Harnessing Digital Twins for Construction Site Management

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Abstract

Digital Twins (DTs) is transforming construction by providing real-time, data-informed solutions that improve project workflows and can aid in achieving decarbonization objectives. In construction, DT was mainly implemented in the operation & maintenance phase. However, by combining DT's functionalities of real-time monitoring, predictive analytics, sophisticated simulations, and collaborative decision-making, construction site management can be revolutionized by enabling site managers and stakeholders to refine construction processes, enhance resource use, lower emissions, boost quality, and reduce expenses. These features tackle essential issues like operational inefficiencies, resource depletion, and communication failures, providing a more integrated and sustainable method for managing construction site activities.

This study uses a Systematics literature review (SLR) to thoroughly examine the function of DTs for onsite construction management, emphasizing their application in managing safety, logistics and material, emissions and energy, quality assurance and detection, real-time decision support, dust, noise, and vibration monitoring, digital collaboration and issue resolution, and real-time worker productivity tracking. Conversely, DTs can facilitate accurate monitoring of carbon emissions and encourage eco-friendly construction methods by integrating technologies such as Internet of Things sensors, cloud computing, and artificial intelligence. Furthermore, DT-driven workflows, including prefabrication and modular building, promote waste reduction and energy conservation, harmonizing onsite activities with net-zero carbon objectives. This research highlights the crucial functions of DTs in optimizing onsite construction workflows, showing their ability to transform the industry and aid in moving towards a more sustainable and decarbonized built environment.

Keywords – Digital-Twins, Decarbonization, Construction Site Management, Construction Planning

1 Introduction

The construction industry is at a pivotal juncture, facing persistent challenges such as inefficiencies, cost overruns, schedule delays, and the need to meet stricter sustainability standards [1]. Despite advances in project management tools and building techniques, construction companies continue to seek new technologies to enhance productivity, achieve sustainability goals, and improve customer satisfaction in an increasingly competitive and complex market [2]. Emerging technologies, particularly DTs, have garnered significant attention as a potential solution to these challenges due to their ability to provide real-time insights and predictive capabilities [3].

DTs present a breakthrough by creating dynamic virtual models of physical construction systems that integrate real-time data, predictive analytics, and advanced simulations. These virtual replicas imitate onsite conditions and processes, enabling stakeholders to monitor material conditions, track equipment performance, and visualize workflows in real time, fostering proactive decision-making and improved quality control [4]. The ability of DTs to merge the physical and virtual environments through data centralization significantly improves communication across stakeholders and reduces errors, aligning construction projects with sustainability and environmental standards [5].

One of the key contributions of DTs is their ability to support sustainability efforts by enabling real-time monitoring of emissions, energy consumption, and waste generation on construction sites. By integrating Internet of Things (IoT) sensors with cloud-based platforms, DTs provide comprehensive feedback loops that ensure construction activities remain aligned with sustainability targets [7, 8]. Moreover, the optimization capabilities of DTs allow teams to simulate and refine workflows before implementation, which is particularly valuable in complex projects where early identification of inefficiencies can save significant time and resources [8]. For instance, DT-enabled simulations of crane operations can help predict potential conflicts in crowded sites, allowing site managers to redesign workflows to prevent delays and accidents [9].

However, despite these promising capabilities, key research gaps remain. There is limited empirical evidence demonstrating the impact of DT-enabled onsite workflows on decarbonization and operational efficiency. Additionally, the industry lacks standardized methodologies for implementing DTs in onsite construction, as well as case studies that illustrate best practices across various project types and regions. Addressing these gaps is essential for validating the role of DTs in transforming onsite construction.

