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Underutilized Potential: A Review of Digital Twin Implementation in Preconstruction

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Emerging technologies in the construction industry include Digital Twins (DTs), which are dynamic digital replicas of physical systems. While DTs are increasingly used in operations and maintenance, their application in preconstruction remains underutilized despite significant potential benefits such as design validation, risk mitigation, real-time estimating, change management, and sustainability assessments. This review synthesizes findings from peer-reviewed articles published between 2018 and 2025. Studies highlight the importance of early DT implementation, yet empirical evidence and standardized workflows for such integration are limited. Sensor cost modeling and lifecycle optimization are particularly underexplored, with very few frameworks providing economic assessments of DTs. Technological and organizational challenges persist, including data interoperability between BIM and DT systems, latency in sensor feedback loops, lack of standardized data and cybersecurity protocols, and cultural resistance to digital transformation. The review highlights the need for pilot projects to validate data, robust data-delivery systems, interoperability standards, and interdisciplinary collaboration to advance DT implementation in the preconstruction phase. Overall, this review underscores the importance of continued research to enable the adoption of Digital Twin technologies in early project phases.

Keywords: Digital Twins, Construction, Preconstruction, Construction Technology

Introduction

The construction industry is undergoing a digital transformation influenced by advanced technologies. One such technology, the Digital Twins (DTs), represents significant progress within the Architecture, Engineering, and Construction (AEC) industry towards integrating digital and physical systems. According to the National Academies of Sciences, Engineering, and Medicine (NASEM), a Digital Twin is a data-rich digital representation of a physical asset that is dynamically updated through bidirectional data exchange (2024). The core components of a DT include the physical asset (the building or system), the digital model, and the real-time data flow that connects the two. This real-time linking enables real-time monitoring, predictive analytics, and enhanced decision-making across the building's lifecycle to improve efficiency and accuracy (Shahzad et al., 2022).

DTs remain underexplored in preconstruction broadly because physical assets have not yet been deployed, limiting the real-time data integration. Additionally, fragmented workflows, uncertain design maturity, organizational separation between teams, high perceived cost of early sensor deployment, and data integration costs reduce industry adoption at this phase (Adu-Amankwa et al., 2023; Opoku et al., 2023). This is a missed opportunity, as early implementation of DTs in a project can improve design validation, risk mitigation, and sustainable decision-making (Kor et al., 2022; Meschini et al., 2022).

Preconstruction services, such as cost estimation, scheduling, risk, feasibility, and sustainability assessments, are essential to the success of the construction project (Menches et al., 2008). The adoption of Building Information Modeling (BIM) during preconstruction is a valuable tool for improving efficiency and mitigating risk (Nisa Lau et al., 2018). BIM integrates critical project information through its lifecycle, making it ideal for developing DT frameworks (Nguyen & Adhikari, 2023). Hence, early development and integration of DTs with BIM could improve accuracy and efficiency in resource planning, real-time design feedback, accurate cost predictions and optimization, minimize errors, and assess feasibility and sustainability before physical construction begins.

While several recent reviews have explored DT applications in construction, most of them focus on operations, maintenance, or smart building performance (Deng et al., 2021; Nguyen & Adhikari, 2023; Shahzad et al., 2022; Visartsakul & Damrianant, 2023). This literature review examines existing research on DTs, specifically in the preconstruction phase, highlighting frameworks for developing DTs using BIM and methodologies for quantifying and estimating costs associated with sensor installation and workflow readiness, rather than operational optimization. This preconstruction focus remains fragmented and underrepresented in previous studies. This paper also seeks to identify research gaps and potential future research on methods and frameworks for developing DTs during preconstruction. This literature review is limited to peer-reviewed studies published between 2018 and 2025 that specifically address the application and development of DTs in preconstruction. The rapidly evolving nature of digital technologies means that some recent developments may not yet be reflected in academic literature.

