they lack specific industry-focused examples or granular strategies for different business contexts. Additionally, while it discusses the importance of digital technologies, it does not delve deeply into the technical challenges or the integration of emerging tools such as artificial intelligence or IoT, which have become increasingly significant.

Successful digital leaders use digital channels to increase engagement and productivity (Kane et al., 2015). They are flexible and sensitive to technological changes. According to (Hess et al., 2020), they must organise and up-skill teams, make strategic decisions about new technologies, and guarantee strong data security measures. The authors also provided a comprehensive exploration of strategic approaches to digital transformation. The authors categorised strategies into four primary dimensions: process digitisation, business model innovation, customer interaction, and data-driven decision-making, offering a structured framework for organisations navigating the complexities of digital transformation. Including practical case examples and theoretical insights helps bridge the gap between strategy formulation and real-world application, making it a valuable resource for academics and practitioners.

A key strength of this work is its multidimensional approach, which emphasises the need for organisations to tailor their digital strategies based on their unique goals, resources, and market dynamics. The chapter highlights the importance of aligning digital initiatives with broader strategic objectives by addressing the interplay between technological capabilities and organisational change. However, the chapter could be critiqued for its limited focus on the challenges of implementing digital transformation strategies, such as resistance to change, skill gaps, and resource constraints. Additionally, while it comprehensively covers strategic options, it offers less guidance on prioritising them in rapidly evolving digital environments. The analysis also focuses on large organisations, leaving gaps in applicability to SMEs. Furthermore, a research vacuum is evident in the minimal attention given to the specific responsibilities of leadership in WELL and sustainability initiatives (Fitzgerald et al., 2014).

Influence of AI and IoT on Building Management

Building management is transforming thanks to the integration of artificial intelligence (AI) and the Internet of Things (IoT), which greatly impacts digital leadership. Based on real-time data and occupancy patterns, AI-driven smart building systems powered by IoT sensors may dynamically modify ambient variables like lighting, temperature, and air quality (GhaffarianHoseini et al., 2013). GhaffarianHoseini et al. (2013) have comprehensively explored integrating information and communication technologies (ICT) with sustainability principles to develop smart housing solutions. The authors effectively highlight the potential of ICT in optimising energy efficiency, resource management, and user comfort, emphasising the role of adaptive technologies in creating intelligent and sustainable living environments. The paper stands out for its multidisciplinary approach, bridging technology, architecture, and environmental science to propose holistic frameworks for future smart homes. A significant strength of the paper is its forward-looking perspective, identifying key trends and challenges in implementing ICT-driven sustainability within residential contexts. It provides a detailed analysis of the benefits of smart housing technologies, such as real-time energy monitoring and occupant behaviour modelling, while acknowledging the barriers, including cost, data security, and user acceptance.

Furthermore, GhaffarianHoseini et al. (2019) extends this innovation by introducing n-dimensional BIM (ND BIM) with knowledge-based systems to enhance post-construction energy efficiency. The authors demonstrate how integrating ND BIM enables detailed energy monitoring, predictive maintenance, and proactive building management. The study highlights the importance of leveraging digital tools for real-time data analysis, facilitating informed decision-making in building operations. A major strength of this paper is its focus on bridging the gap between design and operational phases, emphasising the use of BIM for lifecycle energy management. The authors provide a clear framework that combines BIM's geometric and parametric modelling capabilities with knowledge-based systems, ensuring a comprehensive approach to energy efficiency. Including practical use cases and scenarios further strengthens the relevance of the proposed methodology. However, the study could be critiqued for its limited discussion on the challenges of implementing ND BIM in real-world contexts, such as the high cost of adoption, interoperability issues with legacy systems, and the skill gaps among facility management teams.

Additionally, while the paper highlights the technical benefits of ND BIM, it underexplores the socio-economic and regulatory barriers that could impede its widespread adoption. Despite these technological strides, challenges remain in integrating DT with WELL. Addressing gaps in leadership strategies for incorporating these technologies into holistic building management systems is critical (Yu et al., 2021). The synthesis of AI, IoT, ICT, and ND BIM highlights the potential for transformative impacts on sustainable building management. It also underscores the need for further research to overcome implementation barriers and ensure these innovations achieve their full potential.

Integration of Technologies with Standards

Integrating Digital Twin with the WELL Building Standard for Sustainability Goals

The integration of DT with WELL has opened new possibilities for achieving sustainability goals. By leveraging DT, building managers can continuously monitor and optimise building performance, aligning energy efficiency and occupant well-being with WELL criteria. Kan & Anumba (2019) and Zhang et al. (2024b) have discussed how integrating real-time data from DT into WELL-certified buildings can help track critical parameters such as indoor air quality, lighting, and thermal comfort, ensuring these variables stay within the optimal ranges prescribed by WELL (Akinshipe et al., 2024; Zhang et al., 2024a). DT's ability to provide a comprehensive and dynamic model of a building's performance makes it an invaluable tool for achieving WELL's sustainability and health objectives. For example, in the Edge building in Amsterdam [78], one of the world's most sustainable and smart buildings, a DT was integrated with WELL to enhance energy efficiency and occupant well-being. The building's sensors track lighting, air quality, and thermal comfort, dynamically adjusting these variables to meet WELL criteria, providing a real-world example of how DT can align with WELL to achieve sustainability goals. Byrne et al. (2023) explored how digital technologies, including IoT and AI, were integrated into WELL-certified buildings to enhance occupant well-being and energy efficiency. It provides an in-depth analysis of a WELL-certified smart building, demonstrating how data-driven decision-making improved air quality, lighting control, and overall energy performance. This case study underscores the potential of integrating DT with WELL to achieve optimal occupant comfort and sustainability outcomes.

A major strength of the literature lies in its ability to showcase the technical potential of this integration, particularly in high-profile case studies. The Edge building exemplifies the transformative capabilities of DT in smart buildings, offering a tangible proof-of-concept. Additionally, research by (Byrne et al., 2023) provides valuable insights into the application of IoT and AI, showing the interconnectedness of advanced digital technologies in optimising energy performance while maintaining occupant-centric design principles.

However, despite the potential of this integration, the literature on the interplay between DT and WELL remains fragmented. Few studies systematically explore how these two frameworks can effectively merge to create holistic, health-focused, and sustainable building environments. (Fernández-León et al., 2024) point out that most research has either focused on DT applications for operational efficiency or on WELL's human-centred design, with minimal cross-disciplinary work that ties the two together (Torres et al., 2024). This disciplinary siloing limits the ability to develop comprehensive frameworks that leverage the strengths of both approaches. Furthermore, the socio-economic and organisational challenges of implementing DT in WELL-certified buildings remain underexplored. Existing studies do not adequately address key barriers such as high implementation costs, data privacy concerns, lack of standardisation, and skill gaps among building managers and occupants.

Literature also lacks empirical validation of proposed frameworks in diverse building types and geographic contexts. While case studies like the Edge building provide valuable insights, they represent high-resource environments that may not be scalable to smaller projects or regions with limited access to advanced technologies. This limitation highlights the need for more inclusive research examining DT's adaptability and scalability in varied socio-economic and cultural settings.

Data-Driven Insights Enhancing Occupant Well-Being and Efficiency

Data-driven insights generated by DT offer unprecedented opportunities to enhance occupant well-being and building efficiency in WELL-certified environments. DT provides actionable insights that can improve decision-making processes and ensure optimal building performance by collecting and analysing real-time data on factors such as indoor environmental quality, energy usage, and occupancy patterns. Ogunsakin et al. (2023) and Tahmasebinia et al. (2023a) demonstrate how DT can refine building systems for better energy efficiency while enhancing occupant comfort by maintaining ideal conditions for air quality, lighting, and thermal control (Akinshipe et al., 2024; Tahmasebinia et al., 2023b).

Despite these advancements, gaps remain in developing practical frameworks that guide digital leadership in utilising these technologies to meet WELL certification standards. As noted by Bhandal et al. (2022) and Cespedes-Cubides & Jradi (2024), the absence of cohesive frameworks limits the broader adoption of data-driven approaches to achieve WELL. Current research often focuses on technological capabilities without adequately addressing the integration of human-centred goals or leadership strategies necessary to maximise their potential. This gap is particularly significant as DT offers unprecedented opportunities to balance efficiency and well-being, but without established frameworks, their application remains fragmented and underutilised.

Another limitation is the lack of established leadership models to guide the implementation of DT in WELL-certified buildings. While technology is robust, its success depends on strategic decision-making that integrates technological insights with human-centric considerations. This gap underscores the need for a comprehensive approach incorporating leadership, governance, and interdisciplinary collaboration to achieve sustainable outcomes.

Future research should develop practical frameworks aligning DT with WELL certification requirements. These frameworks should address integrating health and efficiency outcomes, offering guidance on balancing technological capabilities with human-centred design. Leadership models incorporating data-driven approaches must also be explored, ensuring that DT applications are scalable and adaptable across diverse building types and contexts.

FUTURE DIRECTIONS AND RECOMMENDATIONS

Integrating DT with WELL presents transformative opportunities for advancing sustainable building management, yet significant challenges and gaps remain. As highlighted in the literature, empirical studies demonstrating the practical application of DT in WELL-certified buildings are scarce. Future research must prioritise case studies that explore real-world implementations, focusing on how DT can enhance occupant health, energy efficiency, and predictive maintenance. Such studies are crucial for validating the theoretical benefits of this integration and understanding its practical implications.

Another critical area for exploration is the development of leadership frameworks that facilitate the effective adoption of digital tools in achieving WELL's human-centred goals. Digital leadership must bridge technological advancements such as AI and IoT with WELL, ensuring a seamless alignment between innovation and occupant-centric objectives. Without clear guidance and interdisciplinary collaboration, the potential of DT to transform WELL-certified buildings may remain underutilised.

Integrating data-driven insights from DT with WELL also offers a promising avenue for research. Future investigations should focus on how this synergy can optimise building performance, enhance occupant well-being, and contribute to broader sustainability goals. This includes exploring new methodologies for integrating real-time data analytics with WELL metrics and unlocking innovative pathways for achieving holistic building management.

Finally, long-term studies are needed to evaluate the sustained impact of DT on building performance, ecological integrity, and occupant health. These studies can identify implementation challenges, measure long-term benefits, and provide insights into the scalability and adaptability of this integration across diverse building types and geographic contexts. By addressing these gaps, future research can pave the way for smarter, more sustainable building management practices that balance technological innovation with human-centred design.

CONCLUDING REMARKS

The built environment is increasingly recognised as a cornerstone of sustainability, with buildings evolving into dynamic systems that balance energy use, material efficiency, and occupant well-being. Sustainable building management has transitioned from a narrow focus on energy conservation to a broader, more holistic approach encompassing environmental, economic, and social dimensions. Within this context, digital leadership and advanced technologies, particularly DT, have emerged as transformative tools. DT offers real-time digital replicas of physical assets, enabling enhanced monitoring, predictive maintenance, and energy optimisation. When integrated with WELL, which prioritises occupant health, comfort, and sustainability, DT presents unique opportunities for improving building performance.

However, the literature on the integration of DT with WELL remains fragmented. There is a notable lack of empirical studies and practical case examples that explore this integration in detail. While theoretical discussions highlight the potential of this synergy, the absence of real-world validation limits the broader adoption and scalability of these technologies. Additionally, gaps in leadership frameworks hinder the effective implementation of digital tools to achieve sustainability goals. Addressing these deficiencies is critical for advancing sustainable building management practices. This review consolidates existing knowledge, identifies emerging trends, and highlights key research gaps, providing a roadmap for future investigations into integrating DT with WELL.

