

BUILDING INFORMATION MODELLING-BASED DIGITAL TWIN APPLICATIONS IN CONSTRUCTION SAFETY MANAGEMENT: A REVIEW

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In the last decade, digital technologies have led to an industrial transformation that has sparked research attention. The architecture, engineering, and construction (AEC) industry has widely used building information modelling (BIM) and digital twin (DT), particularly in the context of construction safety management. This paper aimed to conduct a science mapping review of BIM-based DT applications to identify current hot topics and future research directions in this domain. In total, 85 relevant articles from the Scopus database were screened and analysed using a bibliometric and science mapping approach. The results show that the prominent research keywords in the literature on BIM-based DT focused on BIM, DT, and the Internet of Things (IoT). Moreover, the current hot topics include advanced technologies, asset management, facility management, and operation and maintenance. Furthermore, a framework for future research directions was presented to offer novel and practical insights to researchers and practitioners. Overall, these findings not only provide current hot topics of BIM-based DT applications in construction safety but also contribute to extending the research agenda towards Construction 4.0.

Keywords: Building Information Modelling; digital twins; safety management; science mapping review

INTRODUCTION

Globally, it is well-established that the construction industry is one of the most highly fatal and dynamic sectors (Anwer *et al.*, 2021). For example, in 2020, fatal workplace injuries in construction accounted for 13.5 per 100,000 full-time employees (Bureau of Labor Statistics, 2020). Moreover, improper worker operation, lack of safety awareness, and poor enforcement of building safety regulations would have an impact on construction safety (Zhang and Hu, 2011). Advanced digital technologies like building information modeling (BIM) can accurately analyze dynamic construction

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processes and operations. Compared to traditional methods, BIM has the advantage of creating several models such as energy, sustainability, and schedules (Liu, 2022). In addition, BIM can enhance holistic and extensible semantic approaches like site monitoring, and environmental aspects (Jupp, 2017).

Diverse fields have demonstrated the applications of digital twin (DT) technology. Shao and Wang (2022) conducted a DT-based approach for clearance inspection and redesign of limited culvert roads to ensure safe transport and personnel through underground roads. Blomfors *et al.*, (2021) also used DT to assess post-crack structures, ensuring the security and maintainability of infrastructure. Liu *et al.*, (2020) suggested that DT can be integrated with several digital technologies like the Internet of Things (IoT), blockchain, and machine learning (ML). Given the digital representation of BIM and DT, they can both enhance effective information exchange, sharing, and storage (Zhang *et al.*, 2022). Baghalzadeh Shishehgarkhaneh *et al.*, (2022) developed a BIM and DT integration framework to facilitate the collection of technical data for construction projects. Jiang and Jiang (2022) implemented BIM and DT to autonomously monitor multiple layers of data operation. Levine and Spencer (2022) combined DT and BIM-guided 3D variation to detect structural damage and predict a capacity reduction in earthquake-damaged buildings.

Several studies have applied BIM and DT technologies in project management and construction health and safety (Radzi *et al.*, 2023; Deng *et al.*, 2021; Pan and Zhang, 2021; Boje *et al.*, 2020); however, most existing studies have limited scope to tunnel construction safety, tunnel operation and maintenance (Ye *et al.*, 2023; Yu *et al.*, 2021). In addition, extant review studies on either BIM or DT have focused on specific areas of construction operations (Ye *et al.*, 2024; Long *et al.*, 2024; Wu *et al.*, 2022; Antwi-Afari *et al.*, 2018). While many studies have been conducted on separate applications of BIM or DT, there is limited research on integrating these technologies for construction safety management. Extant studies have focused on intelligent building representations, advanced project management, and semantic construction; however, there is no study on the current hot topics and future research directions of BIM-based DT applications in construction safety management. Therefore, this paper aims to conduct state-of-the-art research on the current hot topics and future directions of BIM-based DT applications in construction safety management. The research objectives of this study include: (1) applying a scientific mapping method to analyze influential keywords in the field of BIM-based DT in safety management; and (2) discussing the current hot topics and future research directions of BIM-based DT in safety management. The findings of this study would help to strengthen the application of BIM-based DT, thereby fostering research interest and industry support for this cutting-edge study.

METHOD

This paper combines bibliometric, scientometric, and systematic analyses to produce a thorough assessment of BIM-based DT applications in construction safety. The adopted hybrid approach combines both quantitative and qualitative techniques that not only provide a comprehensive understanding but also overcome the shortcomings of these methods (Shi and Antwi-Afari, 2023). Bibliometric analysis explains the literature search and screening of eligible articles and journals. In addition, scientometric analysis discusses keyword co-occurrence analysis whilst systematic analysis highlights the current hot topics and future research directions.

