

Bridging The Gap in Digital Twin Frameworks: A Comparative Analysis on Building Energy Consumption in The Malaysian Context

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Abstract

Buildings contribute to a substantial portion of global energy consumption, necessitating innovative technologies to enhance energy efficiency. Building Information Modelling (BIM) and Digital Twin (DT) technologies offer promising solutions, with BIM supporting energy-efficient designs and DT enabling real-time energy optimisation. However, DT adoption in Malaysia is limited, particularly in building energy management, due to the absence of tailored frameworks addressing local challenges such as infrastructure readiness, technical expertise, and policy support. Hence, this paper systematically reviews and compares ten existing DT frameworks, focusing on their applicability to building energy management and construction practices. Frameworks were selected based on their emphasis on energy optimisation, integration DT and its relevance to building operations. Content analysis was employed using Atlas.ti to categorise recurring themes, gaps, and limitations across these frameworks. The analysis reveals that existing frameworks often assume a high level of technological maturity and infrastructure readiness, making them less applicable to Malaysia's developing context. This study highlights these gaps and proposes strategies, including targeted investments, capacity-building, and policy development, to support DT implementation tailored to Malaysia's needs, advancing energy efficiency in its building sector.

1. Introduction

Buildings contribute to nearly 40% of overall energy consumption in industrialised countries, contributing significantly to energy wastage and environmental degradation [1]. This high energy consumption can be seen in complex building ecosystems, where the primary function of the building, such as retail stores or hospitals, often takes precedence over energy efficiency [2]. Traditional methods that are used in maintaining indoor conditions often result in energy inefficiency [3]. Furthermore, the rise of renewable energy infrastructure and the growing

need for buildings to adopt more flexible energy management strategies such as Demand Response programs are placing additional pressure on building operations [4].

To address this situation, disruptive technologies like Building Information Modelling (BIM) and Digital Twin (DT) are evolving as powerful solutions. A DT is defined as a virtual model that replicates a physical object, system, or process by utilizing real-time data and simulations [5]. This digital replica mirrors the physical entity's characteristics, behavior, and performance, allowing for monitoring, analysis, and optimization [6]. In the context of buildings, a DT integrates data from sensors, meanwhile, BIM, and other sources to reflect the current state of the building, including its energy use, HVAC systems, and occupant activities [7]. This real-time monitoring allows for predictive maintenance, energy optimization, and informed decision-making, ultimately enhancing operational efficiency and sustainability. DT are used across various industries, from manufacturing to healthcare, to improve performance, reduce costs, and support proactive management. BIM creates detailed digital models of buildings, which improve planning, design, and the operation of energy-efficient systems [8]. When integrated with live data from devices sensors and actuators, BIM helps construction managers dynamically adjust heating, cooling, lighting, and other systems to optimize energy consumption [9]. In contrast, DT takes this a step further by creating a virtual, live data representation of a building that mirrors its physical counterpart. This virtual model continuously receives data from systems like HVAC and lighting, utilizing predictive algorithms to optimize energy consumption based on occupancy patterns and external weather conditions [10, 11].

The integration of DT improves energy efficiency in several ways. First, DT enables live data monitoring of energy consumption, allowing building managers to identify inefficiencies and make immediate adjustments [11]. This is particularly beneficial in large, complex buildings, such as hospitals, retail spaces, and office complexes, where managing energy use can be challenging. Moreover, DT can simulate various scenarios to predict future energy consumption, considering factors like seasonal changes, occupancy levels, and energy price fluctuations [12]. This permits for more accurate forecasting and better policymaking in energy management. Finally, DT can be integrated with advanced control systems, such as Model Predictive Control (MPC). MPC is an innovative control approach used in various systems, including building energy management, that involves predicting future system behavior and using this prediction to optimize the current control actions [12].

In Malaysia, the situation mirrors global trends, where building energy consumption continues to grow. The country has recognised the need to improve the energy efficiency of buildings, and several initiatives have been introduced to address this issue. The Malaysia Construction Industry Transformation Plan (CITP) 2016-2020, for instance, emphasises sustainability and energy-efficient building practices within the construction industry [13]. Additionally, Malaysia has adopted the Green Building Index (GBI), which encourages the use of sustainable building practices, though these frameworks are still in the early stages of adoption [14]. Furthermore, Malaysia has introduced the National Construction Policy (NCP) 2030, which intends to improve the construction industry through sustainability, innovation, and enhanced productivity. This policy aligns with the nation's broader sustainability goals and emphasizes energy efficiency in both building design and construction processes. In addition, Construction Industry 4.0 (Construction Strategic 4.0) promotes the integration of digital knowledges such as BIM and automation into construction. By encouraging smart technologies, this initiative seeks to reduce energy consumption and improve operational efficiency in buildings [13]. Also, Malaysia's 12th Malaysia Plan (12MP) further underscores the importance of green infrastructure and low-carbon development. It promotes the incorporation of smart technologies and energy-efficient solutions in buildings as part of the nation's efforts to meet its sustainability targets [15]. This plan prioritises reducing carbon footprints and improving energy management systems, which directly impacts building energy consumption.