To bridge this gap and improve the understanding of the potential of DTs for construction site management, this paper examines in detail the critical role of the four DTs' key functions (i.e., real-time monitoring, predictive analytics, simulation, and collaborative decision-making) in managing construction sites by optimizing schedules and enhancing safety. Depending on project site needs, site managers can integrate these functions to create various onsite applications, optimizing efficiency and decision-making [10]. Building on this concept, this study analyzes eight specific applications fundamental for efficient construction site management that result from these functions' combinations: 1) safety management, 2) logistics and material management, 3) emissions and energy management, 4) quality assurance and defect detection, 5) real-time decision support, 6) dust noise and vibration monitoring, 7) digital collaboration and issue resolution, 8) real-time worker productivity tracking.

By examining these four core functions and their eight applications (detailed in Section 3), this paper highlights how DTs can increase efficiency, reduce costs, time, and complexity, improve onsite construction workflows, address persistent industry challenges, and contribute to sustainable project outcomes, particularly in supporting decarbonization efforts.

2 Methodology

2.1 Systematic Literature Review Approach

This study adopts a systematic review methodology guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, replicability, and comprehensiveness [11]. The PRISMA methodology was employed to identify, screen, and select relevant academic literature on DTs applications for on-site construction. The review focused on identifying peer-reviewed articles (i.e., peer-reviewed conferences and journals) that provide insights into DTs functionalities such as real-time monitoring, predictive maintenance, workflow optimization, and collaborative decision-making, as adopted from [10].

The systematic search for this study was conducted using two major academic/research databases, Web of Science and Google Scholar, for their extensive coverage of broad search capabilities and coverage of emerging research trends [12, 13]. To capture a comprehensive range of studies, we carefully chose search word strings. These search strings utilized Boolean operators and keywords aligned with the study's focus on DTs for on-site construction; the strings are as follows: "Digital Twins" And "Construction Quality" Or "Real-Time Monitoring" Or "Predictive Maintenance" Or "Digital Twins" And "Construction" And "Simulation" And "Optimization" Or "Digital Twins" And "Workflow" Or "Digital Twins" And "Stakeholder Collaboration" And "Construction" Or "Construction Quality" Or "Digital Twins Applications" And "Sustainability" Or "Digital Twins" And "Construction" And "IoT Sensors" Or "Digital Twins" And "Construction Safety" Or "Defect Detection" Or "Digital Twins" And "Construction" Or "Material Management" Or "Digital Twins" And "On-Site Construction" Or "Digital Twins Framework" And "Construction Project Management."

These search strings were continuously refined based on the relevance and quality of the initial search results, ensuring a comprehensive and accurate representation of the topic. In addition to the search strings, multiple filters and inclusion/exclusion criteria, as presented in Table 1, were applied to ensure that only relevant papers were considered for a more comprehensive review.

Table 1. Inclusion criteria of the research.

Criteria	Inclusion Criteria
Publication Type	Peer-reviewed journal and conference papers.
Language	Papers published in English.
Timeframe	Studies that were published between 2018 and 2024.

The initial search resulted in 80 peer-reviewed articles extracted from Google Scholar and Web of Science databases. After applying the filters based on the inclusion/exclusion criteria and reviewing the full text to ensure that the extracted studies align with the research objective, 50 journals were considered for in-depth analysis. Figure 1 below outlines the study selection process, showing the breakdown of how many papers were extracted from each database and how they were filtered based on the inclusion/exclusion criteria.

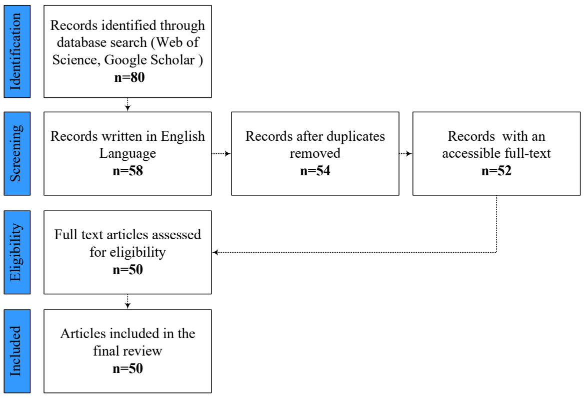

Figure 1. PRISMA Flow Diagram

2.2 Data Extraction and Synthesis

The 50 selected articles were then reviewed carefully, and key points and findings were extracted. The analysis focused on the contributions of DTs for on-site construction, and data was then categorized based on the following areas:

1. General Key Functions.
2. Specific applications.

This methodology provides a detailed account of the systematic review process used, adhering to the PRISMA framework, and highlights the search strings and criteria that were adopted.