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PERFORMANCE EVALUATION OF A GEOPOLYMER CONCRETE IN COMPARISON WITH ORDINARY CONCRETE

Moetaz El-Hawary[1*], Mariam Othman[2] and Mohamed F. Hamoda[3]
[1]Associate Professor, Civil & Architectural Engineering Department, International University of Science and Technology in Kuwait
[2]Graduate Student, Civil Engineering Department, Kuwait University
[3]Professor, Civil & Architectural Engineering Department, International University of Science and Technology in Kuwait

**Corresponding Author: Moetaz.Elhawary@iuk.edu.kw*

Abstract
Geopolymers are inorganic polymers composed of alumina and silica, offering an alternative to conventional concrete. This study compares the performance and durability of geopolymer concrete produced using locally available materials with those of conventional concrete to determine whether geopolymer concrete has the potential to be a suitable replacement in hot climate countries such as Kuwait. To formulate the geopolymer concrete, ground granulated blast furnace Slag (GGBS), sodium hydroxide and sodium meta-silicate solutions were utilized. After curing, the mechanical properties of the Mixes, including tensile strength, modulus of elasticity and compression strength, were tested. The durability of the concrete samples was determined by testing the resistance to freezing and thawing, sulfuric acid, seawater, heat, water penetration and absorption. The shrinkage behaviour of the concrete was also studied through restrained ring test. Results showed that geopolymer concrete had high early strength development, better tensile strength, and increased compressive strength up to 95% when exposed to temperatures of 100, 300, and 500ºC. It also had lower water penetration, suggesting better durability. Both types of concrete showed almost similar mechanical and physical properties at equivalent strength levels; however, geopolymer concrete showed better resistance to acids, showing its potential as a suitable replacement for cement-based concrete.

Keywords: *Concrete Durability; Geopolymer Concrete; Compressive Strength; Tensile Strength; Sustainability; Thermal Degradation; Cement Replacement*

List of Notations:

Abbreviations		Parameters
ASTM	:	American Society for Testing and Materials
DIN	:	Deutsches Institut Fur Normung (German Institute for Standardization)
GPC	:	Geopolymer Concrete
GGBS	:	Ground Granulated Blast Furnace Slag
KCC	:	Kuwait Cement Company
KSS	:	Kuwait Standards Specification
Km/s	:	Kilometers per Second
MPa	:	Megapascal
Mm	:	Millimeters
NaOH	:	Sodium Hydroxide
Na_2SiO_3	:	Sodium Silicate
Psi	:	Pounds per Square Inch
SSD	:	Standard Surface Dry
SP	:	Super Plasticizer

INTRODUCTION

The building materials sector is considered the third largest CO_2-emitting industrial sector worldwide. This is due to the production of clinker, which requires high temperatures of 1500ºC (2732ºF); this process consumes natural resources, carbon-dioxide fuels and electricity; and results in CO_2 emissions. Initiatives to use more environmentally sustainable building materials to replace cement are being investigated, specifically geopolymer cement.

Geopolymer Concrete (GPC) is a product of an inorganic poly-condensation reaction of polymeric alumino-silicates and alkali-silicates. This reaction is often referred to as "geopolymerization". The raw materials can be found in nature, such as metakaolin and natural pozzolans, or as manufacturing by-products, such as fly-ash from thermal power plants, waste incinerators, and GGBS from iron and steel industries. When activated with an alkaline activator, the hardened product is known as geopolymer concrete.

Although the binder was developed by Joseph Davidovits in 1972 when attempting to develop a heat-resistant building material, the resulting concrete had unique properties such as high early strength, low shrinkage, freeze-thaw resistance, fire-resistance, sulfate resistance and corrosion resistance. Additionally, the geopolymer cement used is considered industrial waste; using this results in a lower impact on the environment with regards to its disposal, the energy required for production and dependency on raw materials (Komnitsas, 2011; Zhang et al., 2024 and Ürünveren, et al., 2024).

GPC has been utilized in the repair and rehabilitation of existing concrete structures by using geopolymer paste to bind carbon fib fabrics to a reinforced concrete beam (Balaguru et al., 1997 and Khalifa et al., 2024), as well as the rehabilitation of infrastructures like concrete sewer pipes due to high sulfate resistance of geopolymer (Seedao, 2023). GPC is also considered suitable for producing precast railway sleepers, sewer pipes, culverts, and wall panels due to the high early strength of the concrete after dry heat and steam curing (Sreenivasulu et al., 2019 and Gorde et al., 2023).

In recent years, a considerable number of experimental studies have been conducted to improve GPC performance and replace conventional concrete in construction. Such improvement included designing an optimum Mix as well as attempting to achieve higher compressive strength through an increase in alkaline solution molarity, ratio of fly ash: GGBS, blending with materials such as microwave incinerated rice husk), investigating the effects of curing conditions and quality of aggregates (Hojati et al., 2019 and Nuruddin et al., 2011).

Recent studies also include the performance of geopolymer coatings (Rathinam et al., 2020), the effect of ultrafine Slag on the properties of GPC (Parveen et al., 2019), a flexural strength of GPC beams (Sreeivasulu et al., 2019), behaviour of GPC under elevated temperatures (Palaskar and Vesmawala, 2020), the use of granite with Slag in the production of new geopolymer (Zhang et al., 2020), analysis of strength characteristics of Slag based GPC (Esparham et al., 2021), durability of fibre reinforced geopolymer composite (Aygormez, 2021), review of fly ash geopolymer concrete (Akçaoğlu et al., 2019), durability properties of fly ash geopolymer concrete (Shebli et al., 2023) and the effect of high temperature and properties of heavyweight geopolymer concrete (Amin et al., 2021). The impact of high temperatures up to 800ºC (1472ºF) on the mechanical properties of lightweight GPC was also investigated (Tayeh et al., 2921).

This research aims to compare the performance and durability of geopolymer concrete with that of conventional concrete (control) and to determine whether geopolymer concrete can be a suitable cast-in-situ replacement for cement-based concrete.

GPC may be considered an eco-friendly, sustainable material. It is economical, low energy consumption, thermally stable, easily workable, eco-friendly, cementless, and durable. GPC reduces carbon footprints using industrial solid waste like Slag, fly ash, and rice husk ash (Parathi et al., 2021 and Verma et al., 2022).

Construction and demolition waste may be utilized as aggregates in the production of GPC (Alhawat et al., 2022 and Figiela et al., 2022). This will improve sustainability and reduce the carbon impact of the resulting concrete, as it will further reduce waste and reduce quarrying for aggregates.

MATERIALS AND MIX DESIGN

Ordinary Portland cement (Type I) was provided by the Kuwait cement company (KCC) in accordance with the American standard specification (ASTM C150-11) and the Kuwait standards specification (KSS 381-383). GGBS was supplied by the Acico Company (ACC) in accordance with the American standard specification (ASTM C989-05) and the British standard (BS EN 6699). The chemical composition of the (GGBS) as given by the supplier is shown in Table 1.

Table 1. Chemical Composition of (G.G.B.S)

Chemical	Percentage (%)
SiO_2	33.60
Al_2O_3	12.50
Fe_2O_3	0.52
CaO	42.50
MgO	7.52
SO_3	1.68
C_3S	-
C_2S	1.26
C_3A	-
Alkalis	0.48
Chlorides	0.01
Loss on Ignition	0.02
Specific Surface, m^2/kg	542.50

The fine aggregate used consists of natural sand that was obtained from local quarries in Kuwait. Natural coarse aggregates used are imported from Ras Al-Khaimah in The United Arab Emirates. It consists of Gabbro (crushed stone) of three different sizes (3/8 inches, 1/2 inches and 3/4 inches) (9.5, 12.7 and 19.05 mm). All the natural coarse aggregates and fine aggregates used were at SSD condition at the time of Mixing.

The alkaline activator solution consists of sodium hydroxide and sodium silicate. Sodium hydroxide in the form of white, odourless pellets (NaOH) having a purity of 97% and a solubility of 111g/100g (111 lb/ 100 lb) of water and sodium silicate meta nonahydrate ($Na_2O_3Si.9H_2O$) in the form of a white, odourless powder with appreciable solubility (>10%) in water and mole ratio of 1.1005 were supplied by the Indian company Loba Chemie.

KUT PLAST SP 400 super plasticizing, high range, water-reducing adMixture was used. This adMixture is based on a modified sulfonated naphthalene formaldehyde condensate, complying with BS 5075 and ASTM C494 Type F. It is supplied as a brown solution.

A series of trial Mixes were carried out with the aim of achieving compressive strengths of 25-30 MPa (3.63- 4.35 ksi) in both Slag-based geopolymer and cement-based concrete and slump within 50-150mm (1.97-5.91mm). With regards to the geopolymer concrete Mix, the following criteria were considered from previous studies: the percentage composition of the combined aggregates is within 75-80%, and for all the trial Mixes, an average of 77.5% was used. The optimum fluid-to-binder ratio used was 0.4, and the optimum alkaline activator ratio of NaOH: Na_2SiO_3 is 1:2.5. Finally, water content and adMixture dosage were determined for each trial based on the results achieved from the previous trials. No cement was used in any of the GPC Mixes. The composition of the Mixes is shown in Tables 2 and 3.

Table 2. Composition of Slag-Based Geopolymer Concrete

No.	G.G.B.S (kg/m^3)	C.A (kg/m^3)	F.A (kg/m^3)	NaOH (kg/m^3)	Na_2SiO_3 (kg/m^3)	AdMixture Dosage (L/100kg)	Water/Geopolymer Solids Ratio (by Mass)
Slag Mix -1	387.10	1277.42	580.64	44.24	103.23	3.0	0.40
Slag Mix -2	387.10	1277.42	580.64	44.24	110.60	3.0	0.45
Slag Mix -3	387.10	1277.42	580.64	44.24	110.60	3.0	0.40

Table 3. Composition of Conventional Concrete Mixes K250 and K400

Concrete Mix	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	AdMixture Dosage (L/100kg)	Water/ Cement Ratio
K250	300	710	1175	2.0	0.70
K400	410	655	1090	2.0	0.48

Preparation of Samples

Conventional Concrete Samples

Conventional concrete Mixing, casting and curing were done in accordance with ASTM C192M-19. A wet cloth was used to clean the pan and paddles of the Mixer. The required quantities of coarse aggregate, sand and cement were weighed. The coarse aggregate sizes were placed in the Mixer for 30 seconds. The sand was then added to the Mixer, and the Mixing continued for another 30 seconds. The cement was then added to the Mixer with half the volume of water. Within 1 minute, the adMixture was added to the remaining volume of water and finally added to the Mixture. The Mixing continued for 3 minutes before casting in moulds.

All steel moulds used during casting were coated with a releasing agent. The concrete was cast in two layers; a vibrating table and compacting rod were both used to ensure the release of air bubbles. Once compaction was done, the top of the moulds was finished off with a wet trowel. The cast moulds were covered with wet burlap and polyethylene sheet before demoulding. The following mould sizes were used:

1. 100x100x100 mm (3.94x3.94x3.94 in) cubes.
2. 150x150x150 mm (5.9x5.9x5.9 in) cubes.
3. Cylinders of 300 mm (11.8 in) height and 150 mm (5.9 in) diameter.
4. 75x75x280 mm (2.95x2.95x11 in) prisms.
5. Steel ring of 395 mm (15.55 in) outer diameter, 215 mm (8.46 in) inner diameter and 150 mm (5.9 in) height.

Conventional concrete samples were de-moulded after 24 hours and placed in the curing tanks at approximately 20°C (68°F); the samples were left to cure for 28 days.

Geopolymer Concrete Samples

The following steps were followed in the preparation of the two components of the alkaline activator solution: 400g (0.88 lb) of sodium hydroxide pellets were completely dissolved in every 1 litre of distilled water to prepare a 10M solution. The solution was covered and left overnight to allow all heat to escape. Similarly, NaOH 12M solution was prepared by completely dissolving 480g of sodium hydroxide pellets in every 1 litre of distilled water. All safety precautions were followed. Sodium metasilicate 0.75M solution was prepared by dissolving 222.2g (0.49 lb) of powder in every 1 litre of distilled water. Low heat was added until the powder was completely dissolved. The solution was covered and left overnight to cool.

The following procedure was used to prepare the geopolymer Mixes: a wet cloth was used to clean the pan and paddles of the Mixer. The required quantity of coarse aggregate, sand and Slag were weighed. Three different coarse aggregate sizes were placed in the Mixer for 30 seconds, then sand was added to the Mixer, and the Mixing continued for 30 seconds. The Slag was added and Mixed for an additional 2 minutes. Sodium hydroxide and sodium metasilicate solutions were combined to make up the alkaline activator, which was then added to dry components and Mixed for 3 minutes. Like the previous method of Mixing, half of the volume of water was added, and the concrete was Mixed for 30 seconds. Then, adMixture was added to the remaining volume of water and added to the Mixture, and the Mixing continued for 3 minutes before casting in moulds. The previously mentioned mould sizes were also used.

Geopolymer concrete samples were de-moulded after 24 hours and left to air cure for 28 days in the lab. Ambient temperature and relative humidity were recorded daily for the duration of the curing. Temperature averaged at 22.4°C (72.3°F) and relative humidity at 55%.