Although disruptive technologies like BIM and DT have the possible to revolutionise building energy management, their adoption in Malaysia remains in its infancy [16, 17]. Existing frameworks, such as the Green Building Index (GBI) and the Construction Industry 4.0, have set the stage for more sustainable building practices. However, the gap between existing frameworks and the implementation of these advanced technologies is evident in Malaysia, where there is a lack of localised research, policies, and industry-specific frameworks [17, 18]. Despite the progress made, the adoption of DT and BIM in the building sector is still relatively low [19, 20], and the integration of these technologies into the construction industry faces considerable challenges [17]. To harness the full potential of BIM and DT for improving energy efficiency, Malaysia requires more effective strategies for widespread adoption, alongside further development in both technological capabilities and regulatory frameworks.

The gap between policy development and the practical application of these technologies needs to be bridged to ensure that Malaysia can fully capitalize on the potential of BIM and DT to address energy management challenges in the built environment [17]. Therefore, more localised, context-specific initiatives are needed to enhance the uptake of these technologies, ensuring they contribute to a more energy-efficient and sustainable building sector. Hence, it is crucial to critically examine the existing frameworks related to DT within the construction industry. The purpose is to make a comparative analysis on the current state of DT adoption and its application in managing building energy consumption, focusing on identifying gaps and limitations in the existing frameworks.

2. Research Method

The primary method for data collection in this study is a comparative literature review. A total of ten (10) research papers (Table 1) related to Digital Twin (DT) frameworks were carefully selected, ensuring relevance to the construction industry and energy consumption management.

Table 1 List of ten (10) existing framework related to DT

No	Title	Focus Area
1	Proposed Framework for Digital Twin Technology Implementation in Smart Cities	Smart city development
2	Digital-Twin-Based Fire Safety Management Framework for Smart Buildings	Fire safety and evacuation management
3	Framework Diagram for Conventional LCSA Using Digital Twins	Life Cycle Sustainability Assessment (LCSA)
4	Digital Twin Framework for Precast Concrete Production	Automation and efficiency in precast concrete production
5	Digital Twin Framework for Building Operation	Operations and Maintenance (O&M)
6	Framework for Construction Safety Training Using Dynamic Virtual Reality Games and Digital Twins	Construction safety training
7	A Digital Twin Framework for Improving Energy Efficiency and Occupant Comfort in Public and Commercial Buildings	Energy efficiency and occupant comfort
8	Integrated Digital Twin and Blockchain Framework	Construction project management
9	A Framework for an Indoor Safety Management System Based on Digital Twin	Indoor safety management
10	Digital Twin Hospital Buildings: An Exemplary Case Study Through Continuous Lifecycle Integration	Hospital building management (energy efficiency, predictive maintenance, clash detection)

This method is also being used by researchers with a similar purpose to examine differences and similarities in framework development, application, and effectiveness [21-23]. It also helps in identifying universal principles and context-specific adjustments necessary for addressing energy efficiency challenges in buildings. The selection criteria focused on papers that discuss the development of DT frameworks, their purpose, the target users, and the challenges faced in their adoption. These papers provide insights into the existing state of DT frameworks globally and their applicability to building energy management.

This research is focused on reviewing completed and published frameworks specifically related to Digital Twin (DT) technologies. This approach ensures that the analysis is based in robust, peer-reviewed research and established methodologies, offering a thorough insight into the existing state of DT frameworks. The selection criteria for the reviewed papers are explained in Table 2:

Table 2 *Comparative review criteria*

Step	Description
Database Selection	Use of Scopus, ScienceDirect, IEEEExplorer, Web of Science, and Engineering Village
Keywords Search	Search terms focus on DT frameworks, quality, and applications in building construction
Search Period	Articles published from January 2020 to 2024
Language	English language
Article Selection	Ten articles were selected based on relevance to construction, energy management, and DT implementation
Comparative Review	Analyse differences and similarities in DT frameworks across studies
Content Analysis	Examine themes like key issues, purposes, and target users
Findings & Implications	Highlight research gaps and offer recommendations for improvement