3 Digital Twins Functionalities and Applications for Construction Site Management

The findings extracted from the reviewed articles were divided into two sections: the first section consists of the general key functions of DTs. In contrast, the second section consists of the on-site construction applications of DTs. The general key functionalities section goes over how each function works and how they can be applied. In contrast, the application section discusses in detail how when the functions are combined simultaneously, they can influence and improve the on-site construction processes and workflows, affecting the overall quality, efficiency, decarbonization, and sustainability goals.

3.1 General Key Functions of Digital Twins in Construction

3.1.1 Real-Time Monitoring and Feedback

Real-time monitoring is foundational to DTs, providing continuous visibility and insight into the on-site processes. Through IoT sensors and cloud-based platforms, DTs enable real-time tracking of material conditions, structural integrity, and equipment performance, such as cranes [9]. By monitoring performances, management can keep track of CO_2 emissions, keep track of idle time and fuel consumption for machinery, make instant decisions based on real-time data, or backup decisions that might be contradictory, such as switching to electric-powered equipment [14]. Real-time monitoring is essential in every application under the DT umbrella. By using real-time monitoring and feedback, the engineers and site teams can have insights and information from the virtual realm [15]. This empowers the site team to conduct modifications based on informative insights extracted from real-time data without wasting time, effort, money, and human resources, which brings projects closer to sustainability and environmental goals.

3.1.2 Predictive Analytics

Predictive analytics leverage DTs analytics to predict equipment failures, structural degradation, material shortages, and logistic needs. By using AI, DT can analyze historical and real-time data to identify patterns and anomalies that can indicate potential risks and failures, allowing for timely interventions [16]. For instance, vibration data from cranes monitored by DTs can detect stress or wear-and-tear, enabling teams to schedule maintenance before failures occur, extending the lifecycle of equipment, thus reducing the need for replacements and minimizing the environmental impact of manufacturing and transport [7, 17]. This information reflects on the current production flows and is essential for planning and control systems [18]. Currently, there is an underutilization of data, and this allows for missed opportunities to enhance maintenance efficiency and strategy, improving safety, and reducing costs. [19].

By optimizing equipment ‘health,’ machinery will operate more efficiently, consume less fuel, and emit fewer greenhouse gases. Through predictive analytics, DTs aids in improving on-site construction efficiency, reducing construction-related risks, and ensuring the overall quality of the project [20].

3.1.3 Simulation and Optimization

Simulations powered by DTs are invaluable for optimizing on-site construction workflows and validating designs before implementation. Performance simulation is the domain that duplicates and forecasts multiple aspects of construction by applying fundamental physical concepts and engineering methodologies to a computer-based mathematical model [21]. DTs allow teams to test alternative scenarios, identify inefficiencies, and optimize resource allocation. For instance, simulating crane movements on congested construction sites can help identify conflicts, optimize arrangements, enhance operational efficiency while minimizing risks, and reduce delays, as poor scheduling and planning often contribute to budget overruns in construction projects [9].

Simulation tools also drive decarbonization by enabling construction teams to assess the environmental impact of materials and methods before execution. For instance, DTs can simulate workflows and identify opportunities to minimize energy consumption, such as scheduling heavy equipment usage during off-peak energy hours to leverage cleaner electricity.