TESTING PROCEDURE

Fresh and Mechanical Properties

A slump test was performed in accordance with (ASTM C 143/C143M-15) on freshly Mixed conventional and geopolymer concrete. Compressive strength tests were performed on two (100x100x100) mm (3.94x3.94x3.94 in) cubes at 7, 28 and 56 days. The cube samples were placed in a hydraulic compression testing machine and subjected to a loading rate of

3000 N/s 306 kp/s until failure. Average compressive strengths are shown in Figure 1. Splitting tensile strength and modulus of elasticity tests were carried out on two-cylinder samples of height 300 mm (11.8 in) height and 150 mm (5.9 in) diameter (in conformance with (ASTM C496/C496M-17) average results are shown in Figure 2 and (ASTM C469/C469M-14) respectively at 28 days. For the stress/strain test, each cylinder was fitted with a compress meter and subjected to a loading rate of 5400 N/s (5400 kp/s) in the hydraulic compression testing machine until failure. The modulus of elasticity is concluded from the stress/strain curve when the stress is at 40% of the maximum compressive strength, as seen in Figure 3.

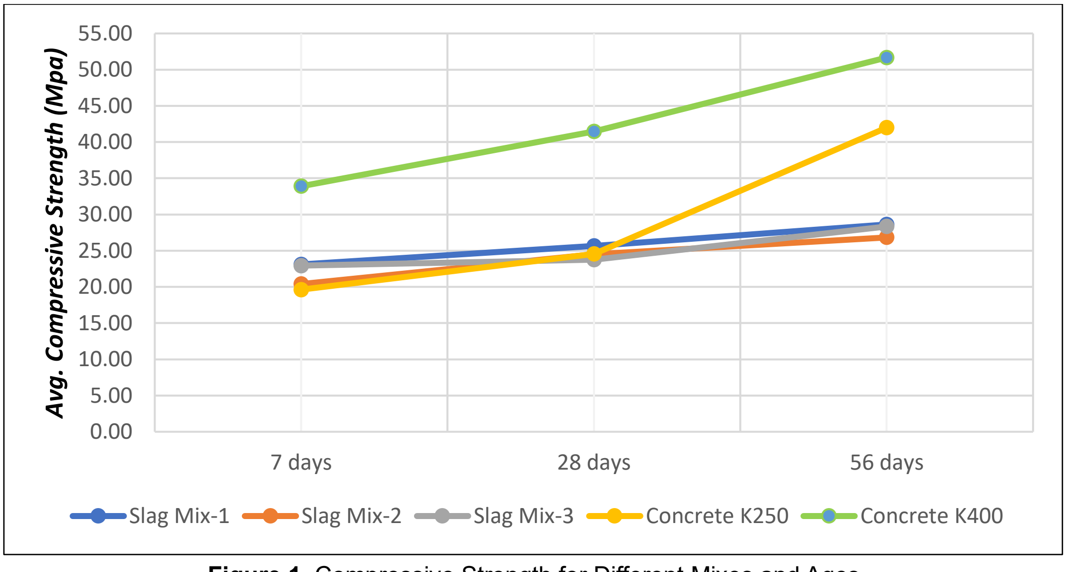

Figure 1. Compressive Strength for Different Mixes and Ages

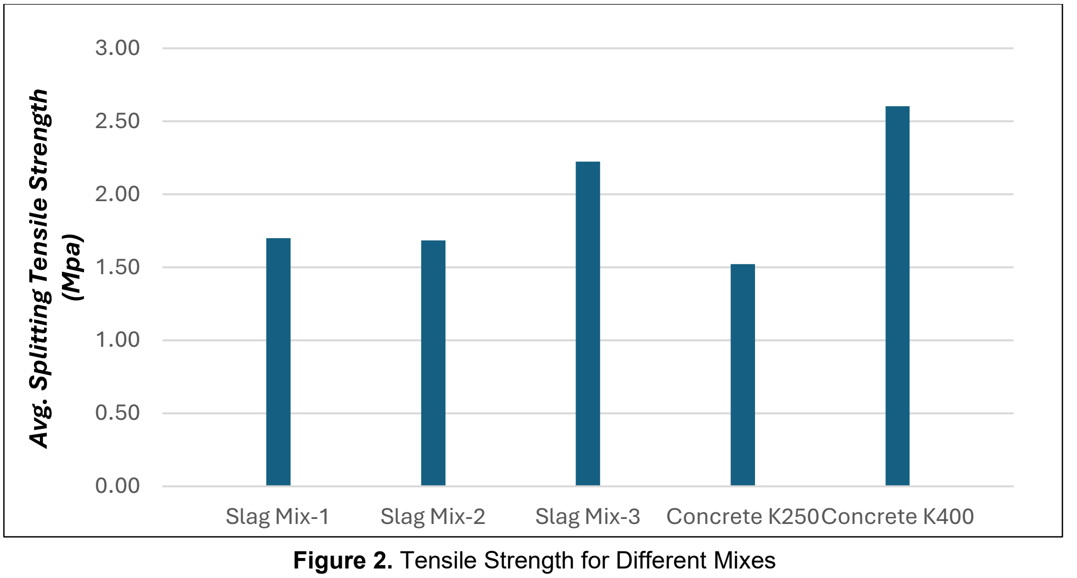

Figure 2. Tensile Strength for Different Mixes

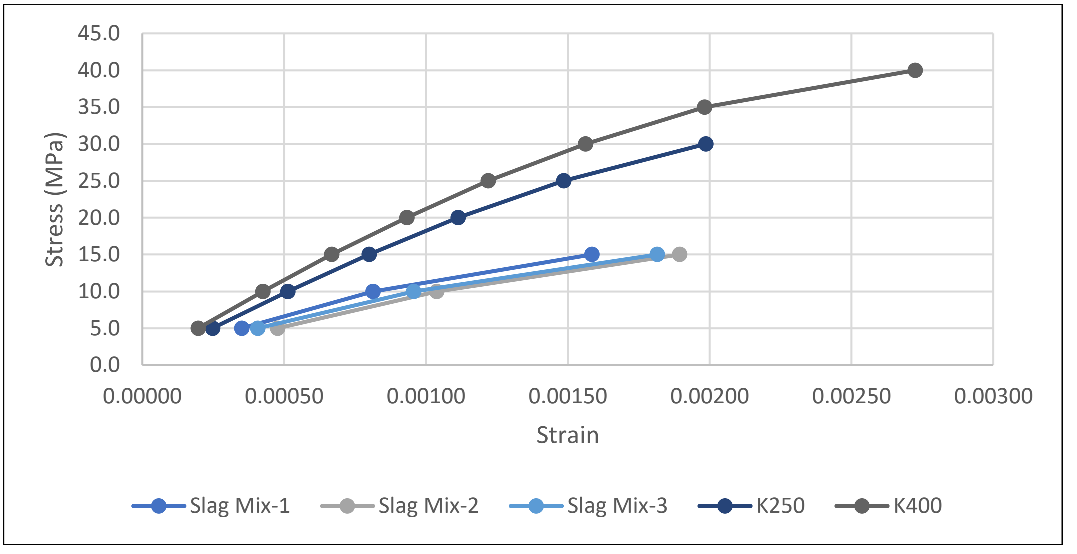

Figure 3. Stress/Strain Curves for Different Mixes

Durability Properties

Heat Resistance Test

Conventional concrete and geopolymer concrete cube samples of size (100x100x100) mm (3.94x3.94x3.94 in) were placed in an electric oven at the temperatures of 100°C, 300°C, 500°C, and 700°C (212, 572, 932 and 1292°F). All the samples were subjected to heat treatment for a total of 6 hours, and the oven was set up to heat from room temperature to the required temperature in 2 hours; then, the samples were left for 2 hours in the oven and finally came down to room temperature in 2 hours. The samples were then left an additional 24 hours to completely cool down from within. The cubes were tested to determine the residual compressive strength (Figure 4). The cubes were also weighed before and after heat treatment to determine weight loss.

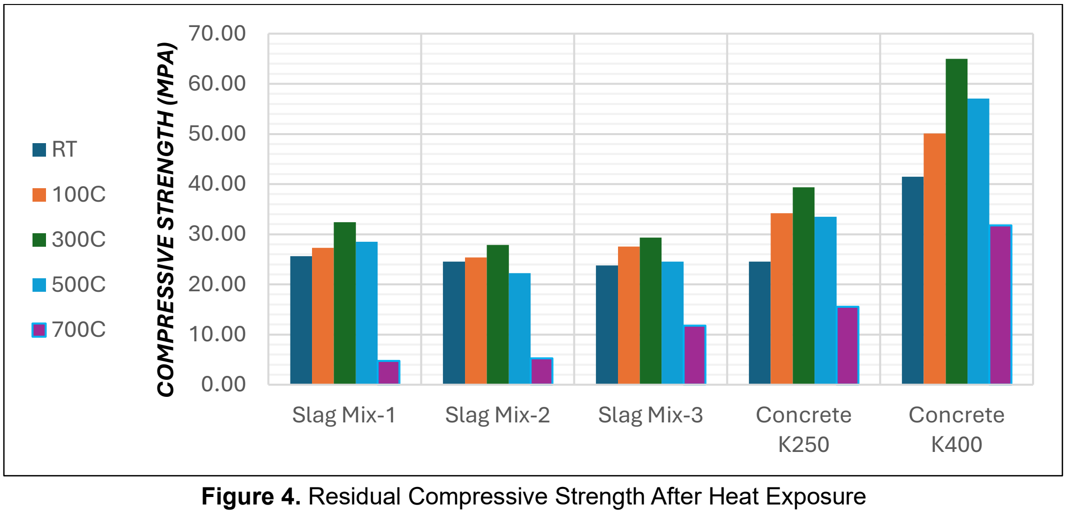

Figure 4. Residual Compressive Strength After Heat Exposure

Water Permeability Test

A water permeability test was performed on conventional and geopolymer concrete cube samples of size (150x150x150) mm (5.9x5.9x5.9 in) in accordance with (DIN 1048 Part 1) to determine the resistance against the penetration of water exerting pressure. The samples were cast and cured for 28 days. The samples were then exposed to a constant water pressure of 0.5 N/mm^2 (72.5 psi) for a period of 3 days. Once the pressure is released, the cubes are removed and immediately split down the centre, where the face exposed to water is placed downwards. The maximum depth of penetration is measured in mm, and the results are shown in Figure 5.

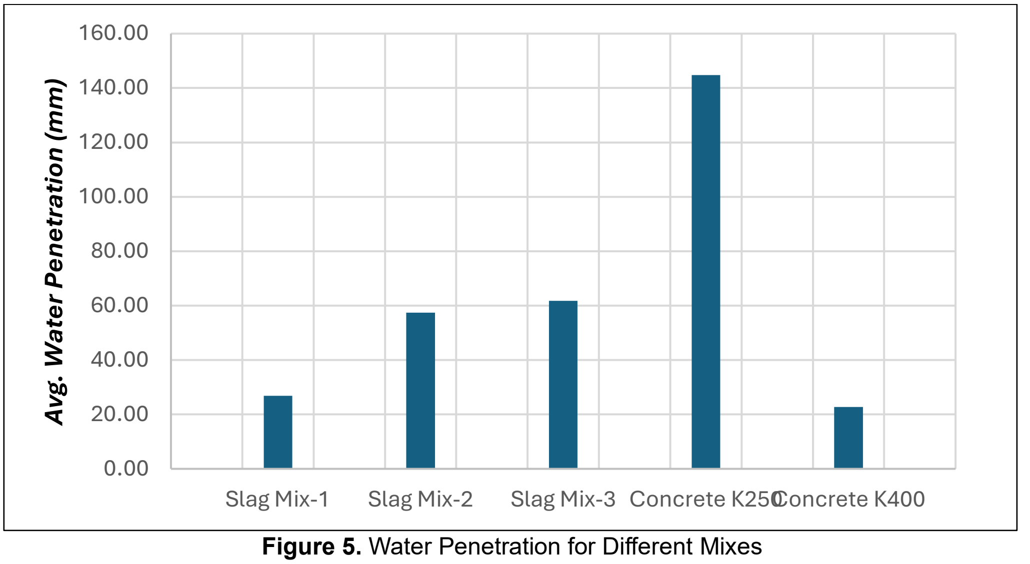

Figure 5. Water Penetration for Different Mixes

Absorption and Voids Test

Absorption of conventional and geopolymer concrete was tested in accordance with ASTM C642-13. Cube samples of size (150x150x150) mm (5.9x5.9x5.9 in) were cast and cured for 28 days. A core was taken from each cube. The samples were then oven-dried for 24 hours at a temperature of 100°C (212°F) and left to cool down to room temperature before being weighed. This was repeated until the mass became constant. Secondly, the samples were then immersed for 48 hours in the curing tanks at a temperature of 22°C (71.6°F). They were surface-dried and weighed. Once again, they were placed in the tank at 24-hour intervals until the surface dried mass became constant. Thirdly, the samples were placed in boiling water for 5 hours, and then they were left to cool down to room temperature, surface dried, and weighed. Finally, the cores were suspended by a wire to determine the apparent mass in the water. The absorption and percentage of voids were determined using Equations 1 to 3, and the average percentage of voids is displayed in Figure 6.