Research Design

This literature review employed a systematic methodology to identify, select, and analyze relevant scholarly works related to the development of DTs, particularly in preconstruction phases. Initially, databases such as Google Scholar and Web of Science were searched using combinations of keywords including ‘Digital Twins’, ‘DTs’, ‘Preconstruction’, ‘BIM’, and ‘Construction’. This search generated a large volume of results, which were narrowed down by selecting peer-reviewed journal articles or conference papers published between 2018 and 2025. This period was chosen to capture research published after DTs became recognized as a distinct concept from BIM, enabled by the advances in Internet of Things (IoT), cloud computing, and real-time analytics technologies that emerged since 2018 (Committee on Foundational Research Gaps and Future Directions for Digital Twins et al., 2024; Deng et al., 2021). In addition, the studies needed to address DT development or application within the preconstruction phase explicitly, and those that focused solely on post-construction operations were excluded. Non-English publications and non-peer-reviewed sources such as blogs, white papers, or editorials were also excluded from consideration.

Following this filtering process, 22 peer-reviewed articles were selected for in-depth analysis. The analysis used a qualitative thematic coding approach. While no specialized software was utilized, key themes and categories were manually coded and tabulated. Papers were categorized into themes such as BIM-DT integration, cost modeling, sustainability applications, framework development, and organizational or technological barriers. Patterns and relationships across these themes were mapped out through analysis of research trends and gaps. This approach provided a foundation for the findings of this review, enabling a critical evaluation of current frameworks and methodologies for DT implementation in preconstruction. Figure 1 shows that the methodology used a systematic approach to identify and analyze the relevant studies.

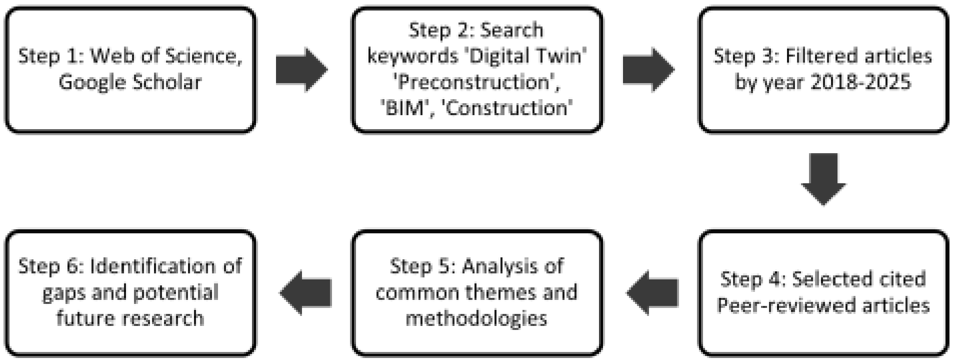

Figure 1. Literature Review Process

Results

The findings from the reviewed literature revealed distinct themes and common challenges in establishing DTs during preconstruction. These results are synthesized into areas that reflect the current direction and maturity of research in the field. Each theme is supported by conceptual models, frameworks, methodologies, or case studies that enhance our understanding of how DTs can be implemented in preconstruction stages. Table 1 summarizes the applications or methods and challenges in implementation identified in the 22 selected articles.

Table 1. Identified Applications and Challenges in the DT Implementation

No	Author Name & Year	Application or Method	Challenges in Implementation
1	Afzal et al. 2023	Systematic Review	Lack of standardization and emerging tech incorporation
2	Aktürk & Çakmak., 2024	BIM-DT integration survey-based	Complexity in sensor integration, data reliability
3	Alvarenga et al., 2024	Literature Review	Cultural resistance, cost barriers
4	Bortolin et al., 2024	Estimation framework of tech components	Lack of standardized costing metrics
5	Chen et al., 2024	DT for university campus	Integration complexity, data management
6	Deng et al., 2021	Systematic Literature Review	Data loss and interoperability between systems
7	Demiss & Elsaigh., 2024	Estimation prediction through IoT-enabled BIM	Real-time data feedback challenges
8	Jiang et al. 2022	Planning Scheduling and execution in precast assembly	Latency in the feedback loop
9	Kaewunruen et al., 2020	Sustainability Audit Case Study	Sensor maintenance, system integration

