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TOWARD A THEORETICAL DIGITAL TWIN FRAMEWORK FOR STRUCTURAL HEALTH MONITORING IN SMART BUILDINGS: A LITERATURE

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Abstract
Digital Twin technology has emerged as a promising approach for improving structural health monitoring (SHM) in smart buildings through real-time data integration, virtual modeling, and predictive analysis. However, a comprehensive theoretical framework integrating Digital Twin concepts within SHM systems remains limited in civil engineering research. This study aims to develop a theoretical Digital Twin framework for structural health monitoring in smart buildings using a literature review approach. The review examines previous studies related to Digital Twin, Building Information Modeling (BIM), Internet of Things (IoT), sensor technologies, and artificial intelligence in smart infrastructure applications. The findings identify key components and integration mechanisms required to support real-time monitoring, anomaly detection, and predictive maintenance of building structures. The proposed framework contributes to the development of intelligent, resilient, and sustainable smart building systems and provides a conceptual foundation for future research and practical implementation in civil engineering.

1. Introduction

The rapid development of digital technologies has significantly transformed the construction industry toward smarter and more sustainable infrastructure systems (Rane 2023; Yusuf et al. 2021). In recent years, Digital Twin technology has attracted considerable attention in the field of structural health monitoring (SHM) due to its ability to integrate physical assets with virtual models through real-time data synchronization (Di Fiore et al. 2026; Wang et al. 2025). This technology enables continuous monitoring, predictive analysis, and efficient maintenance management for smart buildings(Ahmad and Alshurideh 2025; Boukaf, Fadli, and Meskin 2026).

Structural health monitoring plays a critical role in ensuring the safety, durability, and operational performance of building structures (Khubaib and Asghar 2026; Riffat, Samaei, and Pastakkaya 2025). Conventional monitoring approaches are often limited in providing real-time structural assessment and predictive maintenance capabilities (Chen, Cao, and Zhu 2023; Onyechi 2021). Therefore, the integration of Digital Twin with emerging technologies such as Building Information Modeling (BIM), Internet of Things (IoT), and artificial intelligence has become increasingly important for developing intelligent monitoring systems in modern buildings (Baghalzadeh Shishehgarkhaneh et al. 2022; Kayembe and Obadire 2025).

Despite these promising developments, the implementation of Digital Twin-based structural health monitoring in the construction sector still faces several significant challenges (Dong and Moshood 2026; Parida and Moharana 2024). The integration of heterogeneous data sources, interoperability between BIM and IoT platforms, real-time data processing, sensor reliability, and the high computational demands of predictive analytics remain major obstacles to achieving an effective Digital Twin ecosystem (Muhudin et al. 2026; Nguyen and Adhikari 2026). Furthermore, many existing studies primarily focus on isolated technological components rather than developing an integrated framework capable of supporting continuous structural assessment and data-driven decision-making throughout the building lifecycle (Islam 2026). Consequently, further research is required to establish comprehensive Digital Twin frameworks that effectively combine BIM, IoT, sensor networks, and intelligent data analytics to improve

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monitoring accuracy, enhance predictive maintenance strategies, and support sustainable infrastructure management in smart buildings.

Although previous studies have explored the application of Digital Twin in infrastructure and smart building management, research focusing on a comprehensive theoretical framework for SHM integration remains limited. This gap highlights the need for a conceptual framework that identifies key components, data integration processes, and technological interactions within Digital Twin-based SHM systems.

Therefore, this study aims to develop a theoretical Digital Twin framework for structural health monitoring in smart buildings through a literature review approach.

2. Method

This study employed a literature review approach to develop a theoretical framework of Digital Twin for structural health monitoring in smart buildings. The review focused on identifying, analyzing, and synthesizing previous studies related to Digital Twin technology, structural health monitoring (SHM), Building Information Modeling (BIM), Internet of Things (IoT), sensor systems, and artificial intelligence in civil engineering applications (Zhong et al. 2026).