$$\text{Absorption after immersion, \%} = [(B - A)/A \times 100] \quad (1)$$

$$\text{Absorption after immersion and boiling, \%} = [(C - A)/A \times 100] \quad (2)$$

$$\text{Volume of permeable pore space (voids) \%} = [(C - A)/(C - D) \times 100] \quad (3)$$

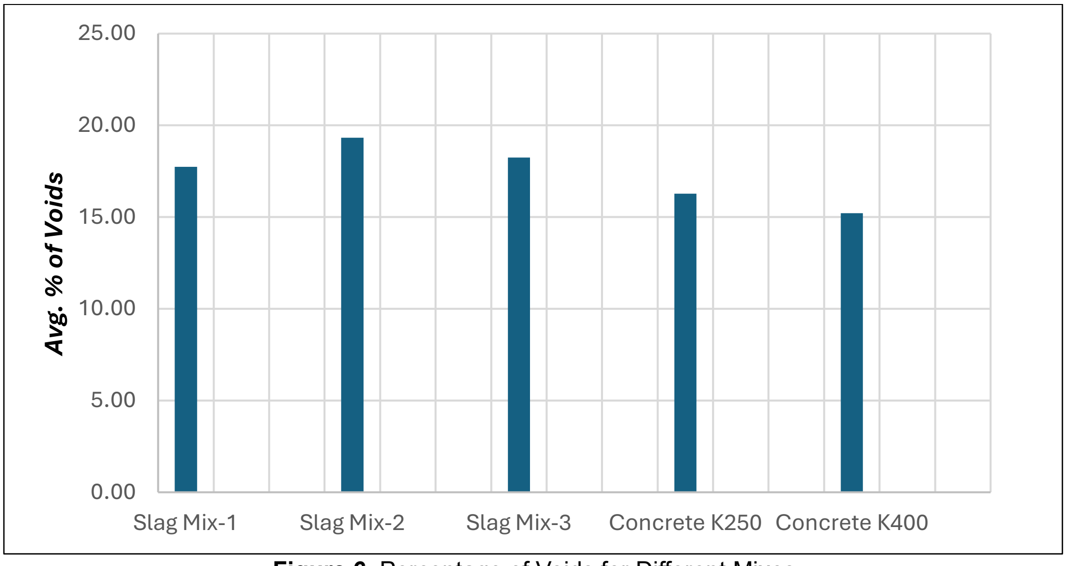

Figure 6. Percentage of Voids for Different Mixes

Sulfuric Acid Resistance Test

Conventional and geopolymer concrete cube samples of size (100x100x100) mm were placed in a 5% sulfuric acid solution after 56 days of curing. Two cube samples from each Mix were immersed for 7, 28 and 56 days, then removed and left to dry for a period of 72 hours. The samples were observed for external damage and capped accordingly before the compression strength test. The cubes were tested to determine the residual compressive strength, as shown in Figure 7. The samples were also weighed before and after placement in the solution to determine weight loss.

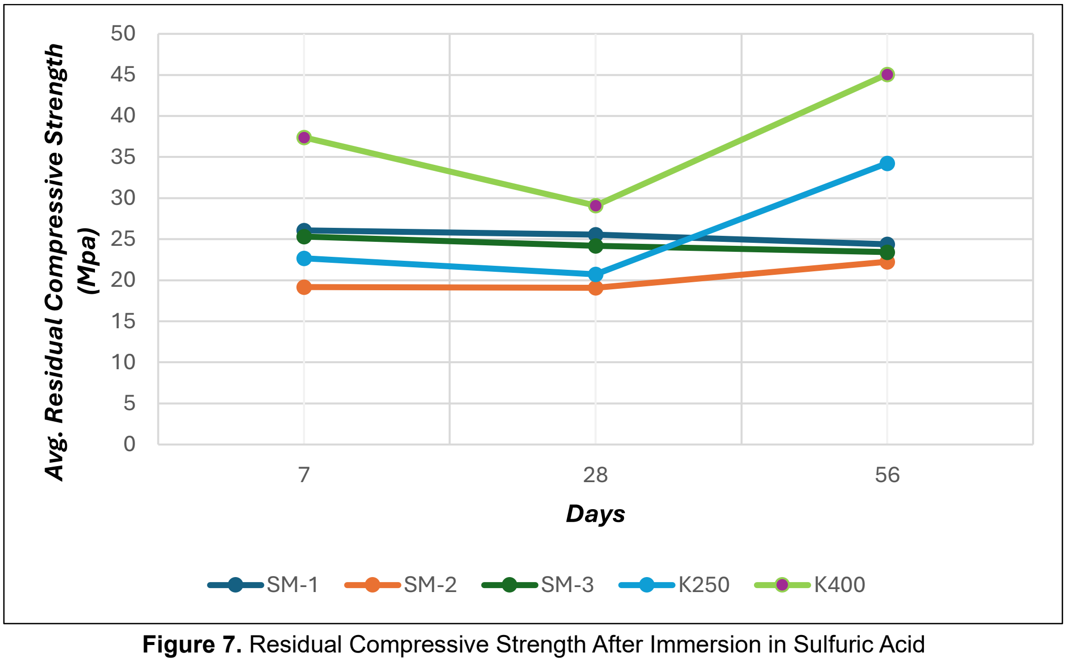

Figure 7. Residual Compressive Strength After Immersion in Sulfuric Acid

Seawater Resistance Test

Conventional and geopolymer concrete cube samples of size (100x100x100) mm (3.94x3.94x3.94 in) were placed in seawater after 56 days of curing. Two cube samples from each Mix were immersed in seawater for 7, 28 and 56 days, then removed and left to dry for a period of 72 hours. The cubes were tested to determine the residual compressive strength, as shown in Figure 8. The samples were also weighed before and after placement in the solution to determine weight loss.

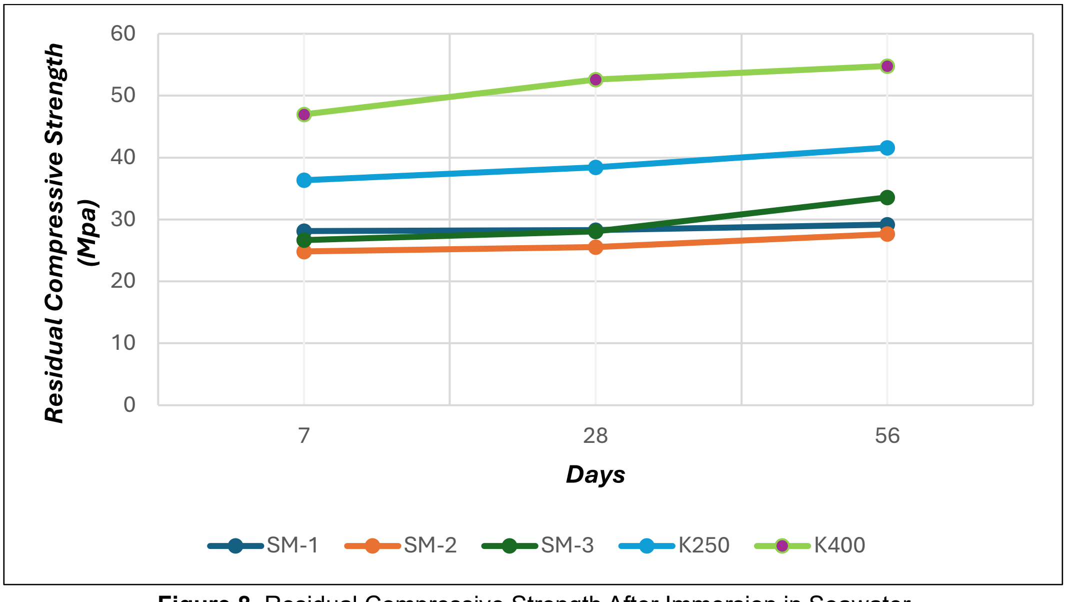

Figure 8. Residual Compressive Strength After Immersion in Seawater

Restrained Ring Test

The age of cracking and rate of tensile strength gain of both conventional and geopolymer concrete ring samples under restrained shrinkage were tested in accordance with ASTM C1581-18a. Steel ring moulds with an 8mm (0.215 in) wall thickness, 395 mm (15.55 in) outer diameter and 150 mm (5.9 in) height were used to restrain the concrete. The concrete was cast in two layers, where each layer was compacted 75 times with a 10mm diameter rod and vibrated. After casting and compaction, two electrical strain gauges were placed on the inner wall of the steel moulds. The strain gauge readings were taken at 6-hour intervals. Conventional concrete was covered with wet burlap and polyethylene sheet for 24 hours while the geopolymer concrete was left to air cure. Ambient temperature and relative humidity readings were taken daily for the period of the test. The sudden decrease in strain indicates the cracking of the specimen, as shown in Figure 9.

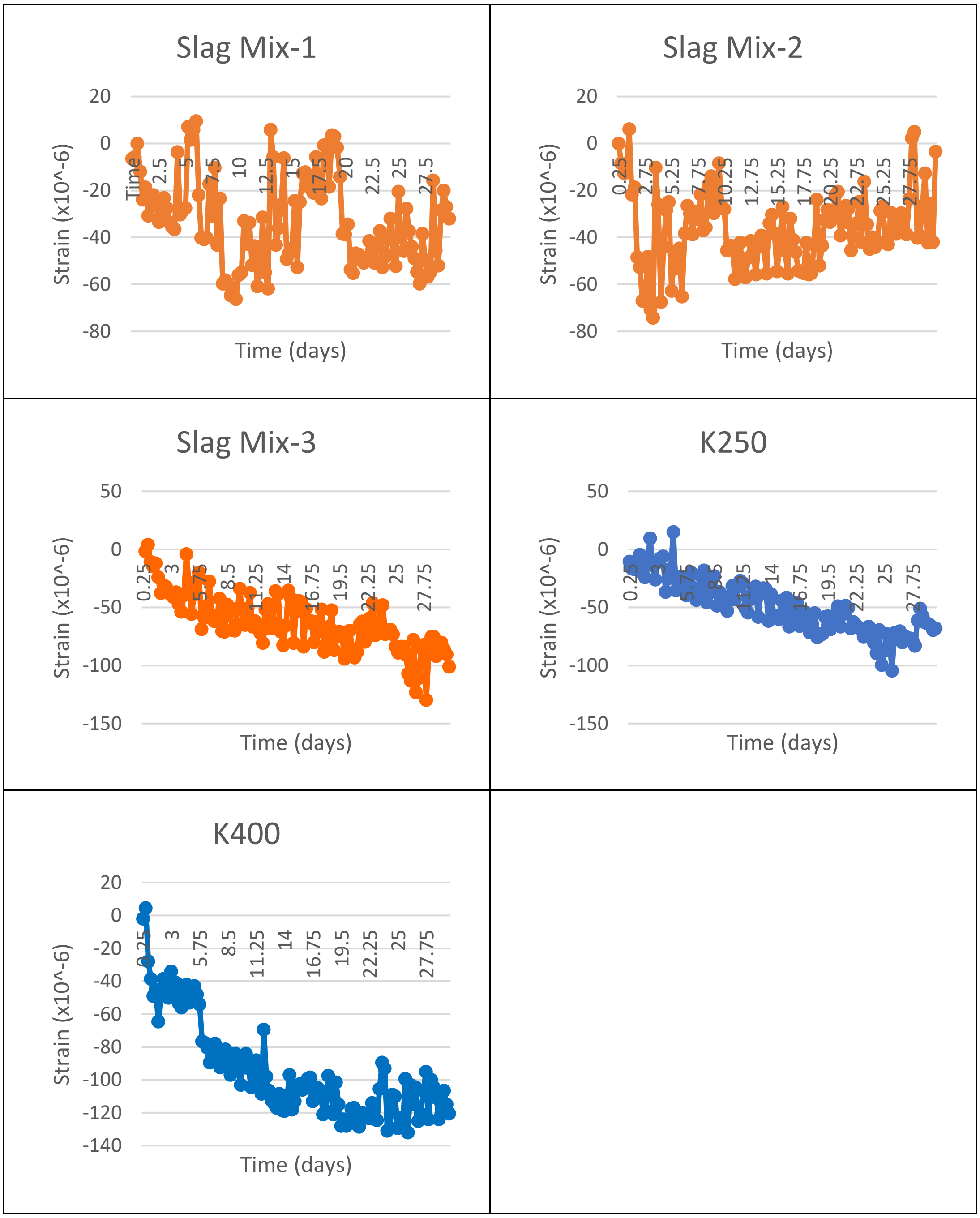

Figure 9. Strain–Time Relations from the Restrained Ring Tests

Rapid Freezing and Thawing Resistance Test

Conventional and geopolymer concrete prisms of size (75x75x280) mm (2.95x2.95x11 in) were subjected to 300 freeze-thaw cycles at 30-cycle intervals to determine the resistance of the concrete to freezing and thawing through mass loss, length change and ultrasonic readings. The testing was conducted in accordance with ASTM C666M-15 procedure B.