Table 1 (Continued). Identified Applications and Challenges in the DT Implementation

No	Author Name & Year	Application or Method	Challenges in Implementation
10	Kim et al., 2021	Conceptual framework	Resource scheduling complexity
11	Lin et al., 2025	DT-enabled safety monitoring system	Safety data capture in unstructured environments, privacy concerns
12	Naji et al., 2024	SEM tool measuring DT readiness	Organizational readiness, infrastructure gaps
13	Nguyen & Adhikari., 2023	Literature Review	Data interoperability and consistency
14	Pan & Zhang., 2021	DT framework for decision-making in project management	Data mining complexity
15	Shahzad et al., 2022	Literature Review	Cultural resistance, fragmented tools
16	Shim et al., 2025	DT for risk mitigation in bridge construction	Supply-chain data fragmentation, lack of interoperability across vendors
17	Tran et al., 2021	Quality assessment of prefabricated facade	Model automation has not been fully realized
18	Visartsakul & Damrianant., 2023	Literature Review	Conceptual ambiguity
19	Wang et al., 2024	Process Twin for schedule and allocation risk visualization	Integrating required with BIM and IoT, skill gaps in process analytics
20	Zhang et al., 2021	Literature Review	Data detail overload and manageability; LOD ambiguity
21	Zhang et al., 2025	DT framework for site monitoring and management	Limited monitoring scope
22	Zhao et al., 2022	Conceptual framework	Data integration from legacy systems

Application of Digital Twins in Preconstruction

The reviewed results of the 22 papers reveal six themes that are vital to DT development and implementation in preconstruction. Below are the identified themes in the order of recurrence.

Integration of BIM and DTs

Several authors have developed frameworks showcasing BIM as a foundational element for DT implementation. Some reviews explain that although BIM and simulation already provide strong visual representations, DTs extend those capabilities by connecting the BIM model to live data and feedback loops (Visartsakul & Damrianant, 2023). According to Nguyen and Adhikari (2023), BIM provides an effective and efficient pathway for DT integration through its potential for detailed modeling that supports simulation, prediction, and real-time monitoring. This integration is typically acquired through cloud-based BIM environments linked with Internet of Things (IoT) systems, enabling continuous data exchange (Alvarenga et al., 2024). Aktürk and Çakmak (2024) suggest that successful DT implementations depend largely on BIM functionalities, including model accuracy, data interoperability, and lifecycle integration capabilities. Their proposed DT-BIM integration framework emphasizes dynamic updates from real-time sensor data, enhancing construction project management through improved real-time monitoring and predictive accuracy.

Sensor and IoT Integration for DTs

Effective sensor integration is crucial to the operational success of DTs, providing essential real-time data for accurate representation and management (Alvarenga et al., 2024). The framework developed by Demiss and Elsaigh (2025) leverages real-time data and predictive analytics to adjust project budgets and reduce financial uncertainty dynamically. These sensor installations require a significant investment in DT projects. The economic burden increases with the complexity of sensor types that are necessary for monitoring temperature, humidity, occupancy, energy flow, and structural behavior (Bortolin et al., 2024).

Cost Optimization of DTs

Bortolin et al. (2024) proposed an extension to the UK New Rules of Measurement 2 (NRM2) to estimate DT technological components, covering data acquisition (sensors and tags), communications, data engineering, storage, security, and interoperability. This method separates hardware (prime costs, itemized) and software (time-related charges), mapping ISO 23247 capabilities to cost items during the preconstruction phase. This 'Preconstruction Bill of Quantities' that DT literature says is missing when projects try to "Add a Twin" later. It also pairs with the reviews that call for gradual (scoped) DT deployment and cost-aware design (Visartsakul & Damrianant, 2023).

