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Original Article

Identifying Key Characteristics of Digital Twin Technology in Green Building Implementation

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Abstract

The construction industry is increasingly embracing green building practices to promote sustainable development. However, the advanced application of Digital Twin (DT) technology in green buildings requires further exploration. This study aims to address this gap by systematically reviewing and defining the key characteristics of DT technology in Malaysia's green building sector. Using an inductive research methodology, data was collected from semi-structured interviews with five industry experts chosen through purposive sampling and snowball sampling. Thematic analysis revealed that DT technology enhances green building performance via advanced tools, real-time monitoring, bi-directional interaction, and feedback mechanisms. The findings suggest that DT technology significantly improves resource management, energy conservation, and building efficiency. These insights are valuable for construction stakeholders leveraging DT technology to advance green building practices and support sustainable development goals. Despite its advantages, technological limitations and data security issues persist. This research provides practical implications for construction practitioners on adopting DT technology for better sustainability outcomes and academic consequences for future studies on DT in green buildings.

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1. Introduction

A green building is defined by its design, construction, and operating procedures targeted at minimizing or eliminating the negative effects of development on the environment and human health [1-3]. For green buildings, productivity, resource conservation, energy efficiency, and environmental stewardship are important considerations [4]. Green buildings should include green principles in all parts of construction, including design, research and development, building materials, sales, construction, operation, and maintenance, and constitute a closed-loop construction industry chain [5]. Digital Twin (DT) technology, or a simulation-based planning and optimization concept, can replicate real buildings digitally. Michael Grieves first suggested this idea at the University of Michigan in 2003. In 2006, the concept evolved to add a “product avatar,” which made it comparable to the basic tenets of green construction by promoting effective planning and resource usage [6].

DT technology is getting noticed because it can be used in many industries. But when it comes to using DT in green buildings, the characteristics of DT to enhance green buildings are not well investigated [6] . Therefore, there is a need to investigate and delineate the unique characteristics of DT tailored for green buildings. The purpose of this research is to systematically review the use of DT technology within the green building industry. The study's objectives include examining the role of DT technology in the Malaysian construction industry, the characteristics of DT, and evaluating its potential to address the specific problems and needs of Malaysia’s construction industry, especially when it comes to green building practices. This study holds significance because it contributes to developing green buildings with DT technologies in the Malaysian construction industry.

2. Literature Review

This section explores the current status and key characteristics of DT technology in green buildings. It outlines essential characteristics from three perspectives: data-related technologies, high-fidelity modeling technologies, and simulation-based models.

2.1. Digital Twin Technologies and Characteristics

Numerous technological obstacles still stand to derail the implementation of DT applications. Understanding and developing DT key technologies is essential. Key technologies for DT can be discussed from three perspectives: data-related technologies, high-fidelity modeling technologies, and simulation-based models.

2.1.1. Data Related Technologies

DT is built on data. Sensors, gauges, Radio Frequency Identification (RFID) tags, readers, cameras, scanners, and so on, should be selected to serve as input for DT, generated from total-element data. Data will be sent in real-time or nearly real-time through various means. DT uses a large volume of data, high in velocity and diverse, for effective operations simulation. Edge computing pre-processes gathered information, minimizing network involvement and reducing data leak risks. Real-time data transmission is made possible by 5G technology. Data mapping and fusion, such as Extensible Markup Language (XML) are essential [7].

This study focuses on industrial Internet of Things (IoT) and signal processing methods in DT systems for online and multi-source data collection [8]. Moreover, various network protocols and communication technologies appropriate for transporting sensor data were evaluated [9]. The streams of data from manufacturing machines were stored in a document-type unstructured schema. This research covers key data-related technologies such as data collection, mapping, processing, transmission, and their various applications [10].

In the built environment, DT improves productivity, health and safety, facility management, operation effectiveness, and cost [11-13]. Wireless sensor network (WSN) technology and data analytics are crucial for constructing [14]. Key aspects include Data Ownership, Physical-to-Virtual and Virtual-to-Physical Connections, Integration between Virtual Entities, and the dynamic state of all parameters [15].

2.1.2. Data Related Technologies

DT is based on models, including semantic and physical data models. Semantic data models combine artificial intelligence (AI) techniques with known input and output examples. Multi-physics modeling is necessary for real-time and accurate DT production [7].