Initial readings of sample size, mass, and ultrasonic were taken at rest and after every 30 cycles, the results are shown in Figure 10. The duration of each freeze-thaw cycle was 4 hours, and each cycle begins in the thawing phase (2°C) (35.6ºF). As it progresses, the temperature drops to -18°C (-0.4ºF), and the freezing phase begins, the temperature then rises to 4°C, and the thawing phase occurs till the cycle ends.

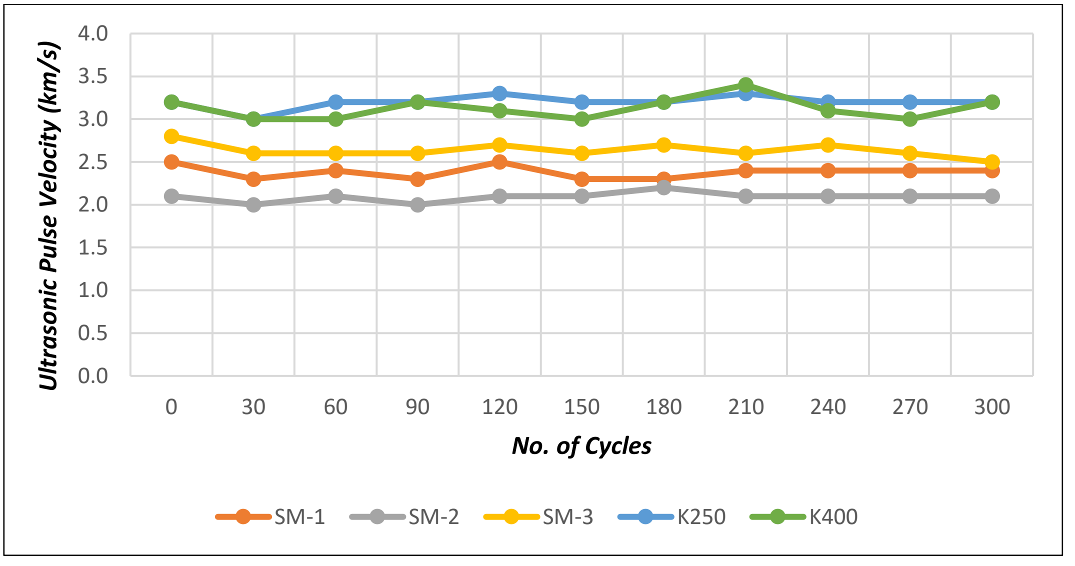

Figure 10. Ultrasonic Pulse Velocity Per Cycle

RESULTS

The compressive strengths of cubes at 28 days for Slag Mix-1, Slag Mix-2 and Slag Mix-3 are (25.65), (24.53) and (23.78) MPa respectively (3.72, 3.56 and 3.45 ksi), while K400 and K250 are (41.47) and (24.56) MPa respectively (6.01 and 3.56 ksi). The geopolymer concrete samples have, in general, comparable compressive strength to the conventional concrete. It can also be seen that the addition of water to geopolymer concrete results in a decrease in strength, as can be seen for Slag Mix-3.

The splitting tensile strengths at 28 days for Slag Mix-1, Slag Mix-2 and Slag Mix-3 are (1.70), (1.68) and (2.22) MPa respectively (0.25, 0.24 and 0.32 ksi), while K400 and K250 are (2.60) and (1.52) MPa respectively (0.38 and 0.22 ksi). Overall, geopolymer concrete samples had higher splitting tensile strengths than K250, specifically Slag Mix-3, where the tensile strength is 46% higher.

With regards to heat resistance, a repetitive pattern can be seen with all Mixes where the residual compressive strengths increase when exposed to temperatures as high as 500°C (932ºF) before they begin to decrease as the samples deteriorate, as can be expected. At 100°C (212ºF) the increase in compressive strengths of Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 are (6.5) %, (3.4) %, (15.8) %, (39.3) % and (20.8) % respectively. At 300°C (572ºF) the increase in compressive strengths of Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 are (26.3) %, (13.7) %, (23.5) %, (60.4) % and (37.7) % respectively. At 500°C (932ºF) the increase in compressive strengths of Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 are (11.2) %, (-9.2) %, (3.15) %, (36.4) % and (37.7) % respectively. At 700°C

(1292ºF) the decrease in compressive strengths of Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 are (81.5) %, (78.6) %, (50.4) %, (36.6) % and (23.4) % respectively. The geopolymer concrete Mixes exhibited a slow increase and better tolerance to heat in comparison to the control Mixes up to 500°C (932ºF), at temperatures higher than that, the deterioration was much higher. Out of the geopolymer Mixes, Slag Mix-3 appeared to have better tolerance to heat.

The highest water penetration was with K250 at 141.8 mm (5.58 in), while the least penetration was found in K400 at 22.8 mm (0.90 in). With regards to the geopolymer concrete Mixes, Slag Mix-1 had the least water penetration of 26.82 mm (1.06 in), while Slag Mix-2 and Slag Mix-3 were closer in values at 57.36 mm (1.46 in) and 61.80 mm (2.67 in) respectively. Similarly, Slag Mix-1 had the lowest percentage of voids amongst the geopolymer concrete samples. Overall, the control concrete Mixes have a lower percentage of voids. The water penetration for geopolymer in Slag Mix-1, therefore, is 81% lower than that for conventional K250 Mix.

The residual compressive strengths of the samples after immersion in 5% sulfuric acid solution at 7 days, Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 had a decrease in compressive strength of (8.9) %, (28.6) %, (10.7) %, (46.0) % and (27.6) % respectively. At 28 days, Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 had a decrease in compressive strength of (10.8) %, (28.9) %, (10.7) %, (50.7) % and (43.7) % respectively. At 56 days, Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 had a decrease in compressive strength of (14.8) %, (17.1) %, (17.3) %, (18.43) % and (12.8) % respectively. The highest percentage decrease is seen in K250, while the lowest is seen in Slag Mix-1. Overall, the geopolymer concrete Mixes showed a lower percentage of compressive strength loss in comparison to the control concrete Mixes.

The residual compressive strengths of the samples after immersion in seawater at 7 days, for Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 had a decrease in compressive strength of (1.7) %, (7.4) %, (5.9) %, (13.5) % and (9.1) % respectively. At 28 days, Slag Mix-1, Slag Mix-2, Slag Mix-3 and K250 had a decrease in compressive strength of (1.2) %, (4.9) %, (0.9) % and (8.5) %, respectively while K400 had an increase of (1.8) %. At 56 days, Slag Mix-1, Slag Mix-2, Slag Mix-3, K250 and K400 had an increase in compressive strength of (2.0) %, (3.0) %, (18.5) %, (1.5) % and (6.1) % respectively. K250 samples had the highest percentage of loss after immersion for 7 and 28 days. At 7 days Slag Mix-1 had the lowest percentage drop, while at 28 days Slag Mix-3 had the lowest drop. After 56 days of immersion, all samples showed an increase in compressive strength relative to initial compressive strength at 56 days.

With the restrained ring test, initial observations show that Slag Mix-1 and Slag Mix-2 do not exhibit the same trend as the control Mixes, after cracking the strain readings continue to fluctuate significantly where huge jumps can be seen, on the other hand, Slag Mix-3 shows a similar trend to K250 and K400 where a distinct jump can be seen at time of cracking. For geopolymer concrete Mixes, the time of cracking for Slag Mix-1 was observed at time 4.0 days, for Slag Mix-2 at time 3.5 days, and for Slag Mix-3 at time 4.25 days. As for the control Mixes, the time of cracking for K250 was observed at 4.25 days and for K400 at 11.75 days. K400 showed the most delayed cracking, while Slag Mix-2 had the earliest cracking time. The time of cracking for K250 and Slag Mix-3 is almost the same.

The effects of freezing and thawing can be deduced through ultrasonic pulse velocity readings of the prisms. K250 and K400 had the highest velocity of 3.2 km/s (1.99 mile/s), while Slag Mix-2 had the lowest velocity of 2.1 km/s (1.3 mile/s). Slag Mix-1 and Slag Mix-3 had approximately the same velocity of 2.4 and 2.5 km/s (1.49 and 1.55 mile/s). These results indicate that the geopolymer concrete Mixes are less than normal conventional Mixes. It can also be seen that for all Mixes, the pulse velocities were not changed with the freeze-thaw cycles, indicating that the freeze-thaw has minimal effect on the quality of conventional or geopolymer concrete.

DISCUSSION

This study compared geopolymer concrete with conventional cement in hot climates like Kuwait, the results indicated that although geopolymer concrete exhibited excellent performance in certain aspects, including strong early strength, acid resistance, and minimal water permeation, however, some limitations may exist at high temperatures and freeze-thaw cycles.

Mechanical Performance

Geopolymer concrete has comparable compressive strength to conventional concrete, with early strength development being a primary advantage. After 28 days, Slag Mix-1 reached a compressive strength of 25.65 MPa, while K250 reached 24.56 MPa. However, geopolymer concrete requires further optimization due to excess water in Mixes, which may lower compressive strength (Shobeiri et al., 2022). The tensile strength of geopolymer concrete is generally higher than conventional concrete, with Slag Mix-3 achieving a high value of 2.22 MPa, likely due to the optimum alkaline activator ratio and specific Mix composition.

Thermal Performance

Geopolymer and conventional concrete initially increase compressive strength up to 500°C when thermally exposed but show significant deterioration beyond this. Slag Mix-1 showed a 6.5% strength gain at 100°C, 26.3% at 300°C, and 81.5% loss at 700°C. Conventional concrete K400 showed better strength retention up to high temperatures, suggesting GPC may not be effective for high-temperature applications.

Durability Analysis

Geopolymer concrete outperforms conventional concrete in resistance to sulfuric acid and seawater (Wong, 2022). Slag Mix-1 shows the lowest decrease in compressive strength after 7 days in a 5% sulfuric acid solution, making it suitable for chemical corrosion-prone environments like industrial facilities or sewage systems. Geopolymer concrete also shows an 18.5% increase in compressive strength after 56 days of immersion.

Water Penetration and Absorption

Geopolymer concrete offers superior water resistance to conventional concrete, with Slag Mix-1 providing the least depth of 26.82 mm. This enhances the durability and longevity of concrete structures (Verma et al., 2022). Geopolymer concrete also has the lowest percentage of voids among geopolymer Mixes, making it more durable and resistant to water. Despite its lower percentage of voids, geopolymer concrete remains durable (Zhang, 2024).

Shrinkage and Cracking Behaviour

The restrained ring test results show that geopolymer concrete does not delay cracking compared to conventional concretes, with Slag Mix-2 cracking after 3.5 days and K400 delayed after 11.75 days. Therefore, geopolymer concrete's shrinkage behaviour and crack resistance under restraint may require optimization for structural applications (Huang et al., 2024).