For the content analysis, Atlas.ti software was employed to systematically examine textual data from the selected articles, allowing the identification of recurring themes, patterns, and critical issues. This analysis focused on three key aspects:

1. **Key Issues:** Identifying challenges and factors influencing the progress and adoption of existing DT frameworks.
2. **Framework Purpose:** Exploring the intended goals of DT frameworks, particularly in energy management and sustainability.
3. **User Profiles:** Understanding the target users, including stakeholders in the construction and building management sectors.

The process began with importing the selected research papers into Atlas.ti, followed by assigning codes to relevant text segments, such as those discussing framework purposes, challenges, and user profiles. These codes were systematically organised into themes, and the software's analytical tools were used to categorise patterns, relationships, and co-occurrences within the data. Visualisation tools, such as network diagrams, were employed to map connections between themes, offering a deeper understanding of the frameworks' strengths, weaknesses, and applicability. This structured approach not only provided insights into the current state of DT frameworks but also highlighted research gaps, such as the need for tailored solutions in developing economies like Malaysia. By synthesising knowledge from the analysis, the study proposes practical recommendations for enhancing DT frameworks to support their implementation in construction and energy management.

The comparative literature review provides a broad perspective by synthesising findings across multiple studies, while the content analysis helps uncover deeper insights into the underlying factors influencing the development and application of DT technologies. By focusing on key aspects such as issues, purpose, and users, the study aims to bridge gaps in the existing knowledge and propose targeted improvements for DT frameworks in managing building energy consumption. Not only that, this approach is expected to offer practical recommendations for enhancing DT frameworks to better meet the specific needs of developing economies like Malaysia.

3. Review on Existing Digital Twins Framework

A framework, in general, refers to a structured and systematic approach or set of guidelines designed to organize or address complex problems [24]. It provides a foundational structure that supports and guides the development of more detailed systems or solutions. Frameworks typically consist of principles, rules, methods, tools, and best practices intended to achieve specific objectives within a given field. In the context of DT, a framework is a structured approach that integrates various technologies, processes, and methodologies to design, implement, and manage DT systems [25]. These systems involve sensors, data models, simulation tools, and predictive algorithms to create real-time digital replicas of physical assets, such as buildings, machinery, or infrastructure. A DT framework enables the collection, processing, and analysis of data to support decision-making, optimize performance, and solve complex problems [25]. Hence, in this review, ten (10) DT frameworks have been examined, and details of these frameworks are provided in Table 3.

Table 3 Summary on ten (10) existing framework related to DT

No	Title	Issue	Purpose	User	Focus
1	Proposed Framework for Digital Twin (DT) Technology Implementation in Smart Cities [17]	Addressing the critical challenges hindering the effective implementation of Digital Twin Technology (DTT) in smart city development, with a specific focus on Malaysia.	To identify and address these barriers, facilitating the adoption of DTT by highlighting the enablers such as technological investments, policy support, and capacity-building initiatives.	Policymakers, urban planners, technology developers, and stakeholders involved in smart city planning and development.	Smart city development
2	Digital-Twin-Based Fire Safety Management Framework for Smart Buildings [26]	Traditional systems often lack real-time data integration and fail to predict fire spread and evacuation dynamics accurately, leading to inefficient emergency responses.	To enhance fire safety and evacuation management by leveraging digital twin (DT) technology. To provide a dynamic, real-time view of building conditions, including fire safety elements, using IoT sensors, BIM data, and predictive algorithms.	Facility managers, emergency responders (such as firefighters), and building occupants.	Fire safety and evacuation management
3	Framework Diagram For Conventional Life Cycle Sustainability Assessment (LCSA) Using Digital Twins. [27]	Conducting LCSA is challenging due to incomplete and disconnected data. Hence, there is a need to tackle this issue by showing how combining BIM and DT technologies can improve data integration and support more effective LCSA.	The proposed novel methodological framework acts as a guideline to leverage existing standards to demonstrate how BIM and DT can deliver value across each module of the sustainability pillars for building assets. By integrating BIM and DT, the framework enables a comprehensive approach to conducting LCSA, ensuring a holistic evaluation of sustainability impacts and benefits.	Researchers, project managers, and sustainability consultants aim to enhance decision-making through detailed lifecycle analysis.	Life Cycle Sustainability Assessment (LCSA)