Relevant articles were collected from reputable scientific databases, including Scopus, ScienceDirect, SpringerLink, IEEE Xplore, and Google Scholar. The selection process prioritized peer-reviewed journal articles, conference papers, and review studies published within the last ten years to ensure the relevance and recency of the research trends. Keywords used in the search process included "Digital Twin," "Structural Health Monitoring," "Smart Buildings," "BIM," "IoT," and "Predictive Maintenance."

The collected literature was analyzed using a qualitative synthesis approach (Afshari, Bayazidi, and Yazdani 2024). The analysis focused on identifying the main components of Digital Twin systems, data integration mechanisms, monitoring architectures, and predictive maintenance strategies applied in smart building environments (Aasa et al. 2026). Furthermore, similarities, limitations, and research gaps among previous studies were evaluated to construct a comprehensive theoretical framework.

The proposed framework was then conceptually developed by integrating the identified technological components and operational relationships to support real-time structural monitoring and intelligent decision-making in smart buildings.

3. Result and Discussion

3.1 Overview of Digital Twin Technology in Smart Buildings

Digital Twin technology has emerged as one of the most significant innovations in the development of smart infrastructure and intelligent building systems. A Digital Twin refers to a virtual representation of a physical asset, system, or process that is continuously updated using real-time data collected through sensors and digital communication technologies. This technology enables the synchronization between physical and virtual environments, allowing monitoring, simulation, analysis, and predictive decision-making throughout the lifecycle of a building.

Initially, Digital Twin technology was widely applied in the manufacturing and aerospace industries to improve operational efficiency and predictive maintenance. However, its application has gradually expanded into civil engineering and construction sectors due to the increasing demand for intelligent infrastructure management and real-time monitoring systems. In civil engineering, Digital Twin technology is increasingly utilized for structural health monitoring, asset management, energy optimization, and building lifecycle management.

In smart building systems, Digital Twin plays an important role in integrating physical building conditions with digital models to support real-time structural monitoring and maintenance planning. Through continuous data acquisition and analysis, the technology enhances building safety, operational performance, and sustainability. Furthermore, Digital Twin enables predictive maintenance strategies that reduce operational risks and maintenance costs.

The implementation of Digital Twin technology is strongly supported by Industry 4.0 technologies, including Building Information Modeling (BIM), Internet of Things (IoT), artificial intelligence (AI), cloud computing, and big data analytics. The integration of these technologies creates an intelligent and interconnected system capable of improving efficiency, automation, and decision-making processes in smart buildings.

3.2 Structural Health Monitoring (SHM) in Smart Buildings

Structural Health Monitoring (SHM) is an essential process for evaluating the condition, performance, and safety of building structures throughout their operational lifecycle. In smart buildings, SHM plays a significant role in detecting structural deterioration, identifying potential damage, and supporting preventive maintenance strategies. Effective SHM systems contribute to improving structural reliability, occupant safety, and long-term infrastructure sustainability. Moreover, continuous monitoring can reduce maintenance costs and minimize the risk of structural failure caused by aging, excessive loading, environmental conditions, or natural hazards.

Conventional SHM methods generally rely on periodic manual inspections, visual observations, and offline structural assessments. Although these methods are widely used in the construction industry, they often face several limitations, including delayed damage detection, limited monitoring frequency, high labor costs, and reduced accuracy in identifying hidden structural problems. In many cases, conventional approaches are unable to provide continuous real-time information regarding structural conditions, which may increase safety risks and maintenance inefficiencies.

The development of smart buildings has increased the demand for real-time structural monitoring systems capable of providing continuous and accurate data acquisition. Modern SHM systems require the integration of advanced technologies such as sensors, wireless communication, Internet of Things (IoT), and cloud-based data processing to support rapid decision-making and predictive maintenance. Real-time monitoring enables early detection of structural anomalies and improves the overall responsiveness of building management systems in maintaining structural performance and safety.

3.4 Key Technologies Supporting Digital Twin-Based SHM

The implementation of Digital Twin-based Structural Health Monitoring (SHM) systems in smart buildings is strongly supported by several advanced digital technologies that enable real-time monitoring, data integration, predictive analysis, and intelligent decision-making. These technologies form the fundamental infrastructure required to establish effective communication between physical structures and their virtual representations.