Freezing and Thawing Resistance

Traditional concrete demonstrated higher pulse velocities compared to geopolymer concrete and showed higher resistance to the freeze-thaw cycle as well (Wei et al., 2024). For example, K250 and K400 concretes had a velocity of 3.2 km/s, while the minimum velocity was obtained for Slag Mix-2, with 2.1 km/s. That is so important when it comes to regions with cold weather.

Sustainability and Environmental Impact

Geopolymers, a type of concrete, are environmentally friendly due to their use of industrial waste materials like GGBS and lower carbon dioxide emissions from cement production (Islam et al., 2025). They also have lower water usage, making them a desirable option in countries with water scarcity. Geopolymer concrete is also more durable in acidic and marine environments, making it an eco-friendly alternative to conventional concrete (Kanagaraj et al., 2024).

Geopolymer Concrete is more than just a material – it's a more economic approach in construction. For instance, in India, by replacing cement with fly ash and Slag-based concrete, the country reduced emissions, cut on costs, and promoted green infrastructure (AbdulAleem and Arumairaj, 2012).

Geopolymer concrete can replace conventional concrete in hot climates that are damaged by chemical corrosion and water penetration. The advanced acid and seawater resistance with reduced water dependence of this material makes it ideal for industrial and marine applications. Nevertheless, further research is needed on high-temperature and freeze-thaw environments so that Mix designs can be further optimized for excellent long-term performance of geopolymer concrete (Al-Bakri et al., 2013 and Sambucci et al., 2021).

CONCLUSIONS

Geopolymer concrete had a slightly higher percentage of voids than conventional concrete, with lower molarity and alkaline activator ratios. It also had better resistance to sulfuric acid and seawater, with lower compressive strength deterioration compared to conventional concrete. Both geopolymer and conventional concrete gained compressive strength with prolonged immersion in seawater after 28 days. The complete replacement of ordinary Portland cement with Slag did not result in a delay in cracking. Geopolymer and conventional concrete exhibited similar patterns of behaviour when exposed to rapid freezing and thawing, but conventional concrete had better tolerance to freezing and thawing than geopolymer concrete. In conclusion, geopolymer concrete has comparable mechanical and physical properties but shows better resistance to acids. It is more sustainable and environmentally friendly due to its recycling of Slag, which is a recyclable industrial waste material. Geopolymer concrete's sustainability is also increased due to less dependency on water in Mixing and curing, increased durability against acids and water penetration, and reduced dependency on water in Mixing and curing. Therefore, the use of geopolymer concrete is recommended.

LIMITATION AND STRENGTHS

This paper introduced geopolymer concrete as an environmentally friendly cement concrete class, focusing on sustainability due to carbon emissions and energy-intensive cement production. Geopolymer concretes have been tested for resistance to freezing, thawing, sulfuric acid, seawater, heat, water penetration, and absorption. They have high early strength development, making them suitable for construction projects with rapid turnarounds and load-bearing capacity. Geopolymer concrete also has lower water dependence, making it attractive in hot but arid countries like Kuwait. It performs better in acidic environments than Portland cement concrete, making it suitable for industrial applications in corrosive environments. The study emphasizes local materials, reducing transportation costs and promoting sustainable construction. However, the study has its own limitations, including not accurately representing natural environmental conditions, providing limited mechanical properties without considering long-term creep, shrinkage, and carbonation resistance, and being limited to specific alkaline activator ratio ranges. Additionally, the study does not consider the economic feasibility of massive construction with geopolymer concrete and lacks long-term performance data in aggressive environments. Such aspects could be the subject for further studies.

FUTURE IMPLICATIONS

Future research should focus on field trials and long-term performance monitoring of geopolymer concrete structures to validate laboratory results. Optimization for various applications will require expanding Mix designs to include different molarities and alkaline activator ratios. Economic and lifecycle cost analysis will determine the cost-benefit of geopolymer concrete compared to conventional concrete. Further research should explore its potential to reduce environmental impact and performance under extreme conditions.

ACKNOWLEDGEMENTS

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THE DELPHI TECHNIQUE ANALYSIS ON EVALUATION OF CRITICAL SUCCESS FACTOR IN FACILITIES MANAGEMENT FOR ICONIC BUILDING IN MALAYSIA

Alias Abdul Rashid[1], Muhammad Azwan Sulaiman[1*], Abdul Jalil Omar[2] and Anis Syazwani Sukereman[1]
[1]*Faculty of Built Environment, UiTM Shah Alam, Selangor, Malaysia*
[2]*Faculty of Technology Management & Business, UTHM, Johor, Malaysia*

**Corresponding Author: azwan@uitm.edu.my*

Abstract
Iconic building defined as a building high in figure of form and be obvious from the city and offer a new briefed image. Iconic Buildings architectural works that embody exceptional aesthetic, cultural, or technological values, contributing to the identity and image of their context. An iconic building is a structure that is instantly recognizable and symbolically represents a city, nation, or organization because of its unique design, cultural significance, or historical importance. Iconic building plays a crucial role in promoting economic growth and urban development. However, over time the time, features of iconic buildings have changed. During each time period, the architectures of the building have special aspects. There are four special characteristics should be present in any iconic building including unique design, large scale, high level and specific message signified by the building. However, all the features can affect maintenance of the iconic building. The issues and challenges of iconic buildings including to Iconic designs often use unique forms, high-end materials, and complex engineering systems, leading to cost overruns. Maintenance requires specialized skills and materials, making upkeep expensive. The maintenance for iconic building needs has a critical success factor for better facilities management. Therefore, the objective of this study is to evaluate of critical success factors in order to give a positive impact of facilities management on iconic building in Malaysia. Delphi Method was selected as a reliable qualitative method based on the local context in developing critical success factor of iconic building through the viewpoints of local expert panels. It is believed that the viewpoints can deliver guidance to the researcher in recognizing the quality of each iconic building factors in local environment. There are three rounds Delphi Method used through expert panels in various field including facility manager, architecture, contractor, consultant and association. The finding of this study is determining the critical success factor in facilities management for iconic building in Malaysia. The study identified a set of five critical success factors (CSFs) that significantly influence the effective management and maintenance of iconic buildings in Malaysia. These CSFs emerged from empirical analysis and were validated through expert input. The key results are as FM trend (technology), Life-Cycle Cost Analysis (LCCA), upscaling staffing, logistic/location, parking, maintenance, concerned with users and their interactions, physical attributes, specific message signified by the building, unique design, large scale, city image, community, sustainability and tourism. By clearly identifying and evaluating these factors, the study provides practical insights that facilities managers and industry stakeholders can apply to enhance the performance, sustainability, and long-term value of iconic buildings in Malaysia.

Keywords: *Delphi Method; Iconic Building in Malaysia; Criteria; Expert Panel; Critical Success Factor*

INTRODUCTION

Iconic buildings are not merely functional structures; they embody cultural narratives, shape urban identity, and symbolize collective aspirations. In contemporary urban discourse, iconic architecture is often regarded as an “identity artefact” that represents both present realities and future ambitions of a city (Zamparini, Gualtieri, & Lurati, 2023). Beyond aesthetics, such buildings act as powerful tools of place branding and socio-political representation, strengthening the symbolic connection between built form and community identity (Cao, Mustafa, & Isa, 2024). For example, iconic designs such as the Petronas Twin Towers in Malaysia or the Burj Khalifa in Dubai do more than define skylines—they reinforce narratives of national pride, global competitiveness, and modernity.

Recent studies emphasize that iconic architecture also serves as a medium of cultural continuity, where traditional elements are reinterpreted in contemporary forms to maintain relevance while embracing modernity (Hilmee & Kosman, 2023). This duality—preserving heritage while projecting innovation—explains why iconic buildings remain central in architectural debates, urban planning strategies, and national identity formation in the 21st century. The iconic building may affect its environment by giving benefit to the place which is already dominant. Creating a building with the natural characteristics of an iconic building will make it glow and emerge it to higher status. (Anthony, 2008). Many iconic or landmark buildings exceed their original budgets, sometimes by large margins. Unforeseen engineering challenges, inflated material costs, scope changes, and regulatory hurdles are common culprits. For example, new high-rise projects in India have shown frequent cost overruns tied to poor planning, fluctuating material prices, and lack of experience. Iconic / heritage buildings often suffer from neglected maintenance, failing lighting / systems, structural deterioration, which degrade their symbolic value and physical integrity. For example, Mumbai's Rajabai Clock Tower lighting and clock mechanism have failed multiple times due to poor upkeep (The Times India, 2025).

Large or iconic building projects frequently go over budget or are delayed. Causes include change orders, planning and design modifications, under-estimated initial costs, inflation, supply chain issues. For instance, a recent study on Spanish public works found that modifications under legal frameworks contribute significantly to cost overruns (Guillermo, 2023). Architects/designers of iconic buildings often push for dramatic or novel aesthetics, which can conflict with functional needs (energy efficiency, maintainability, weather resilience). Also, issues of "green maintainability" arise: for example, building-integrated photovoltaics (BIPV) façades having high maintenance costs if maintainability wasn't considered early in design. (Conejos et al., 2023).

Maintenance issues of iconic buildings are often more complex than those of conventional structures because of their architectural uniqueness, cultural significance, and high public visibility. Maintenance cost is usually 2–4% of building replacement cost per year (Jabatan Kerja Raya [JKR] guidelines, Malaysian Asset Management standards). Commercial high-rise buildings including RM 3.00 – 6.00 per square foot annually (source: property management industry practice, recent facility management research in Malaysia, 2022–2023). The serious problem prevalent in Malaysia is the lack of funding for the maintenance and improvement of basic services at the state and local government levels. This may be due to low wages, lack of workers and equipment to carry out the maintenance work and lack of routine inspections.

As a result, there are serious and consistent problems in daily basic services that are not addressed thus posing a security risk to the people. Some of these issues need to be resolved as soon as possible because they threaten the safety and health of the public. The iconic building involves many people who come to visit. (Sinar Harian, 2023). The provision of infrastructure is carried out with good design and architectural considerations but often ignores the aspects of cost engineering and cost considerations when occupying assets developed by the government. This causes the government or asset owners to bear high maintenance, operation and energy costs every year to ensure that all service activities are provided at the best rate for the well-being of the people.

For example, the Telecommunications Landmark – KL Tower (2025) spent tens of millions RM for Electrical & drainage system upgrades, Facade and safety repairs (glass dome, exposed railings), Cleaning & repainting works and Replacement of communication systems, CCTV, and fixtures. The Figure 1 shows the data of property market in Q1, 2025. Thus, commercial buildings state 10.89 billion which is second place after residential sector with 24.51billion. This data shows the iconic buildings (commercial) is the vital property in Malaysia. Thus, the maintenance of iconic building in Malaysia needs improvement through the critical success factor. The purpose of this paper is to come out with details Critical Success Factor (CSF) of iconic building using Delphi Method from Delphi Round 1 until Delphi Round 3 of iconic building maintenance.

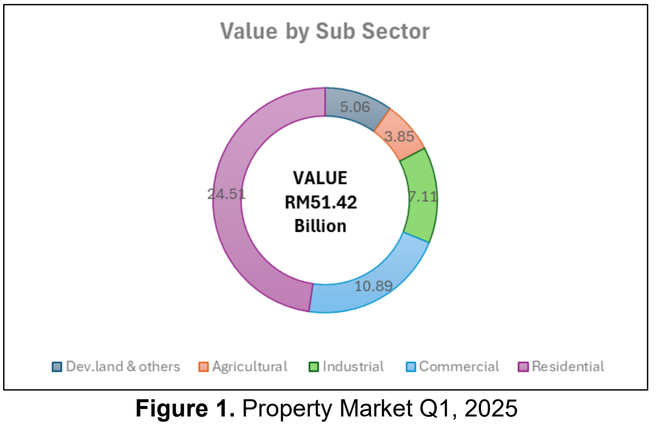

Figure 1. Property Market Q1, 2025

DEFINITION OF ICONIC BUILDING

The word iconic comes from the Greek language, namely 'icon' which means image, figure, representation which is then added to the suffix – ic to become an adjective 'iconic' which means an iconic characteristic or feature that depicts or represents an object. An iconic building is a built structure that — beyond merely serving its functional use — attains symbolic, cultural, or architectural significance: it becomes a visually distinctive, memorable landmark that helps define or represent its city, region, or era. Key aspects often associated with iconic buildings include uniqueness in design and form; high visibility and recognizability in the urban context; an aesthetic or symbolic value; and a capacity to communicate identity, history or meaning to people (Gaber et al., 2022). Iconic architecture is called a symbol of a city or country, the location of a building. Although it is a symbol, it is not the same as a monument, because iconic buildings have historical value and are linked to the past history, culture of an area or community. Iconic architecture is generally defined by society differently, which means that it is different from the surrounding buildings, in terms of design, size, visual appearance, urbanization fabric, architectural style, and so on. It has an impact on the community and the area where the building was built. This perspective and its lasting impact are what make it iconic. Iconic is not only famous because it is famous today.

