

INTEGRATION OF DIGITAL TWIN TECHNOLOGY FOR ENHANCING SUSTAINABILITY IN BUILDING LIFECYCLE: A SYSTEMATIC REVIEW

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ABSTRACT: A Digital Twin (DT) can be defined as a virtual replica of a physical entity that imitates the state of its physical counterpart in real-time. It consumes real-time data from a physical entity, such as performance metrics, and links the two entities for synchronization and feedback between the digital and physical worlds, which adapt throughout the physical entity's lifecycle. DT can be used for various applications, including real-time monitoring, predictive maintenance, and optimization of processes in various areas. Sustainable construction is a prominent area that has recently drawn a significant research interest in DT. Since there is a lack of systematic reviews on this consideration, the present study aims to explore the recent efforts to utilize the DT concept in sustainable construction. Within the broad area of the construction industry, this study primarily focuses on each phase of the building lifecycle where DT can be adopted to enhance sustainable performances. A systematic literature review was conducted to identify the latest scholarly publications on the Digital Twin concept and its potential applications across each phase of the building lifecycle to improve sustainability. The findings of the study mainly reveal that the DT technology is emerging as a powerful tool to improve sustainability performances throughout a building's lifecycle. However, a limitation was identified in research literature and case studies related to integrating DT technology to improve sustainability in the demolition phase. One of the main contributions of DT to sustainable construction is enabling real-time monitoring and analysis at each phase of the building lifecycle. This allows for optimizing energy and resource consumption, which leads to reducing carbon emissions in each phase. Predictive maintenance, enhanced collaboration among stakeholders, efficient management of manpower, machinery and equipment are the other key areas where DT has contributed to sustainability throughout a building's lifecycle.

Keywords: building lifecycle, construction industry, digital twin, sustainability, sustainable construction

1. INTRODUCTION

With the emergence of Industry 4.0, Digital Twin (DT) has become a crucial technology, offering numerous advantages throughout the product's lifecycle (Sun et al., 2024). Moreover, DT plays a pivotal role in shaping the industry 5.0 by supporting its three main pillars identified as human-centric, sustainable, and resilient industry transformation (Barata & Kayser, 2024). Due to the rapid development of the construction industry and the drastic increase in the need for the digitalization, is a considerable potential to integrate DT into the industry (Jiang et al., 2021). DT technology consists of three components: a physical entity, a digital replica of that physical entity and the connections of data and information between that physical entity and the digital model (Jones et al., 2020). With these three components, DT allows real-time surveillance, mapping and data evaluation, followed by the decision making, in the construction industry (Kamari & Ham, 2022).

Sustainable practices ensure a viable future for the construction industry by balancing the environmental, social and economic considerations. There is a high capacity to enhance sustainability in the construction industry by adapting DT into sustainable construction practices (Zhang et al., 2024). A study by Kaewunruen et al. (2020) revealed that by adopting DT, stakeholders can identify issues and execute strategies to improve sustainable performances throughout a project's lifecycle in the construction industry. A comprehensive review of the applications of DT technology across the different phases of a project's lifecycle to enhance sustainable performances is lacking in the construction industry. Therefore, this study aims to address this gap by developing a systematic review on integrating DT technology to improve sustainability throughout the building lifecycle.

2. METHODOLOGY

A systematic literature review was employed to address the research question: What are the applications of Digital Twin (DT) technology in addressing sustainability challenges across various

stages of the building lifecycle?” This research question was framed within the scope considered for the present study. With the aim of enhancing the sustainability of the construction industry, the above research question was developed to include basic concepts, theories, recent developments, and trends in DT technology integration in the building construction industry. A combination of key terms, Digital Twin, Building Construction Industry, Sustainable Construction, Building Lifecycle and Sustainability, was used to develop a search query to obtain the relevant research articles related to the above research question. A detailed representation of the methodology followed for the systematic literature review is shown in Fig. 1.