One of the primary technologies supporting Digital Twin systems is Building Information Modeling (BIM), which provides a digital representation of building geometry, structural information, and lifecycle data. BIM enables efficient visualization and integration of structural information within the Digital Twin environment. In addition, the Internet of Things (IoT) and sensor technologies play a crucial role in collecting real-time structural data such as strain, vibration, displacement, temperature, and crack development. These sensors continuously transmit data to monitoring platforms for further analysis.

Artificial Intelligence (AI) and machine learning technologies are also important components in Digital Twin-based SHM systems. These technologies support anomaly detection, predictive maintenance, and structural performance prediction by analyzing large volumes of monitoring data. Furthermore, cloud computing and big data technologies facilitate data storage, processing, and accessibility in real time, enabling efficient management of complex monitoring systems.

The integration of these technologies creates an interconnected and intelligent monitoring framework capable of improving structural safety, operational efficiency, and maintenance management in smart buildings. Therefore, the successful implementation of Digital Twin-based SHM systems highly depends on the interoperability and synchronization among these supporting technologies.

3.5 Proposed Theoretical Digital Twin Framework

Based on the literature review findings, this study proposes a theoretical Digital Twin framework for Structural Health Monitoring (SHM) in smart buildings by integrating physical structures, digital models, real-time data acquisition, and intelligent analytical systems. The framework is designed to support continuous structural monitoring, predictive maintenance, and data-driven decision-making processes throughout the building lifecycle.

The proposed framework consists of several interconnected components. The first component is the physical building structure equipped with various sensors and IoT devices for monitoring structural parameters such as vibration, strain, displacement, temperature, and crack conditions. These sensors continuously collect real-time data from the physical environment. The second component is the digital representation layer, which utilizes Building Information Modeling (BIM) to create a virtual model of the building structure. This virtual model serves as the core platform for integrating structural information and monitoring data.

The third component involves data communication and cloud-based systems that enable real-time data transmission, storage, and processing. Artificial intelligence and machine learning algorithms are integrated into the framework to analyze structural behavior, detect anomalies, and predict potential structural failures. The final component is the decision-support system, which provides maintenance recommendations and operational insights for building managers and engineers.

The proposed theoretical framework demonstrates the interaction between physical assets and digital systems within a smart building environment. This integration enables more efficient structural monitoring, enhances building safety, and supports sustainable infrastructure management through predictive and intelligent maintenance strategies.

3.6 Benefits and Potential Applications

The implementation of Digital Twin-based Structural Health Monitoring (SHM) systems offers significant benefits for smart building management and infrastructure sustainability. One of the primary advantages is the ability to perform real-time structural monitoring, allowing building operators and engineers to continuously assess structural conditions and detect potential damage at an early stage. This capability improves structural safety and reduces the risk of unexpected failures that may threaten occupants and infrastructure performance.

Another important benefit is the enhancement of predictive maintenance strategies. By integrating real-time sensor data, artificial intelligence, and predictive analytics, Digital Twin systems can identify structural anomalies and estimate potential deterioration before critical failures occur. This approach minimizes maintenance costs, reduces downtime, and increases operational efficiency throughout the building lifecycle.

Digital Twin technology also supports data-driven decision-making by providing accurate and continuously updated structural information. The integration of BIM, IoT, and cloud computing enables better coordination among stakeholders involved in building operation and maintenance processes. Furthermore, the technology contributes to sustainable infrastructure management by optimizing energy use, extending structural service life, and improving resource efficiency.

Potential applications of Digital Twin-based SHM systems include high-rise buildings, bridges, hospitals, airports, industrial facilities, and other critical infrastructure requiring continuous structural monitoring. In smart city development, Digital Twin technology can also support resilient infrastructure systems capable of adapting to environmental changes, natural hazards, and increasing urban demands.