However, there is no definition that shows that a building is an icon in its own right. It depends on the characteristics of the architecture itself and is influenced by the surrounding context to determine it as an iconic building in a certain area. The architecture of a building that is called iconic must have an 'attractive' shape and be in a strategic place and become the main point or 'focal point' of a place. It emphasizes that iconicity is not just about size or height, but about the combination of form, context, symbolism, and recognition — a building becomes iconic because people perceive it as such (Zamparini et al., 2023). Based on a quote from Charles Jencks in the book "iconic buildings"; "to become iconic a building must provide a new and condensed image, be high in figural shape or gestalt, and stand out from the city.

On the other hand, to become powerful it must be reminiscent in some ways of unlikely but important metaphors and be a symbol fit to be worshipped, a hard task in a secular society." The quote states that, to become an iconic building, a building must give a new and unique image, have a taller and larger size in terms of design size and a great impression compared to other buildings in its surroundings. The building must be able to become iconic, become a sign of grandeur and have a strong influence and identity and stand out in an area to influence people so that it will always be remembered. In addition, if the building is built to be an iconic building, the building must give a strong meaning and have a reason why it was built in that design an iconic building should be able to tell implicitly to the people who see it.

CRITICAL SUCCESS FACTOR (CSF) OF ICONIC BUILDING

Iconic Buildings differ from monuments as they symbolize the place were built in city scale or country scale; buildings that have historic or cultural values of their own or even connected to a significant place or person. Generally, they are different, regarding the design, size, visual appeal, urban fabric, or architectural style etc. (Zamparini et al., 2023). The greatest opportunities for creating iconic buildings can be shown in different impacts beginning by the building itself ending by how it affects the surroundings and the community.

Iconic buildings are mainly built to be visually attractive before being used with their proposed function. This is the main motivation point for the building designer to increase its symbolic image. Over time, features of iconic buildings have been changed. During each time period, the architecture of the building has special aspects. Therefore, the philosophical definition of an icon must communicate the sign to the object that it signifies. Iconic buildings have an impact on community and the place in which they are created with their durable impression on all visitors of the place. Yildiz (2018) identifies a set of special characteristics elements should be present in any iconic building. This list contains, but not limited to:

i) Unique Design

In architecture, unique design describes a structure whose form, aesthetics, and spatial composition are intentionally crafted to be visually distinctive, symbolically meaningful, and unlike typical building typologies. It often contributes to the building's identity, iconicity, and landmark status (Zheng, 2023).

ii) Large Scale

The iconic building may affect its environment by giving benefit to the place which is already dominant. The famous iconic buildings have a significant reputation mostly driven by the media which attracts the attention to the city and makes it well-known. This indicates that iconic building constitutes a challenge to the improvement of the city branding.

iii) High Level

The building as whole is amazingly modest. The cylinder truncates and inclines circular form is selected carefully in response to the disadvantage of the ground topography. It is best solution that offers the less catch to the climatic conditions. This option creates protection from sandstorms (coming from the south).

iv) Specific Message Signified by The Building

Different approaches for understanding the building will be pursued. Architecture appears at many levels, and a building should be viewed and discussed at these different levels.

v) City Image

Giving image to the city is a special kind of design problem at the urban scale and city planning, in order to make the city's image more vivid and memorable. Monumental buildings, public sites or other special characters are the ones which form the image of a city. For better or worse, personage visual reliance is used to represent architecture and the environment around it.

vi) Quality of Life

Another recent study, Sustainable High-Rise Buildings: Toward Resilient Built Environment (2022), examines sustainable high-rise buildings and highlights that when tall buildings (often iconic or landmark in nature) are designed with sustainability, resilience, and human-centred urban planning in mind, they contribute positively to long-term urban livability. Factors such as energy efficiency, reduced environmental impact, and resilient infrastructure influence overall urban quality of life. (Kodmany, 2022).

NOTION OF "ICONICITY" IN ARCHITECTURE AND THEIR MAINTENANCE

The philosophical definition of an icon must relate the sign to the object that it represents. This innate relationship presents the simple notion that icons habitually have some factors in common with the things they represent. If we drift to an architectural context, we realize that an iconic building stands out from the city with a conspicuous form and style, and sometimes in high contrast with its surrounding. A good example is the Gherkin tower (Figure2) which is represents a radical use of technology, unique style and gives a glaring positive shock to its surrounding. Building maintenance units – BMUs – provide access for cleaning and maintenance and usually run on tracks fitted on a flat roof, where they can be stored out of sight. The uniquely shaped 'Gherkin', designed by Foster + Partners, has no flat roof. So, an equally unique access solution was required; and it had to be one that would not compromise the appearance of the building. This posed a challenge that many considered too difficult.

Figure 2. Gherkin Tower

The other case is the National Stadium of Beijing in China. The unique structure of the Olympic building has been shaped from the steel skeleton in the formation of 'birds nest'. The main concept is to construct the new ecological building which has uniqueness in its style. The innovative design through a dominant structure and ecological idea which has a high contrast with environment has been created the Olympic building as an icon. (Figure3). The bird's nest can withstand an earthquake of up to magnitude 8 on the Richter Scale. At the peak of construction there were over 9,000 workers on the project. The project budget began at $500M before it was drastically reduced to just under $300M. Beijing is located near one of the most seismically active locations on earth. For this reason, the design required an HVAC infrastructure based on a pipework system that was flexible and simple to install at the required angles. The Victaulic grooved joint system consists of a housing coupling, a bolt, a nut and a gasket. This customizable pipework solution provides flexible couplings, so the HVAC pipes could be installed at any of the different angles to meet the various deflection requirements of the Bird's Nest.

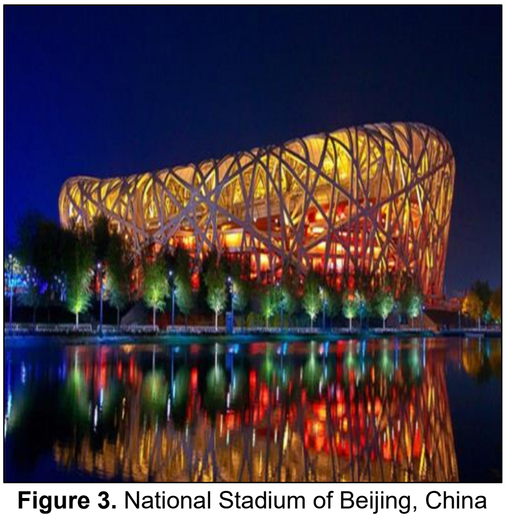

Figure 3. National Stadium of Beijing, China

Figure 4. Sydney Opera House

The Sydney Opera House is an undisputed icon that was built at the right time, has an amazing radical but very aesthetic view, has a peculiar shape, size and represents the socio-cultural aspect of Sydney. The Sydney Opera House is a World Heritage-listed masterpiece of 'human creative genius' and an icon that belongs to all Australians. It is the Country's number one tourist destination and its busiest performing arts centre, welcoming more than 10.9 million visitors a year on-site and hosting more than 1,800 performances attended by more than 1.4 million people. The Sydney Opera House (SOH), a Mainpac client of over 20 years, use BCAT (Building Condition Assessment Tool) to provide SOH field technicians with 2D plans derived from 3D modelling of the SOH to clearly identify assets and record condition assessments. BCAT asset condition assessments also capture timestamped photographs, voice recordings and any additional relevant asset condition details. Real-time integration service from BCAT to Mainpac EAM was determined as the most appropriate solution, this eliminates the need to manually rekey data and ensures asset alignment. "The Mainpac EAM integration with BCAT has facilitated a significant increase in information captured in the field. This has resulted in improved decision making, more timely rectification of maintenance issues and improved staff productivity."

There are matrix table listings for the Critical Success Factor (CSF) for iconic building.

Table 1. Matrix Table Listing of Critical Success Factor (CSF) for Iconic Building

	Gherkin Tower, London	Beijing National Stadium (Bird's Nest)	Sydney Opera House	Zamparini et al., 2023	Zheng (2023)	Yildiz (2018)
City Image	/	/	/			
Large Scale	/	/	/		/	
Unique Design	/	/	/	/		
Specific Message Signified by The Building	/	/	/	/		
Maintenance	/	/	/		/	
Logistic/location	/	/	/	/		
Physical Attributes	/	/	/		/	
Concerned With Users and Their Interactions	/	/	/	/		/
FM Trend (Technology)	/	/	/		/	/
Life-Cycle Cost Analysis (LCCA)	/	/	/	/		/
Upscaling Staffing				/	/	/
Parking	/	/	/		/	/
Community	/	/	/	/		/

Based on the matric table listing above, the researcher elected to incorporate all critical success factor (CSF) encompassed within resources. The CSF including city image, large scale unique design, specific message signified by the building, maintenance, logistic/location, physical attributes, concerned with users and their interactions, FM trend (technology), life-cycle cost analysis (LCCA), upscaling staffing, parking and community. All the CSF will be use as a part of question structure of Delphi Method Process.

METHODOLOGY: EVALUATION OF CRITICAL SUCCESS FACTOR (CSF) FOR ICONIC BUILDING IN MALAYSIA

Delphi method was used as a methodology in this research. As originally created in the late 1940s– early 1950s by a group of RAND Project AIR FORCE researchers, the Delphi method is an iterative, anonymous, structured, group-based elicitation technique. It was envisioned as a method for making more accurate social and technological forecasts and as a way to improve policy decision making. With time, the Delphi method evolved in terms of the meaning of its key characteristics, use cases, ultimate goals, and the types of individuals whose perspectives are elicited. Delphi is widely used today by a wide variety of academic disciplines, particularly the medical field, which is responsible for introducing numerous modifications of the method (Khodyakov et al., 2023).

Delphi was originally developed as an expert elicitation methodology, but it is now used for stakeholder engagement, as well. Although the Delphi method has been used by multiple disciplines for more than 70 years, we still lack methodological guidance for how to conduct rigorous Delphi studies that cuts across a wide range of use cases; that is not specific to a particular field, such as palliative care (Jünger et al., 2017); and that is not specific to a single Delphi study (Beiderbeck et al., 2021; Trevelyan and Robinson, 2015).

While useful, these paper focus on how to report a completed Delphi panel, to evaluate criteria and sub criteria of critical success factor for iconic building in Malaysia. Guidelines for designing, conducting, and assessing Delphi studies can increase methodological rigor and provide standards for evaluating methodological quality of research that can be useful for quality assurance.

The Delphi method is used in iconic building research because the concept of an iconic building is inherently subjective, complex, and multi-dimensional in nature. Unlike measurable physical attributes such as height or floor area, iconicity involves symbolic value, cultural meaning, public perception, architectural originality, and the identity of a city or nation. These elements cannot be accurately evaluated using numerical data alone and therefore require informed judgment from experts in the field. The Delphi method is particularly suitable for this purpose because it systematically gathers and refines expert opinions to address issues that lack a single, universally accepted definition.

Furthermore, the Delphi method is effective in establishing expert consensus on the defining criteria of iconic buildings. Since scholars and practitioners often differ in their interpretations of what makes a building iconic, this method allows diverse professional viewpoints from architects, urban planners, academicians, conservationists, and industry experts to be collected through several rounds of structured questionnaires. Each round allows respondents to reconsider their views based on anonymized group feedback, ultimately leading to a more stable and reliable consensus. This process strengthens the validity of the selected iconic building indicators.

In addition, the Delphi method is appropriate for iconic building research because it serves as a robust tool for developing, validating, and refining evaluation criteria. In many studies, researchers begin with a large number of possible indicators derived from literature, such as uniqueness of design, symbolic meaning, functional performance, tourism attraction, and contribution to urban image. Through iterative Delphi rounds, less relevant indicators can be systematically eliminated, while the most essential and widely agreed-upon criteria are retained. This ensures that the final framework of iconic building attributes is both comprehensive and expert-validated.