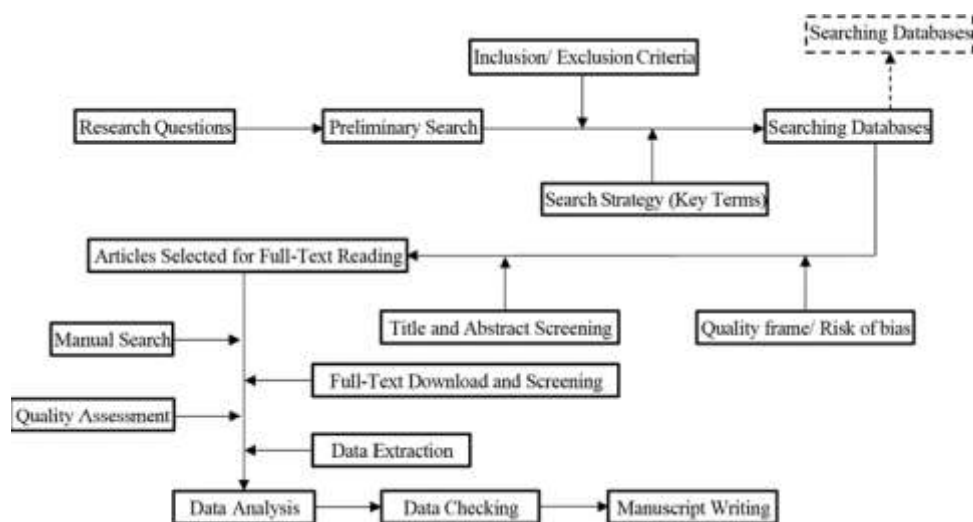


Fig. 1. Steps Followed for the Systematic Literature Review

Research articles published in journals, conferences, and book chapters on DT technology and its application in the sustainable construction industry were considered as inclusion criteria. Additionally, only articles published within the last five years and available in Science Direct, Scopus and Web of Science were included. A total of 55 research articles were ultimately analysed for this systematic literature review. There, various criteria were utilized to select the appropriate articles under the “Title and Abstract Screening” and “Full Text Download and Screening” steps.

3. RESULTS AND DISCUSSION

This section presents the main findings of the systematic literature review. The key applications of DT technology across the four main phases of the building lifecycle, aimed at enhancing sustainability performances are presented in the following four sub sections.

3.1 Planning and Design

Analysing and forecasting energy consumption to optimize it is one of the key methods by which DT can be utilized during the planning and design stage to improve sustainability (Bocullo et al., 2023). For instances, a DT model can be developed to demonstrate the solar chimneys integration and predict the impact of double layer façade systems on energy storage (Tariq et al., 2022). Both examples highlight the considerable operational cost reductions compared to repetitive physical models. By integrating DT, rework costs can be reduced, allowing designers to use acquired data for future endeavours (Singh et al., 2022). Furthermore, the DT technology has been adapted to optimize material utilization by developing and analysing a model in a virtual space (Su et al., 2023). Moreover, DT can be incorporated into sustainable assessment in this phase by evaluating user centered sustainability criteria and executing analyzing (Tagliabue et al., 2021).

3.2 Construction Phase

Integrating DT during the construction phase is crucial due to high resource and energy consumption. DT enables virtual mapping and real-time monitoring of construction sites, supporting detailed analysis to optimize the energy and resources consumption (Su et al., 2023). By collaborating with Light Detection and Ranging technology DT technology has been adopted to minimize material wastage (Mêda et al., 2023). Moreover, the DT technology can be used to enhance the sustainability of the material production by reducing carbon emissions (Metallidou et al., 2022). Additionally, other advanced technologies like 3D printing can be incorporated with the DT technology to enhance material performance and overall construction sustainability (Wang et al., 2023).

3.3 Operation and Maintenance Phase

DT technology has been predominantly integrated into this phase through real-time management systems for electrical equipment, enhancing sustainability by optimizing energy consumption and minimizing the carbon emissions (Mohseni et al., 2023). Artificial intelligence combined with DT predicts the energy demand and enhances the efficiency of the systems like HVAC by addressing individual thermal preferences of occupants (Clausen et al., 2021). With the integration of Building Information Modelling (BIM) technology, DT can be utilized to enhance the energy efficiency of indoor lighting (Tan et al., 2022). Smart maintenance and automated inspection mechanisms such as detecting structural cracks have been adopted with DT technology, enabling autonomous maintenance mechanism that reduce energy and resource consumption while mitigating unnecessary maintenance costs (Loverdos & Sarhosis, 2023).

3.4 Demolition and Recovery Phase

While studies on DT technology in the demolition phase are limited, DT can be utilized to develop a real-time model to track the location and working condition of staff vehicles, machinery, and equipment, minimizing resource and energy consumption (Omran et al., 2023). Circular Economy can be incorporated with DT technology in the construction industry to overcome challenges in demolition phases such as optimize waste generation and disposal (Meng et al., 2023). The Monte Carlo simulation was utilized by (Züst et al., 2021) with DT technology to highlight an effective method of managing the demolition material. Additionally, (Zheng et al., 2022) has used DT technology to investigate a method to avoid accidents during the demolition phase, thereby reducing the casualties and improving the social comfortability during this phase.

4. CONCLUSION

The present systematic review underscores the significance of DT in enhancing the sustainability of the throughout the building lifecycle. The DT concept has been utilized in various ways throughout each phase of building lifecycle, often in combination with the latest technologies such as IoT, Artificial Intelligence and Machine Learning. Optimizing energy consumption is the prominent sustainability factor that DT successfully integrates into each phase. Additionally, DT technology has been adopted to achieve efficient material and resource consumption and reduce carbon emissions in planning and design, construction, operational and maintenance phases. However, limited research and case-studies were found related to DT application for sustainable practices in the demolition, despite the potential benefits for material recovery and risk mitigation. Therefore, as a future recommendation, it would be beneficial to focus on applying DT in demolition phases as it plays a crucial role in maintaining sustainability. Further empirical studies and quantitative data are needed to validate the findings of the present review and fully explore DT's potential to enhance sustainability throughout the building lifecycle.

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