BIM and Data Mining for Planning

DTs significantly enhance construction site management through improved project monitoring, safety, and operational efficiency. Real-time monitoring capabilities enabled by DTs allow project managers to identify and rectify problems swiftly, minimizing delays and reducing costs. Again, IoT sensors integrated with BIM frameworks provide continuous data flow, facilitating dynamic updates and real-time analytics. This also improves construction site safety by promptly identifying hazards, ensuring compliance with safety regulations, and enhancing overall site management efficiency (Aktürk & Irlayıcı Çakmak, 2024). Pan & Zhang (2021) present a BIM, IoT, and data mining loop that identifies process bottlenecks and predicts task completion. Although it is verified in a construction case, their main structure is preconstruction-applied because it stipulates that data objects, event logs, and identifiers must exist before site mobilization, so the twin can diagnose and forecast later.

Sustainability Assessments

Kaewunruen et al. (2020) found that a BIM-integrated DT simulation model, combined with IoT sensor data, effectively conducted vulnerability audits and lifecycle assessments (LCAs) to support structural improvements in the Dadongmen Subway station project. This demonstrates that DTs support energy-use optimization and enhance resilience. Thus, DT platforms become instrumental in achieving sustainable urban infrastructure by improving resource efficiency and reducing environmental impacts. Naji et al. (2024) used Structural Equation Modeling (SEM) to evaluate the potential of preconstruction practices for digital transformation, with a focus on sustainability and cost optimization.

Large-Scale Implementations of DTs

The versatility of DTs is highlighted by the model frameworks ranging from individual buildings to entire urban infrastructures, in contexts such as university campuses (Chen et al., 2024). This framework uses detailed BIM data layers to support asset lifecycle management, enabling real-time monitoring and management of asset categories, including structural elements, energy systems, and environmental conditions. This allows the stakeholders to manage complex operational demands and respond promptly to issues. For example, in campus management scenarios, DT models can support energy management initiatives, structural health monitoring, and safety protocols simultaneously.

Challenges in Implementing DTs in Preconstruction

Across the reviewed literature, numerous challenges are presented in implementing DT technologies during the preconstruction phase: technological and organizational. Firstly, achieving interoperability, especially between BIM platforms and DT environments, is difficult. While BIM serves as the foundation for data-rich modeling, many DT systems rely on different architectures, which can lead to integration difficulties. This disconnect creates data overload and limits the flow of information across the phases, diminishing real-time synchronization and collaborative planning opportunities between stakeholders (Nguyen & Adhikari, 2023; Pan & Zhang, 2021).

An important ongoing concern is data standardization. Without structured, standardized protocols for data formats, sensor outputs, and the layers between BIM and DT platforms, integration becomes inconsistent and prone to issues in interfacing among different stakeholders. Another challenge is data latency, which refers to delays in transmitting sensor data to the DT model for visualization and analysis. In preconstruction, where design modifications and sequencing decisions are often time-sensitive, these delays can reduce the predictive value of DTs (Demiss & Elsaigh, 2024). Sensor integration is further complicated by technical requirements such as calibration differences, power demands, and inconsistent protocols. Large datasets from a range of sensors to support real-time model updates add another layer of complexity (Alvarenga et al., 2024).

Organizational challenges are just as critical. Cultural resistance to digital transformation continues to hinder the adoption of DTs in preconstruction. In many firms, stakeholders are either unfamiliar with DT technologies or perceive them as too complex to implement. High initial costs - including both hardware and the human resources needed for data management and training- act as another major barrier (Bortolin et al., 2024; Committee on Foundational Research Gaps and Future Directions for Digital Twins et al., 2024; Shahzad et al., 2022). Moreover, cybersecurity risks and data privacy issues associated with continuous sensor feeds and cloud-based infrastructure create additional concerns for full-scale deployment.