3.1.4 Collaborative Decision-Making

Collaboration is central to successful construction projects, and DTs facilitate this by providing a unified platform for data sharing and analysis. Cloud-enabled DT systems can accomplish near-real-time data exchange between a digital replica and the physical environment, which can help designers make management site execution decisions. [22].

In the context of decarbonization, collaborative platforms supported by DTs simulate built environmental changes and assist in decision-making for environmental optimization through platforms, thus reducing the need to visit the site and delaying actions [23].

3.2 Applications for Digital Twins in On-Site Construction

In addition to the general key functions, DTs enables a range of applications in site construction by integrating multiple functionalities simultaneously. Rather than requiring multiple DTs, a single DT equipped with the necessary IoT sensors *(depending on the case and need)* can support eight key applications.

While not exhaustive, these applications represent essential site operations, demonstrating how four fundamental DT functions can drive efficiency, optimization, and sustainability for on-site construction management. By leveraging DTs technology, construction projects can enhance operational workflows while contributing to decarbonization efforts. This section examines eight critical applications where DTs play a transformative role in modern site operations in construction.

3.2.1 Safety Management

Safety management is a top priority in construction, and DTs enhance this by integrating IoT-enabled wearables and real-time monitoring systems. DTs can track worker locations, proximity to hazards, and adherence to safety protocols, preventing accidents and improving compliance [24]. As demonstrated by [25], site management can use drones to monitor potential hazards, allowing them to prevent incidents from occurring. Furthermore, by utilizing real-time analysis, DTs enables site teams in their preparedness to respond to possible accidents [26] properly. This allows the site to not only be prepared in case of emergencies but possibly prevent them altogether.

3.2.2 Logistics and Material Management

DTs streamline material tracking to ensure that resources are utilized efficiently and minimize waste. By monitoring material inventories and deliveries in real-time, DTs enable precise ordering schedules and prevent overstocking or spoilage [27]. Various technologies are adopted into DTs to be able to track materials and stay on top of logistics, such as Radio-Frequency Identification (RFID), which detects items, materials, or targets by utilizing radio frequencies for data processing [28] or Blockchain, which allows for traceability throughout chain activities that are fragmented or isolated [29]. While tracking is fundamental in material management and logistics, other important aspects result from it, such as recycling and waste reduction.

By tracking materials and always knowing the leftovers present on-site from deliveries, excavations, or demolitions, recycling and waste reduction become critical, easier, and needed for better sustainability and environmental metrics [30]. By tracking these activities, DTs can help identify the sources of high embodied carbon emissions (ECE) emissions that are present in materials and products in construction and buildings [31] in real-time [28]. It also includes the activities used to transform these materials for buildings [32]. Through this DTs application, a site can keep track of its material handling and quantity management, resulting in a better ability to manage recycling, reusing, and waste management.

3.2.3 Emissions and Energy Management

As of 2021, carbon emissions are currently on a global rise, with buildings making up to 37% of carbon emissions and 34% of energy consumption, with the construction industry (concrete, steel, and aluminum) occupying 4% and 9%, respectively [33]. These numbers are estimated to rise as the number of floor areas is estimated to rise by 75% between 2020 and 2050, of which 80% will be in developing economies, which is equivalent to the floor area of Paris being constructed every week till 2050 [34].

With the use of DT, reducing energy consumption and carbon emissions has become easier. DTs can calculate shadow areas, allowing project managers to use renewable energy resources (RES) and hybrid systems better and monitor and simulate energy expenditure, thus contributing to reducing the site's dependency on fossil fuels and furthering the decarbonization agenda [35].

Furthermore, DTs can provide transformative solutions by utilizing real-time data, predictive analytics, and sensors such as smart meters to reduce emissions and energy usage and identify areas that require improvement [43, 44]. This helps site management know if something is left operating by mistake, ensure no consumption occurs when not needed, and keep a better eye on energy expenditure.