3.7 Challenges and Research Gaps

Despite the significant potential of Digital Twin-based Structural Health Monitoring (SHM) systems, several challenges and research gaps remain in their implementation within smart buildings. One of the major challenges is the integration and interoperability of various technologies, including Building Information Modeling (BIM), Internet of Things (IoT), sensor networks, cloud computing, and artificial intelligence. Differences in data formats, communication protocols, and software platforms often limit efficient data exchange and system synchronization.

Another challenge is the high cost associated with sensor installation, data infrastructure, and real-time monitoring systems. The implementation of advanced Digital Twin technologies requires substantial investment in hardware, software, and technical expertise, which may limit adoption in developing regions and small-scale infrastructure projects. In addition, cybersecurity and data privacy issues have become increasingly important due to the continuous exchange and storage of large volumes of structural and operational data.

From a research perspective, many previous studies have primarily focused on conceptual discussions and small-scale experimental applications, while real-world implementation in complex smart building environments remains limited. Furthermore, there is still a lack of comprehensive theoretical frameworks that clearly define the relationships among Digital Twin components, monitoring systems, and predictive maintenance strategies in civil engineering applications.

Future research should focus on improving system interoperability, developing standardized Digital Twin architectures, enhancing AI-driven predictive models, and validating Digital Twin frameworks through real-world case studies in smart building environments.

3.8 Implications for Civil Engineering Practice

The development of Digital Twin-based Structural Health Monitoring (SHM) systems has significant implications for civil engineering practice, particularly in the planning, operation, and maintenance of smart buildings and infrastructure systems. The integration of Digital Twin technology enables engineers to monitor structural conditions in real time, improving the accuracy and efficiency of structural assessment and maintenance decision-making processes. This capability supports a transition from conventional reactive maintenance toward predictive and data-driven infrastructure management.

In practical applications, Digital Twin technology can assist civil engineers in identifying structural deterioration at an early stage, reducing the risk of structural failure, and improving overall building safety. The integration of Building Information Modeling (BIM), IoT sensors, and artificial intelligence also enhances collaboration among stakeholders involved in construction, operation, and facility management processes. As a result, infrastructure management becomes more efficient, transparent, and sustainable.

Furthermore, the adoption of Digital Twin systems contributes to the development of resilient and sustainable infrastructure capable of adapting to environmental changes and increasing urban demands. The technology also supports lifecycle management by optimizing maintenance scheduling, extending structural service life, and minimizing operational costs. In the context of smart cities, Digital Twin-based SHM systems can become an essential component of intelligent infrastructure management and future digital construction practices.

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Therefore, the implementation of Digital Twin technology presents significant opportunities for advancing innovation, sustainability, and operational efficiency in modern civil engineering practice.