No	Title	Issue	Purpose	User	Focus
4	Digital Twin Framework for Precast Concrete Production [28]	The need to address inefficiencies in traditional precast concrete production processes.	This framework focuses on enhancing automation and efficiency focusing on the production of precast concrete elements by integrating Industry 4.0 and BIM. It aims to advance quality assurance and control throughout the lifecycle of precast components by allowing unified communication between physical assets and digital assets.	Precast manufacturers, production managers, and Industry 4.0 operators who oversee the automation of production processes.	Automation and efficiency in precast concrete production
5	Digital Twin Framework For Building Operation [29]	Challenges in the traditional O&M approach can be effectively addressed by enhancing the model's intelligence.	To deliver intelligent O&M services, including predicting a building's condition and remaining lifespan, identifying potential risks, and formulating targeted maintenance plans, ensuring optimal operational health and efficiency.	Facility management team	Operations and Maintenance (O&M)
6	Framework for Construction Safety Training using Dynamic Virtual Reality Games and Digital Twins [30]	Workplace accidents, lack of engaging training, underutilisation of VR/digital twins in safety	Focuses on improving construction safety training through immersive VR games supported by digital twins. It uses live data digital twin assets to create dynamic and realistic scenarios for workers to learn safety protocols effectively.	Construction workers, safety trainers, and site managers who aim to enhance safety awareness and reduce workplace accidents.	Construction safety training

No	Title	Issue	Purpose	User	Focus
7	A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings [31]	Traditional model Predictive Control (MPC) frameworks used for building automation faced limitations due to inflexible cost functions that required constant re-tuning, particularly when applied to buildings with heterogeneous characteristics.	Facilitating the development of a virtual replica of a building's physical environment, enabling facility managers to optimize energy consumption, monitor performance, and enhance decision-making processes.	Facility managers, building operators, and energy managers	Energy efficiency and occupant comfort
8	Integrated digital twin and blockchain framework [32]	Data fragmentation, compliance issues, lack of collaboration, storage limitations	To improve construction project management by collecting real-time data from IoT, updating the as-built BIM in the digital twin, and generating compliance statements. These statements ensure transparency and traceability by being stored on the blockchain, which facilitates collaboration and contract execution among stakeholders without requiring extensive storage for raw data.	Project managers, contractors, and stakeholders who require transparent collaboration and decision-making tools	Construction project management
9	A Framework For An Indoor Safety Management System Based On Digital Twin [33]	The necessity for efficient indoor safety management in buildings, as traditional methods frequently lack the capability for real-time monitoring and predictive analysis of safety risks.	To combine BIM and IoT technologies into a unified system that enhances the management of building safety.	Safety management personnel, such as facility managers and security teams,	Indoor safety management
10	Digital Twin Hospital Buildings: An Exemplary Case Study Through Continuous Lifecycle Integration [34]	A need to address the complexity and scale of integrating diverse data sources in a hospital environment for efficient and real-time management.	To improve clash detection through VR/AR, optimize energy management in buildings, and enhance predictive maintenance for performance forecasting.	Hospital management teams, including safety management staff, engineers, and decision-makers.	Hospital building management (energy efficiency, predictive maintenance, clash detection)

4. Discussion: Gaps and Contextual Challenges in Existing Digital Twin (DT) Frameworks for Building Energy Efficiency in Malaysia

The analysis of existing Digital Twin (DT) frameworks reveals significant potential for improving building energy management through the integration of live data from BIM, Internet of Things (IoT) sensors, and predictive analytics. These technologies enable dynamic virtual representations of buildings that support real-time monitoring, resource optimisation, and enhanced operational efficiency. For instance, frameworks such as the Digital Twin Framework for Improving Energy Efficiency and Occupant Comfort in Public and Commercial Buildings demonstrate the benefits of DT in managing energy usage across diverse systems, adapting to changing conditions, and aligning with broader smart city goals [31].

However, a comparative review highlights critical limitations when these frameworks are applied in developing countries, particularly Malaysia. Most globally developed DT frameworks assume the presence of advanced technological infrastructure, robust data ecosystems, and skilled human capital. This assumption poses a significant challenge in contexts like Malaysia, where technological maturity, infrastructure readiness, and expertise remain inconsistent across the construction industry. For example, DT applications in areas such as fire safety, indoor air quality monitoring, and predictive maintenance enabled by sophisticated sensor networks and real-time data analytics [12, 26] are often impractical for local implementation due to infrastructure and cost limitations. Moreover, some advanced DT frameworks target large-scale or high-tech environments such as hospitals [34], which differ greatly from Malaysia's heterogeneous building stock, comprising residential, commercial, and institutional facilities of varying technological readiness. As such, direct adoption of these frameworks without contextual adaptation risks poor performance or non-adoption.