Altogether, addressing these challenges will require not only technological advancement but also stronger policy frameworks, workforce training programs, and cross-sector collaboration to enforce practical standards for digital construction technologies.

Discussion

While the literature discusses the great potential of DT technologies to enhance preconstruction processes, several gaps have been consistently identified across the reviewed literature, reinforcing observations from national-level studies such as the NASEM report (2024). As shown in Table 2, unlike postconstruction DTs, which rely on real-time sensor feedback from physical assets, preconstruction DTs are predictive and scenario-driven, focusing on design alternatives, cost forecasting, and risk mitigation under uncertainty.

Table 2. Differences in Preconstruction and Post-Construction DTs

Application of DT	Key Characteristics	Data Certainty
Preconstruction DT	Scenario-based, Predictive, Decision-Support	Uncertain since the physical asset is not yet integrated
Post construction DT	Performance Monitoring and Optimization	Certain because a physical asset is integrated in real-time (Here, the uncertain data from technological issues is not considered)

Although machine learning is increasingly used, the requirements for continuous verification, validation, and uncertainty quantification (VVUQ) of DTs remain incomplete due to a lack of standards and confidence in modeling outputs (NASEM 2024). Preconstruction teams must prioritize model quality, fidelity, and change management to trust the modeling outputs for subsequent applications. This can be potentially enabled through standardized workflows in creating a high-quality, LOD-defined base BIM model for DTs. Structured and validated workflows should be identified and adopted in the model authoring phase to benefit from standardized, high-quality, consistent BIM model data. This can also reduce data interoperability issues between different software and stakeholders (designers, engineers, estimators, schedulers, facility managers, etc.) and add downstream value in the establishment of DTs. For example, workflows such as the Integrated Estimating Workflow Framework have specific model authoring characteristics that address deficiencies in model quality and consistency necessary for BIM integration (Pilgrim & Valdes-Vasquez, 2025)

There is an urgent need for more stringent standards to guide the BIM–DT integration. The lack of research studying data interoperability between BIM and DT platforms has made it challenging to streamline the data. Second, there remains a gap in the evidence base for BIM-DT integration at the preconstruction stage. Many of the reviewed papers reference conceptual frameworks or retrospective case studies, but few offer empirical validation of how early DT implementation influences the project outcomes. The NASEM 2024 report reiterates this concern, calling for pilot programs and evaluations of DT implementations in the construction industry.

Despite increasing interest in the cost estimation of DTs, there is limited research quantifying the process of implementing DTs, particularly the costs of deploying and optimizing IoT sensors and related infrastructure. Although studies such as those by Bortolin et al. (2024) have begun to explore cost modeling, the data collection is insufficient. These gaps hinder the development of return-on-investment models that are crucial for convincing industry stakeholders to adopt DT technologies in their projects.

Conclusion

As the construction industry moves toward digital transformation, a robust understanding of DTs in preconstruction presents a powerful tool to improve project outcomes through enhanced design coordination, risk mitigation, and cost forecasting. Yet such developments remain underutilized in industry practice. This review highlights the significance of addressing the challenges in planning for DT implementation in preconstruction.

Although it is widely accepted that the BIM model provides the foundational data environment for DT frameworks to leverage sensor data, low trust in model quality and consistency puts this integration at risk. The need for structured workflows for BIM modelling can enable subsequent uses, including DT integration. Cost estimation of the DTs needs more verifiable research across different building types, Levels of Development (LODs), and construction phases. Another important research direction is to develop and evaluate DT performance across different scales, from small facilities to innovative city environments. Finally, research on the regulations of data collection through DTs is essential to ensure the security of these data streams against breaches and inaccuracies.

Addressing these gaps and overcoming the challenges in implementing DTs promises innovative advances in construction management, sustainability, and urban planning. Continued research and collaboration across academia and industry are essential for realizing the full potential of Digital Twins in the construction industry.

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