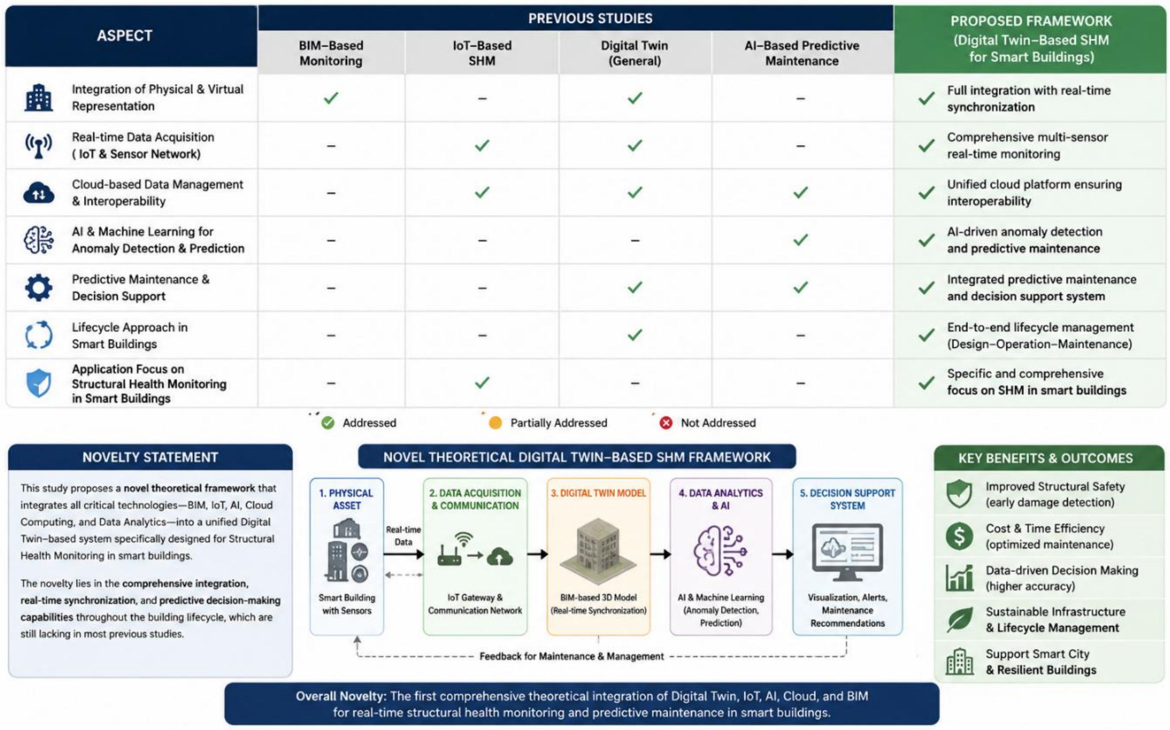

Figure 1. Novelty of the Proposed Digital Twin-Based SHM Framework for Smart Buildings

Figure 1 illustrates the novelty of the proposed theoretical framework for Digital Twin-based Structural Health Monitoring (SHM) in smart buildings. The figure compares the proposed framework with previous studies involving BIM-based monitoring, IoT-based SHM, general Digital Twin systems, and AI-based predictive maintenance. The comparison demonstrates that previous studies generally focused on specific technologies separately, while the proposed framework integrates all major technologies into a comprehensive and interconnected monitoring system.

The framework consists of five main components: physical assets equipped with sensors, data acquisition and communication systems, Digital Twin models integrated with BIM, artificial intelligence and data analytics, and decision-support systems. These components operate collaboratively through real-time data synchronization and cloud-based communication to support structural monitoring and predictive maintenance processes.

The novelty of the proposed framework lies in its comprehensive integration of BIM, IoT, cloud computing, Digital Twin, and artificial intelligence technologies within a unified SHM system specifically designed for smart buildings. Unlike previous approaches, the framework emphasizes real-time synchronization, anomaly detection, predictive maintenance, lifecycle management, and intelligent decision-making simultaneously.

The figure also highlights the potential benefits of the framework, including improved structural safety, optimized maintenance efficiency, data-driven management, and sustainable infrastructure operation. Therefore, the proposed framework provides a conceptual foundation for future implementation of intelligent and resilient structural monitoring systems in modern civil engineering practice.

4. Conclusion

This study developed a theoretical Digital Twin framework for Structural Health Monitoring (SHM) in smart buildings through a comprehensive literature review approach. The findings indicate that the integration of Digital Twin technology with Building Information Modeling (BIM), Internet of Things (IoT), artificial intelligence, cloud computing, and sensor systems has significant potential to improve real-time structural monitoring, predictive maintenance, and intelligent decision-making processes in modern buildings.

The proposed framework demonstrates how physical structures and digital systems can be interconnected through continuous data synchronization to support safer, more efficient, and sustainable infrastructure management. In addition, the framework highlights the importance of interoperability among advanced technologies in establishing an intelligent monitoring environment for smart buildings.

This study also identifies several challenges, including technological integration, data interoperability, implementation cost, and cybersecurity issues, which remain important considerations for future research and practical applications. Nevertheless, the proposed framework provides a conceptual foundation for the future development and implementation of Digital Twin-based SHM systems in civil engineering practice.

Therefore, Digital Twin technology is expected to play an important role in advancing smart infrastructure systems, improving structural resilience, and supporting sustainable building management in the era of Industry 4.0 and smart city development.

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