In Malaysia, existing DT-related frameworks such as the Proposed Framework for Digital Twin Technology Implementation in Smart Cities tend to emphasise enabling factors such as policy support, infrastructure development, and digital readiness [17]. While such frameworks acknowledge key adoption barriers, they often lack practical guidelines for implementing DT specifically for building energy optimisation. Their heavy technical orientation tends to overshadow equally important managerial, organisational, and socio-economic considerations essential for success in developing environments. The Malaysian construction industry faces additional constraints, including fragmented supply chains, inconsistent digital maturity among stakeholders, and limited exposure to advanced tools like BIM and IoT. Integrating these technologies into DT systems demands substantial investment in hardware, software, and data infrastructure resources that may be inaccessible to many local actors [35, 36]. Furthermore, there is a noticeable absence of DT frameworks that are tailored to Malaysia's specific regulatory, economic, and operational contexts. Global models rarely address foundational barriers such as fragmented data ecosystems, inadequate policy mechanisms, and low levels of digital skill among construction professionals.

This comparative analysis therefore, underscores the pressing need for a balanced and localised approach to DT framework development. While technical capabilities such as real-time data integration and predictive analytics are crucial, successful DT adoption in Malaysia requires equal attention to governance, stakeholder engagement, policy alignment, and capacity building [37]. Future frameworks must prioritise scalable, cost-effective technologies, and be accompanied by structured training and upskilling programmes to build local expertise. Moreover, they should consider foundational barriers such as institutional fragmentation and limited interoperability between data systems to foster a supportive ecosystem for DT deployment.

Hence, despite the growing number of DT frameworks globally, the literature reveals a critical gap in context-specific models that address the challenges faced by developing countries in achieving energy-efficient building operations. Many existing frameworks, designed for high-income settings, are underpinned by assumptions of advanced digital integration, strong regulatory frameworks, and mature infrastructure. This limits their direct applicability in developing countries like Malaysia and underscores the core research problem: the absence of a practical, scalable, and contextually relevant DT framework for energy optimisation in Malaysia's resource-constrained built environment.

Furthermore, while several frameworks reviewed demonstrate technical robustness particularly in lifecycle sustainability, predictive maintenance, and real-time monitoring. Additionally, the literature review process would benefit from greater methodological transparency regarding the selection criteria, data sources, and comparative lens. Addressing these methodological limitations would strengthen the credibility and relevance of the analysis and form a more solid foundation for the development of a novel DT framework tailored to Malaysia's unique socio-economic and technological context.

5. Conclusion and Further Research

This study comprehensively reviews existing DT frameworks by identifying their strengths, limitations, and potential applications across various domains such as smart cities, fire safety, energy efficiency, and construction project management. The findings align with the research objective by evaluating the effectiveness of these frameworks in addressing key challenges, including real-time data integration, predictive analytics, and

operational efficiency. While many existing frameworks successfully improve building management and safety, gaps remain in their adaptability to diverse contexts, particularly in regions with varying levels of DT maturity and infrastructure readiness. The study highlights that despite DT's transformative potential, its widespread implementation is often hindered by fragmented data ecosystems, high costs, and limited technical expertise.

Beyond Malaysia, these findings have broader international implications, particularly for developing economies seeking to adopt DT technology. The study emphasizes the importance of developing adaptable and scalable frameworks that cater to both technologically advanced nations and regions still in the early stages of digital adoption. A balanced approach to incorporating technological innovation alongside policy support, capacity-building, and cost-effective solutions is crucial to ensuring the global applicability of DT frameworks. Future research should focus on refining DT strategies to bridge the gap between high-tech solutions and practical implementation, fostering a more inclusive and effective integration of DT technology worldwide.

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Conflict of Interest

The authors affirm that there are no conflicts of interest related to the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Juliana Brahim, Mohamad Syazli Fathi; **data collection:** Juliana Brahim, Thuy Ninh Dao; **analysis and interpretation of results:** Juliana Brahim, Mohamad Syazli Fathi; **draft manuscript preparation:** Juliana Brahim, Mohamad Syazli Fathi, Suzila Mohd. All authors reviewed the results and approved the final version of the manuscript.*

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