Another important justification for using the Delphi method is its ability to minimize bias and reduce the influence of dominant individuals. Since experts respond independently and anonymously, the method prevents senior professionals, institutional authorities, or outspoken individuals from dominating the decision-making process. This anonymity encourages honest and unbiased feedback, thereby enhancing the reliability and objectivity of the research findings. This is particularly critical in architectural and urban studies, where professional reputation and hierarchy often influence group discussions.

Delphi Method Process

Therefore, the main purpose of this paper is to provide criteria and sub criteria of critical success factor for iconic building in Malaysia for what to consider when designing, implementing, and reporting the results of a Delphi study that is applicable to different disciplines and use cases. The guidance is based on expert panel that have experience more than 10 years in facilities management field. The findings and analysis part will summarize all the recommendations make throughout this research. This manual is structured around the four Delphi steps: study design, data collection, data analysis, and result reporting. The Delphi method has been used by multiple disciplines for more than 70 years, we still lack methodological guidance for how to conduct rigorous Delphi studies that cuts across a wide range of use cases, that is not specific to a particular field, and that is not specific to a single Delphi study. STEP 1 Design a study STEP 3 Analyse data STEP 4 Report results STEP 2 Collect data RAND Methodological Guidance for Conducting and Critically Appraising Delphi Panels 4 is that use Delphi and to guide the rigorous design of their own studies by making quality standards explicit (Shea et al., 2017). Figure 5 shows the Delphi Method Process.

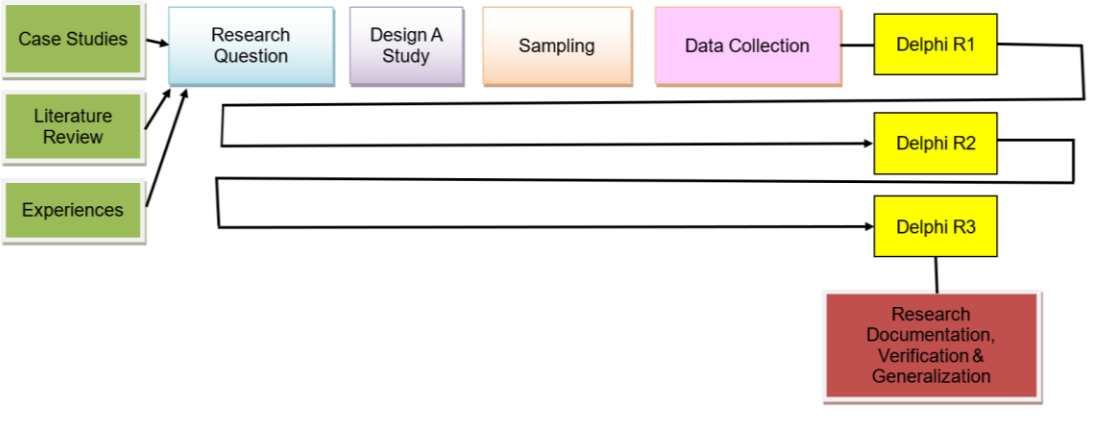

Figure 5. Delphi Method Process

The first way of using Delphi Method is to develop a research question. The research question can be developed through literature review, case studies, and experiences of respondents. The characteristic of shopping complex was done through literature review and observation method. After developing the feasible research question, a qualitative and quantitative method was used for designing the questionnaire. Semi-structured interviews were used for the qualitative method and open-ended questionnaires were used for the quantitative method.

For the numbers of participants, there are 10 respondents chosen from developers as expert panels. Based on Etikan & Bala (2020), snowball sampling is a non-probability sampling strategy in which initial participants identify additional individuals who meet the study's criteria. This method is especially useful for studying hidden, hard-to-reach, or specialised social groups, where formal lists or sampling frames do not exist. The sample grows progressively, similar to a snowball rolling and expanding. The number of rounds again is variable and dependent upon the purpose of the research. There are 3 rounds to conduct the Delphi Method in this research.

Specifying Panel

The characteristic of critical success factor on iconic building management in Malaysia was validated by 7 experts in the facilities management field. They are senior management personnel/officers from the government agencies and practitioners. All selected respondents have working experience of more than 10 years onwards. This method includes three rounds of allocation of the questionnaire to the expert panel in the field of facility manager, architecture, contractor, consultant and association as Table 2.

Table 2. Numbers of Expert Selected

No	Expert Panel	No. of Expert
1.	Facility manager	2
2.	Architect	1
3.	Contractor	1
4.	Consultant	2
5.	Association	1
	Total	7

Linear Scale is used in determining the importance of characteristic in success factor on iconic building management. Jebb, A.T., et al. (2021). Table 2 shows the importance of numerical linear scale. From the literate review analyse, the characteristics in success factor on iconic building management is shown in Table 3.

Table 3. Importance of Numerical Linear Scale

Numerical Linear Scale	Level of Assessment
$1 < \overline{X} \leq 1.8$	Very not Important
$1.8 < \overline{X} \leq 2.6$	Not Important
$2.6 < \overline{X} \leq 3.4$	Moderate
$3.4 < \overline{X} \leq 4.2$	Important
$\overline{X} \geq 4.2$	Very Important

Source: Jebb, A. T., et al. (2021)

RESULTS AND DISCUSSION

Delphi Round 1

The selection of characteristic of critical success factor on iconic building management is analysed by the matrix method which is based on the literature review and observation method. The greatest number of frequencies of critical success factor on iconic building management characteristic will be used as the final selection. The respondents will choose and give any opinion on the final selection of characteristic. They also can add on and suggest any characteristic that suit for building management. The questionnaires are distributed to the Delphi participants, who complete and return them to the researcher. According to literature review (benchmarking process), there are fifteen (15) criteria. The rest criteria are FM trend (technology), Life-Cycle Cost Analysis (LCCA), Upscaling staffing, logistic/location, parking, maintenance, concerned with users and their interactions, physical attributes, specific message signified by the building, unique design, large scale, city image, community, sustainability and tourism. Based on the result of 1st round Delphi, the criteria for community include as a critical success factor for iconic building. The expert panel suggested community as a criteria. This criteria is agreed by others expert panel. The result shows 100% for the community criteria are then analysed according to the research paradigm. The mean score was used to analyse the data of the questionnaire in the Delphi Method.

Table 4. Delphi Method Round 1

Critical Success Factor	1st Delphi Round
FM trend (technology)	0.9
Life-Cycle Cost Analysis (LCCA)	0.9
Upscaling Staffing	0.8
Logistic/location	0.8
Parking	0.9
Maintenance	0.8
Concerned with users and their Interactions	0.9
Physical attributes	0.9
Specific message signified by the building	0.8
Unique design	0.9
Large scale	0.8
City image	0.9
Community	1.0

Delphi Round 2

For the second round, each Delphi participant receives a second questionnaire and is asked to review the items summarized by the investigators based on the information provided in the first round. Delphi panellist's need to rate items to establish preliminary priorities among items. In some cases, Delphi panellists are asked to state the rationale concerning rating priorities among items. The result of 2nd round Delphi, the criteria of sustainability and tourism was suggested by expert panel as one of critical success factor for iconic building in Malaysia. The results also show 100% for the sustainability and tourism criteria. The results show all the criteria was accepted by expert because the overall rating was over than 60%.

Table 5. Delphi Method Round 2

Critical Success Factor	2^{nd} Delphi Round
FM trend (technology)	0.9
Life-Cycle Cost Analysis (LCCA)	0.9
Upscaling Staffing	0.8
Logistic/location	0.8
Parking	0.9
Maintenance	0.8
Concerned with users and their Interactions	0.9
Physical attributes	0.9
Specific message signified by the building	0.8
Unique design	0.9
Large scale	0.8
City image	0.8
Community	1.0
Sustainability	**1.0**

Delphi Round 3

The process stops if the research question is answered: for example, when the consensus is reached, theoretical saturation is achieved, or sufficient information has been exchanged. This round allows Delphi panellists to make further clarifications of both the information and their judgments of the relative importance of the items. The last result of 3rd round Delphi method, all the expert panels was agreed with all the criteria that suggested at 1st and 2nd round of Delphi Method.

Table 6. Delphi Method Round 3

Critical Success Factor	3^{rd} Delphi Round
FM trend (technology)	0.9
Life-Cycle Cost Analysis (LCCA)	0.9
Upscaling Staffing	0.8
Logistic/location	0.8
Parking	0.9
Maintenance	0.8
Concerned with users and their Interactions	0.9
Physical attributes	0.9
Specific message signified by the building	0.8
Unique design	0.9
Large scale	0.8
City image	0.8
Community	1.0
Sustainability	1.0
Tourism	**1.0**

CONCLUSION

Finally, based on result from Delphi process start from 1^{st} round until 3^{rd} round analysis, it can be concluded that the result shows there are fifteen (15) suitable categories of iconic building can be adapted in local context to develop the critical success factor facilities management for iconic building in Malaysia. The indicator main CSF including FM trend (technology), Life-Cycle Cost Analysis (LCCA), upscaling staffing, logistic/location, parking, maintenance, concerned with users and their interactions, physical attributes, specific message signified by the building, unique design, large scale, city image, community, sustainability and tourism. This CSF will be used as an indicator to develop a critical success factor for iconic building framework in Malaysia using the questionnaire survey on facility manager at selected case studies. It can be betterment benchmarking for Facilities Management Industry in general and expected to provide insights to the stakeholders in improving their skills and knowledge decision how to manage the iconic building in Malaysia.

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GUIDE TO AUTHORS

Aims and Scope:

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

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CODIFICATION AND APPLICATION OF SEMI-LOOF ELEMENTS FOR COMPLEX STRUCTURES

(FULL NAME) Ahmad Abd Rahman[1,2], Maria Diyana Musa[2] and Sumiana Yusoff[2]
[1]Department of Quantity Surveying, Faculty of Architecture, Planning and Surveying, Universiti Teknologi MARA, Sarawak, Malaysia
[2]Institute of Ocean and Earth Sciences (IOES), University of Malaya, Malaysia

Abstract (Arial Bold, 9pt)
Damage assessment …… ……(Arial, 9pt. Left and right indent 0.64 cm, it should be single paragraph of about 100 – 250 words.)

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

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Figures: Figures should be in box with line width 0.5pt. All illustrations and photographs must be numbered consecutively as it appears in the text and accompanied with appropriate captions below them.

Figures caption: Arial Bold + Arial, 9pt. + Capitalize Each Word, should be written below the figures.

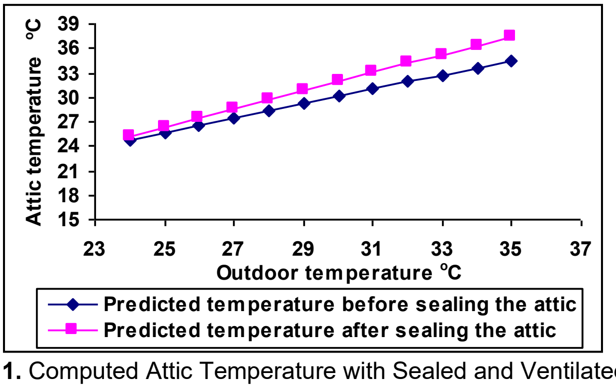

Figure 1. Computed Attic Temperature with Sealed and Ventilated Attic

Tables: Arial, 8pt. Table should be incorporated in the text.

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

Table Line: 0.5pt.

Table 1. Recommended/Acceptable Physical Water Quality Criteria

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

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

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

Citation:

Passage Type	First Reference in Text	Next Reference in Text	Bracket Format, First Reference in Text	Bracket Format, Next Reference Marker in Text
One author	Walker (2007)	(Walker, 2007)	(Walker, 2007)	(Walker, 2007)
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Three authors	Bradley, Ramirez, and Soo (1999)	Bradley et al. (1999)	(Bradley, Ramirez, & Soo, 1999)	(Bradley et al., 1999)
Four authors	Bradley, Ramirez, Soo, and Walsh (2006)	Bradley et al. (2006)	(Bradley, Ramirez, Soo, & Walsh, 2006)	(Bradley et al., 2006)
Five authors	Walker, Allen, Bradley, Ramirez, and Soo (2008)	Walker et al. (2008)	(Walker, Allen, Bradley, Ramirez, & Soo, 2008)	(Walker et al., 2008)
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