A DT model with a moderate scenario with flexible, modular, black box modules is suggested. In these models, it should be activated only when necessary, and interact with the main simulation model through interfaces [16]. High-fidelity DT models are constructed at different levels of modeling complexity [17]. DT has been developed to build rules that explain dynamic systems through hidden Markov models for complex phenomena [18]. Theoretical and physical methods were also used to establish high-precision product assemblies [19].

Furthermore, physical twin models can be converted to physics-based models using either a black box or grey box approach [20]. Building Information Modeling (BIM) or custom-created can extract DT models as 3D models. These DT models improve construction efficiency by contributing to both design and construction phases and monitoring physical assets regarding operational efficiency and predictive maintenance [21,22].

High-fidelity modeling technologies are critical to ensuring realism in both physical and virtual objects in DT systems. These technologies include the physical and virtual entities, environments, fidelity levels, technical implementations, and use of the DT across the Product Life Cycle [15].

2.1.3. Simulation-based Model

A key element of DT is simulation, enabling virtual interaction with physical entities in real-time and bi-directional communication. A high-level model based on Automation Markup Language (AutomationML) facilitates data exchange between systems [23]. IoT systems provide data features for other applications, integrating data from various fields [24]. Unlike traditional simulation, DT simulation uses real-time data from physical systems [25]. Simulation based on multi-scale physics is essential. It involves input-output relations, boundary links, and well-integrated models at different levels of detail [26]. Multi-scale, multi-physics problems are solved by partitioning solution domains and exchanging data for interfaces [27].

Simulation-based models involve Physical and Virtual Processes, twinning, synchronization, Physical-to-Virtual and Virtual-to-Physical Connections, and coupling between Virtual Entities. Technical Implementations refer to computational strategies in simulation models [15].

DT generates a digital replica of physical assets using real-time sensor data for simulation and data analysis [22]. It optimizes building interaction, reduces energy wastage, and enhances occupant comfort.

3. Research Method

The inductive research approach is used as the researcher starts with the particular phenomena and comes up with general theories and conclusions [28,29]. This work uses an inductive approach to assess the potential positive and negative effects due to the interconnectedness of green buildings and DT technology. The study starts with a quantitative data analysis to determine the patterns and themes that can later be utilized to establish the strengths and weaknesses of DT in green building practices [28,29].

The population of interest for this research is people with experience with the DT application in green building projects. Site supervisors and site engineers in Malaysia are included in this. The roles were chosen to bring different perspectives on how DT is carried out and managed in green building projects.

This research used non-random sampling [30]. For instance, this study adopted non-random sampling involving purposive sampling and snowball sampling. Non-random sampling is a method where the participants are picked with relevance to the study, and they have the relevant experience and knowledge. The first part targeted individuals with huge expertise in the DT application in green buildings. Snowball sampling was also used to grow the participant pool by asking initial respondents to suggest other potential individuals from their network. This study found that this approach successfully identified information-rich participants who provided rich details regarding the use of DT technology in green building projects.

According to [31,32], which emphasize the importance of selecting information-rich participants in qualitative research, the sample size of five respondents was chosen. These studies show that data saturation is possible using a small sample size with in-depth qualitative research as long as the participants are chosen carefully to provide insight. In addition, interviews continued until new themes were not produced, and data thus became saturated. This approach aligns with better qualitative research practices, especially for exploratory studies in a special area.

Semi-structured interviews are the primary data source of this research. This method allows the researcher flexibility while maintaining attention on important topics, allowing the researcher to probe participants' experience and perception of the impact of DT on green buildings. Table 1 presents the sources of indicators used in designing the interview questions.

Table 1: Tool development.

Item	Description	Sources
Characteristics of Digital Twin (CoDT)		
CoDT 1	Physical Dimension	**(Andrea Matta, 2023)**
CoDT 2	Virtual or Digital Dimension	
CoDT 3	Model–based Approach	
CoDT 4	Model–free Approach	
CoDT 5	Service Dimension	
CoDT 6	Data Dimension	
CoDT 7	Connection Dimension	
CoDT 8	**Physical-to-Virtual Connection**	**(Jones et al., 2020)**

In qualitative research, fresh ideas and reviews from academics and peers allow for better improvements [33]. The interview questions were piloted through two peer evaluations to confirm their clarity and answerability. One academician and one construction professional participated as members of the evaluation panel.