Literature search

The first step was to search in the Scopus database. The Scopus database was chosen because it covers multidisciplinary research areas and displays more cited publications (Antwi-Afari *et al.*, 2018). After several search trials, the complete search strings used were TITLE-ABS-KEY (“BIM” OR “building information modeling” OR “models”), TITLE-ABS-KEY (“DT” OR “digital twin” OR “twinning”), and TITLE-ABS-KEY (“risk” OR “health” OR “wellbeing” OR “safety” OR “management”). The initial search yielded 264 documents. The literature search was conducted in March 2023.

Screening

To ensure credibility and reproducibility, the retrieved documents were defined based on the studied topic and eligibility criteria. Therefore, a screening exercise was conducted to remove irrelevant documents. For example, the subject area, document type, source type, publication stage, and language were limited to engineering, articles, journals, final, and English, respectively. After screening, 115 articles were obtained. Next, 115 articles were examined by reading the titles, abstracts, and full texts. In addition, some eligibility criteria were set to remove irrelevant articles. For example, articles were excluded when they had no full text, were not related to construction safety, outside the scope of the studied topic in BIM and DT applications. Subsequently, 85 articles were used for further analysis.

Scientometric analysis

The text-mining tool, VOSviewer, was used for scientometric analysis. VOSviewer is useful for the development of bibliometric maps, visualisation, and exploration of a research field (Van Eck and Waltman, 2010). The 85 selected articles were extracted from the Scopus database and used as input variables in VOSviewer. In this study, scientometric analysis was conducted for keyword co-occurrence analysis.

Qualitative discussion

The qualitative discussion provides a thorough assessment of the primary research goals of current hot topics and future research directions for BIM-based DT applications in construction safety. To advance the studied topic, a framework connecting the current hot topics and future research directions is proposed.

FINDINGS AND DISCUSSION

Keyword co-occurrence analysis

Keywords define a research topic within a certain field and serve as a representation of the main ideas of previous studies whereas connecting links represent the relationships between keywords. Additionally, fractional counting was used to analyse author keywords in VOSviewer. The minimum number of occurrences of a keyword was set at 3. Of the 313 keywords, 16 keywords met this threshold. The keyword that appeared most often was DT, and the network diagram shows the connection between construction management and BIM. Afterwards, similar keywords were removed. For example, keywords such as “digital twin” and “digital twins”, “BIM” and “building information modelling”. Figure 1 shows the co-occurrence of keywords. It shows 11 items, 3 clusters, and 25 links. Among the 11 keywords, DT, BIM, and IoT occurred frequently.

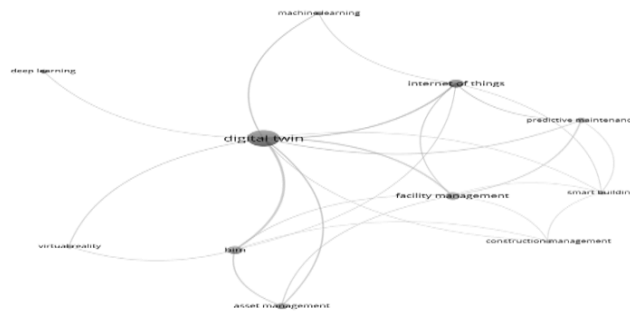


Figure 1: A network of keyword co-occurrence analysis on BIM-based DT applications in construction safety management

Current hot topics in BIM-based DT in construction safety management

Integration of advanced digital technologies in safety management

The construction sector has adopted several digital technologies as part of the digitisation process. These digital technologies include IoT, blockchain, artificial intelligence (AI), ML, and augmented reality (AR), which are areas that have been growing in recent years. The integration of digital frameworks based on IoT and BIM platforms allows remote visualisation of the condition of building facilities (Villa et al., 2021; Wang et al., 2022). Besides, a recent study developed a DT for lifting tasks to provide safe operations. The suggested model fuses data from the lifting site and the virtual model provides visual management using IoT, BIM, and a safety risk analysis method that combines priori algorithms (Liu et al., 2021). Similarly, Jiang and Jiang (2022) identified IoT monitoring and then developed a secondary BIM-based multi-information monitoring system for tunnel construction information management. Meschini et al., (2022) presented a methodology for developing a BIM-GIS web-based platform (i.e. AMS-app) that provides real-time visualisation of assets in an interactive 3D map connected to an analytics dashboard to provide management support. Lastly, a study developed a method of collecting and analysing certain environmental data using a sensor network to create a DT with IoT platform (Khajavi et al., 2019). Overall, integration of advanced digital technologies could enhance construction safety management applications such as resource monitoring, and risk management, thus improving real-time and intelligent data collection.