3.2.4 Quality Assurance and Defect Detection

For quality assurance and defect detection, DTs can delve into details that are not purely construction-based and are often carried out on-site. For instance, DTs can be applied to the welding of large excavation motor arms [38]. Also, DTs can be used to form a model that can adapt to a variety of situations to monitor the quality of spot welding (i.e., structural steel welding) to achieve dynamic control over welding quality and ensure product stability [39].

Early defect detection reduces the material and energy demands associated with rework. By preventing this waste, DTs can directly contribute to lower emissions and resource conservation. By utilizing predictive analytics and real-time feedback, DTs provide the ability to predict the condition of machines and prevent unplanned halts in work. In some cases, such as diesel-operated motors, it can lead to a reduction in air pollutants produced by ill-maintained diesel engines.

3.2.5 Real-Time Decision Support

Decision-making has been revolutionized for on-site applications by DTs. By integrating IoT devices and sensors, DTs allow for a dynamic decision-making environment. By using up-to-date real-time deviations, DTs enhance planning and scheduling and optimize modular construction processes while ensuring seamless integration and minimizing disruption in cases like precast concrete assembly [40]. As mentioned previously in Section 3.2.2, DTs improve material management by providing visibility and traceability of resources [41]. This feature allows site managers to anticipate and resolve material shortages and enable predictive decision-making to forecast risks and bottlenecks to ensure uninterrupted progress [42]. Also, as discussed in section 3.2.4, when DTs provides a prompt to perform maintenance preemptively, it can provide advice on when to perform it and ensure that the site management is well-informed to understand the implications better and take a well-informed approach.

Furthermore, DTs also support the reduction of the carbon footprint by optimizing resource use, reducing waste through real-time decision-making, and performing energy consumption planning to adjust energy use [43].

3.2.6 Dust, Noise, and Vibration Monitoring

Dust, noise, and environmental monitoring are becoming increasingly important. With DTs, site managers can monitor these factors continuously to improve the management of environmental risks. This data helps mitigate health hazards associated with dust exposure, implement noise-reduction strategies, and offer comprehensive monitoring solutions for construction operations to reduce vibrations [44].

In a case study conducted by the authors of [1], DT models were able to control tunnel dust levels, ensure safe working conditions, and adhere to environmental guidelines. These applications underscore DTs' potential in reducing and possibly in the future eliminating environmental impacts and ensuring regulatory compliance with green metrics [37].

3.2.7 Digital Collaboration and Issue Resolution

In construction projects, conflicts often occur. This might be due to miscommunication, design discrepancies, scheduling clashes, or multiple other reasons. Multiple approaches can be used to reduce such conflicts. The authors of [45] showed how DTs could create a shared platform for all stakeholders to access real-time data, reduce misunderstandings, and accelerate the decision-making process, while [46] integrated data mining with building information modelling (BIM) in a DTs platform to enhance project management, and allow for swift changes in the schedule by detecting conflicts and inconsistencies. Similarly, the authors of [47] noted that DTs can foster collaboration between practitioners, stakeholders, and authorities by providing a unified interface for problem-solving and discussions. When such platforms are applied, conflict resolution significantly improves through the decision-making capabilities of DTs by creating an accountable record of decisions and changes [48]. By reducing conflicts, rework also decreases significantly, reduces construction time, and improves construction/project management. This implies that DTs not only improve project outcomes but also significantly contribute to the industry's social and environmental goals [43].

3.2.8 Real-Time Worker Productivity Tracking

DTs are reshaping worker productivity tracking. The authors of [40] highlighted how the use of synchronized DTs for managing workflows in construction ensures worker productivity aligns with project milestones.

DTs can identify worker output inefficiencies by using a cyber-physical system, which allows them to provide actionable insights to improve workforce performance [49].

While some approaches focus on human productivity monitoring, other approaches focus on increasing human productivity via human-robot collaboration to optimize both human and machine productivity [50]. Productivity doesn't always decrease due to uncontrollable events. They might be caused due to fatigue or health issues. To avoid such issues, the authors of [51] discussed how wearable devices can monitor laborers' health and avoid problems that might arise due to such issues.