The data collected from the interviews is coded and analyzed using thematic analysis. Coding might be defined as the process of analyzing data by sorting it systematically to evaluate the major themes and patterns. Thematic analysis enables one to comprehend the latent features and implications of the participants' use of DT technology in green buildings.

4. Interview Findings and Interpretations

Concerning content validity, this study ensures that the type of behavior required in a test aligns with the intended objective of training or some related activity. The interview questions were developed based on the research questions revised by other researchers.

Following the initial pilot test, some changes were made in line with established guidelines [34, 35].This refinement process helped to check the clarity and comprehensiveness of the questions formulated with respect to the phenomena under investigation. In this research, there were five participants for the semi-structured interview shown in Table 2.

Table 2: Demographic of Respondents.

Respondent	Educational Background	Current Position	Experience in the Industry	Involvement in DT Projects	Involvement in Green Building Projects
A	Engineering Degree	Senior Project Manager	15 - 20 years	1-3 years	< 3 projects
B	Architecture Degree	BIM Manager	10 - 15 years	> 7 years	< 3 projects
C	Civil Engineering Degree	Project Manager	10 – 15 years	3 – 5 years	< 3 projects
D	Quantity Surveying Degree	Site Supervisor	5 – 10 years	3 – 5 years	< 3 projects
E	**Mechanical Engineering Degree**	**Assistant Project Manager**	**15- 20 years**	**1 – 3 years**	**< 3 projects**

Table 3: Characteristics with Respondents' Agreement.

Characteristics		Respondents				
		A	B	C	D	E
Data-Related Technologies	Incorporation of Modern Technologies	✓				✓
	Real time Monitoring and Management	✓	✓	✓		✓
	Bi-Directional Interaction and Feedback		✓	✓		
	Creation of Digital Twin			✓		
High-fidelity Modeling Technology	Enhanced Collaboration and Communication	✓				✓
	Performance Simulation and Optimization				✓	✓
	Predictive Analysis and Error Minimization			✓		
Simulation Base Models	Comprehensive Lifecycle Management		✓		✓	
	Sustainable Outcomes and User Satisfaction				✓	✓

4.1. Data Related Technologies

The implementation of data-related technologies plays a central role in the effective application of DT technology in green buildings. These technologies help establish the integration of advanced tools, real-time monitoring and management, bi-directional interaction and feedback, and the creation of DT.

4.1.1. Integration of Advanced Tools

Respondent A stated, "*DT technology is similar to 'Revit on steroids,' which expresses the change DT creates on conventional BIM.*" This means DT technology takes it to a higher level where data from the real building is constantly integrated into the digital model. Respondent E underlines *"DT technology applies digital models and real-time data to systematically and iteratively schedule, update, and coordinate construction work."* It means that DT technology uses these tools not only at the stage of designing but also at the construction and operation stages.

4.1.2. Real Time Monitoring and Management

Respondent A underlines the necessity of real-time data integration, which enables monitoring and managing the performance of buildings. Respondent B mentioned that DT expands on how real-time monitoring relates to energy efficiency and sustainability of buildings. Respondent C continues that incorporating data from IoT sensors into the DT model allows for a constant feedback loop that ensures the building's performance remains on track with sustainability objectives. Respondent E said that real-time monitoring and digital simulation enable the change of response based on conditions to make better decisions that improve building performance.

4.1.3. Bi-Directional Interaction and Feedback

Respondent B stresses the need for constant interaction between the DT and the actual building to align construction and performance. Respondent C notes that this feedback helps maintain operational and ecological conditions.

4.1.4. Creation of Digital Twin

Only Respondent C's points: *"Active creation of DT allows maintaining an up-to-date model of the actual building."* This digital model can be used for online monitoring and control to ensure that the functioning of the building corresponds to the goals set for the sustainable development of society.

4.2. High-fidelity Modeling Technology

High fidelity modeling technology in DT provides an extremely accurate and detailed model of the physical objects. It includes enhanced collaboration and communication, performance simulation and optimization, and predictive analysis and error minimization in this discussion. The specifics of these aspects are described in the following subsection.

4.3.1. Enhanced Collaboration and Communication

Respondent A also pointed out that DT technology enhances the acquisition of new project data to boost the understanding of its stakeholders because it is only through cooperation that sustainability can be achieved. From Respondent E, it notes that DT tools allow for the constant updating of information and flow, ensuring that the team has a unified understanding and direction.