By offering real-time insights, DTs empower construction managers and superintendents to monitor and improve worker productivity dynamically without sacrificing health, cost, and quality.

4 Results & Conclusion

This study highlights the potential of DT technology in on-site construction, demonstrating how it integrates real-time monitoring and feedback, predictive maintenance, simulation and optimization, and collaborative decision-making to enhance site management, efficiency, and decarbonization efforts. By applying these four key functions using the eight applications discussed in section 3, DT can address safety concerns and maintenance issues, monitor and track workers & worker productivity, enhance decision-making & collaboration, increase quality of work and reduce the effort needed for recycling and material management.

The findings illustrate that DTs play a crucial role in ensuring that site management has a proper hold on what is going on on-site. With DTs receiving real-time feedback, tracking inventory, prompting action when an incident might occur, and tracking workers, site management will be able to manage better and relay progress to the higher-ups, increasing collaboration efficiency and critical decision-making.

Beyond efficiency gains, DTs significantly contribute to sustainability and decarbonization. By minimizing rework, reducing waste, preventing equipment failure, reducing fossil fuel dependency, and optimizing energy consumption, DTs help construction projects lower carbon emissions and overall environmental impact. Their ability to monitor pollutants, track emissions, and support recycling & material reuse efforts further strengthens their role in site decarbonization initiatives. Figure 2 below illustrates how the four functions are applied to support each of the eight identified specific applications, ultimately contributing to decarbonization efforts in on-site construction.

In essence, DTs represent a major advancement in modern site operations, offering a scalable, data-driven solution to enhance overall productivity. As the industry continues to embrace digitalization and sustainability, DTs will be critical in driving innovation, improving resilience, and shaping a more efficient, collaborative, and eco-friendly built environment. Future research should focus on standardized DTs frameworks to allow for one DT to perform seamlessly between projects and improve interoperability further to enhance automation and predictive capabilities in site construction.

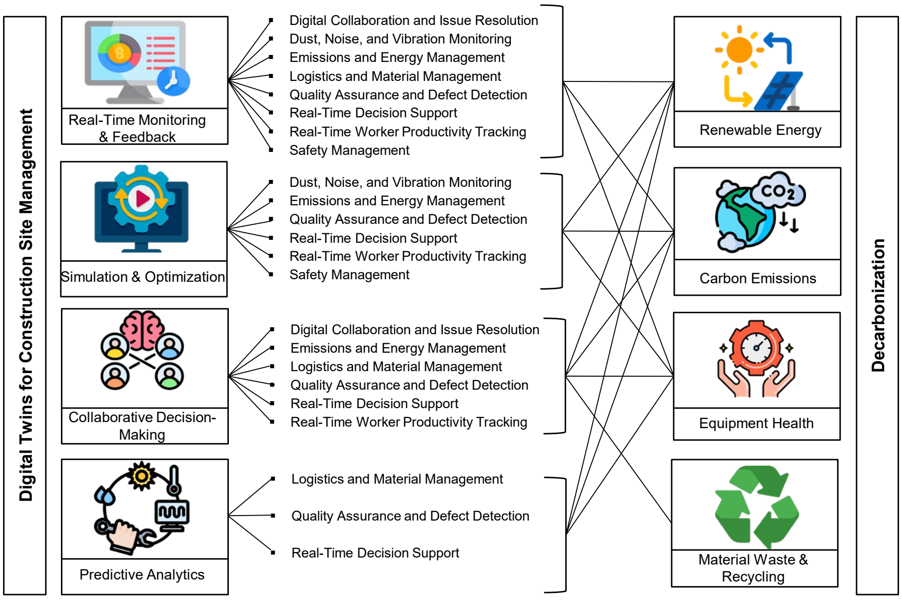

Figure 2. Digital Twins functionalities and applications for construction site management in supporting decarbonization

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