4.3.2. Performance Simulation and Optimization

Respondent D believes that performance simulations play an essential role in enhancing building operations in various circumstances. The same opinion is shared by Respondent E, who stressed that such tools effectively maintain the necessary conditions and organizational and technical requirements.

4.3.3. Predictive Analysis and Error Minimization

Respondent C has shared that DT technology particularly analyses and predicts the errors that would have occurred in resource consumption, which enhances sustainable construction and efficiency.

4.3. Simulation-Based Models

Simulation-based models enable comprehensive lifecycle management, sustainable outcomes, and user satisfaction with the functionality of DT technology. These models offer precise emulation of the building functions and efficiency and help in improving decisions.

4.3.1. Comprehensive Lifecycle Management

Regarding the role of DT technologies in improving building performance, Respondent B explains that it optimizes control over a building's life cycle, including design, construction, and decommissioning, as well as sustainability and operational efficiency. This is supported by Respondent D, who pointed out that DT technology assists in decision making for the improvement of resource optimization for the built environment at different stages of a building's life cycle.

4.3.2. Sustainable Outcomes and User Satisfaction

Specifically, Respondent D also emphasizes that DT technology ensures that operational performance, environmental goals, and occupants' requirements are all met to achieve good performance and comfort levels in the building. Respondent E points out that DT technology entails environmentally friendly and functionally optimized environments that meet green building project goals.

5. Discussion

In exploring the integration of DT technology in green building, both the literature review and thematic analysis reveal several key characteristics that underscore its value.

5.1. Data-Related Technologies

Data-related technologies are key to DT, integrating advanced tools, real-time monitoring and management, bi-directional interaction and feedback, and creation of digital twins. These technologies ensure consistency between physical and digital models, providing the right information for decision-making.

5.1.1. Integration of Advanced Tools

Respondent A described DT as 'Revit on steroids,' enabling data integration for preventive maintenance. Respondent E noted DT's systematic planning, real-time synchronization, and efficient resource use, consistent with literature highlighting DT's high integration potential [36].

5.1.2. Real-time Monitoring and Management

Respondent A emphasized real-time data for building performance management. Respondents B and C highlighted resource allocation adjustments for proper indoor environments. Respondent E mentioned digital simulations adapting to conditions, supporting literature on real-time data's vital role in DT [36, 37].

5.1.3. Bi-Directional Interaction and Feedback

Respondents B and C stressed regular communication between models for design and sustainability goals. Literature supports feedback loops in DT for operational objectives [36].

5.1.4. Creation of Digital Twin

Respondent C noted the importance of an updated digital model for facility control. Literature supports dynamic digital models reflecting current conditions [36,38].

5.2. High-fidelity Modeling Technology

High-fidelity modeling in DT, enhancing collaboration, performance simulation, and predictive analysis.

5.2.1. Enhanced Collaboration and Communication

Respondents A and E described DT's role in promoting transparency, teamwork, and continuous communication for sustainability. Literature aligns with DT fostering collaboration [36,39].

5.2.2. Performance Simulation and Optimization

Respondents D and E highlighted performance simulations for building functionality and sustainability. Literature supports simulations for decision-making [36].

5.2.3. Predictive Analysis and Error Minimization

Respondent C mentioned that predictive analysis reduces errors and improves resource use. Literature supports DT's role in error prediction and resource utilization [36].

5.3. Simulation-Based Models

Simulation-based models support lifecycle management, sustainable outcomes, and user satisfaction.

5.3.1. Comprehensive Lifecycle Management

Respondents B and D highlighted DT's effectiveness in managing a building's lifecycle. Literature supports DT's lifecycle management capabilities [36,38].

5.3.2. Sustainable Outcomes and User Satisfaction

Respondents D and E emphasized DT's role in sustainable solutions and user satisfaction, aligning operational performance with environmental goals. Literature supports DT's enhancement of green environments and user satisfaction [36,39]. Fig.1 summarizes the key characteristics of DT technology in green buildings.

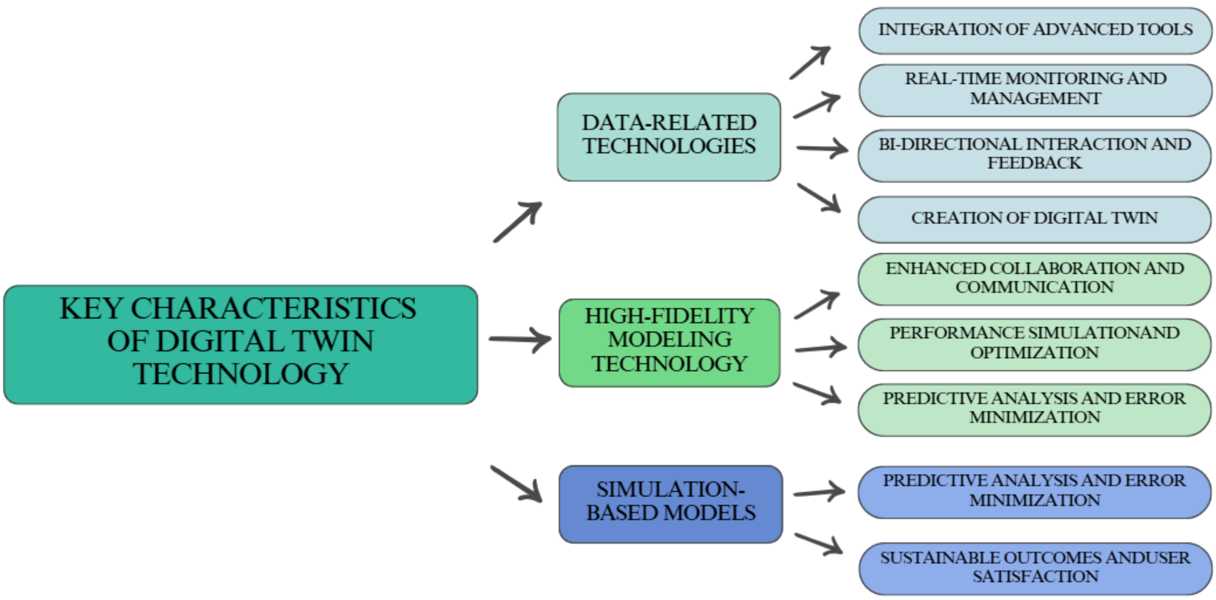

Fig. 1: Key Characteristics of Digital Twin Technology in Green Building.

6. Conclusion

The practical implications of this study are directed to the construction and green building industries, with a focus on the adoption of DT technology. The findings help understand how DT technology can be used to improve green buildings' sustainability and operational efficiency. This study reveals the prevailing characteristics of Digital Twin (DT) technology used in green building construction projects.

In thematic analysis of expert interviews, three major domain categories of prevailing features were found: data-related technologies, high-fidelity modelling technology, and simulation-based models.

First, information technologies such as real-time monitoring and management, bi-directional interaction and feedback and incorporation of modern technologies offer continuous physical and digital property synchronization, improving situational awareness and responsiveness in green buildings.

Second, high-fidelity modelling technology facilitates project collaboration, predictive analysis, and operation optimization. These features facilitate intelligent decision-making and proactive trouble-shooting throughout a building's life cycle.

Third, simulation-based models provide comprehensive lifecycle management and help align building performance with sustainability goals and user satisfaction.

This study, from an academic perspective, contributes to the growing body of knowledge on DT technology by identifying the key characteristics of DT technology based on their experience in its application to green buildings. Nonetheless, this study has limitations. The research is specific to the Malaysian construction industry; therefore, findings may not be universally applicable due to variations in construction practices, regulations, and technologies between regions. Interpretation of these results must be in the context of Malaysia's socioeconomic and environmental context. Future studies should extend the research to other countries or regions to broaden the applicability of the findings.

This study has another limitation as it is based on a qualitative approach, which involves interviews with five experts. While this method is deep, it lacks the breadth and precision that a quantitative approach could bring. Future research could do well to incorporate quantitative methods, such as larger-scale surveys or questionnaires, to pick up on broader patterns and relationships between variables. Statistical analysis would also be facilitated to determine the effect of DT technology on energy consumption, cost savings, and environmental performance.

Furthermore, the scope of research might be expanded to include cross-cultural comparisons that might provide insights into how different economic and regulatory environments affect the adoption and effectiveness of DT technology in green buildings. Comparing practices and policies of DT technology implementation in Malaysia and those of other countries may provide useful lessons to enhance DT technology implementation. Future studies can then build upon the current findings, address these limitations, and be better positioned for journal publication.

Declaration of Conflict of Interest

The authors declared no conflict of interest with any other party on the publication of the current work.

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