BIM-based DT application in asset management (AM)

Mohammadi (2023) proposed an advanced asset management system that uses bridge information modeling (BrIM) to include a DT of bridge assets associated with geometric information and non-geometric inspection data, and to optimise remedial actions for bridges in a practical way while maintaining them in a safe condition. Besides, Keskin *et al.*, (2022) suggested a scalable, modular BIM-based platform architecture that uses systems modeling language (SysML) and is based on model-based systems engineering (MBSE) concepts to improve the gathering, integration, management, and use of airport critical asset data. Moretti *et al.*, (2021) used a variety of GeoBIM software systems to deliver pertinent data for asset management purposes. Similarly, Moretti *et al.*, (2020) developed an open BIM methodology to support dynamic asset management applications. For asset management practitioners, policymakers, and researchers, DT served as a roadmap for future industrial adoption (Lu *et al.*, 2020). Moreover, Love and Matthews, (2019) gave building companies and asset owners a reference framework for benefits realisation and information workflow. Meschini *et al.*, (2022) defined effective asset visualisation and monitoring

methods by deploying appropriate sensors and IoT networks. By introducing advanced system modeling techniques, the efficiency of asset data can be improved, facilitating decision-making and practical guidance for construction safety management.

BIM-based DT applications in facility management (FM)

The framework for the interoperable visualisation of DT collects relevant metrics, feedback, selecting, processing, and displaying meaningful data to improve facilities management (FM) procedures (Huynh and Nguyen-Ky, 2020). Hosamo *et al.*, (2023) and Hosamo *et al.*, (2022b) examined how the facilities maintenance management (FMM) process can benefit from the use of DT for proactive and dynamic maintenance. Jiang *et al.*, (2022) developed a DT and BIM model of an underpass for a significantly extended road to help with clearance checks and redesign for overpasses, bridges, tunnels, and traffic safety features. Villa *et al.*, (2021) created a network for FM to monitor the components of the heating, ventilation, and air conditioning (HVAC) system and detect its faults. Zhao *et al.*, (2022) provided a top-down conceptual framework to facilitate the wider implementation of DT technology and to support FM during the operations and maintenance phase of a building. Besides, Antonino *et al.*, (2019) proposed to store real-time occupancy data in the BIM model and use it for FM. Additionally, they identified services that can be optimised for service delivery, environmental efficiency, and enhanced user safety and satisfaction. Fialho *et al.*, (2020) explained tactics and choices used in the prototype of BIM and IoT-based intelligent lighting maintenance systems. Ultimately, BIM-based DT applications not only improve operational efficiency and user experience of facilities but also enhance real-time data collection, processing, and visualisation of FM activities.

BIM-based DT application for operation and maintenance (O&M)

As per Hong *et al.*, (2022), the application of DT can improve the design, construction, operation, and maintenance. For example, Sagarna *et al.*, (2022) presented a dynamic BIM to demonstrate its ability to support diagnosis and maintenance decisions and to facilitate the management of the life cycle of residential buildings through a DT model of a building. Yu *et al.*, (2020) developed a DT-based tunnel pavement performance prediction method for O&M management of urban road tunnel life span. Kaewunruen and Lian (2019) showed that BIM can provide its owners with greater operational efficiency over its lifecycle. Moreover, it was suggested to use model predictive control and other optimisation techniques for operational planning to build a predictive model that covers the complete HVAC system (Matsuda and Ooka, 2022). Similarly, an interactive planning platform for adaptive maintenance operations in urban areas (IPPODAMO) was developed to provide and ingest diverse urban data providers' varied data sources. This enabled intelligent operational scheduling, designed to minimise disruption and operational costs (Bujari *et al.*, 2021). Likewise, Kaewunruen *et al.*, (2023) demonstrated the feasibility of using DT to determine greenhouse gas emissions and cost consumption in railway maintenance and resilience optimisation through the integration of BIM. In summary, predictive control and safety optimisation could be achieved at all stages of the project lifecycle.

Future research directions

A framework of future research directions is proposed based on keyword analysis, current hot topics, and research gaps, as illustrated in Figure 2.

- Designing a standardised workflow that integrates the use of models with defined information exchange by building a framework for IFC-BIM along with the application of advanced technologies (Jiang *et al.*, 2019).
- Reducing the data latency associated with data capture with advanced technologies like cloud computing and IoT devices (Shukla *et al.*, 2023).
- Leveraging technologies such as AI, IoT, and building digital platforms to integrate real-time data extraction and analysis, enabling network-level asset management and predictive maintenance (Cheng *et al.*, 2020).
- Investigating how to integrate data from different buildings with the wider asset ecosystem and how to develop change management and a holistic approach to asset management (Shen *et al.*, 20210).
- Complementary visualisation for data mining and clustering techniques to train asset information and identify problems in maintaining buildings (Jiang *et al.*, 2023).
- Deploy decision support systems that combine AI algorithms and facility predictive maintenance management systems to analyze historical maintenance data and predict potential facility problems (Andronie *et al.*, 2021).

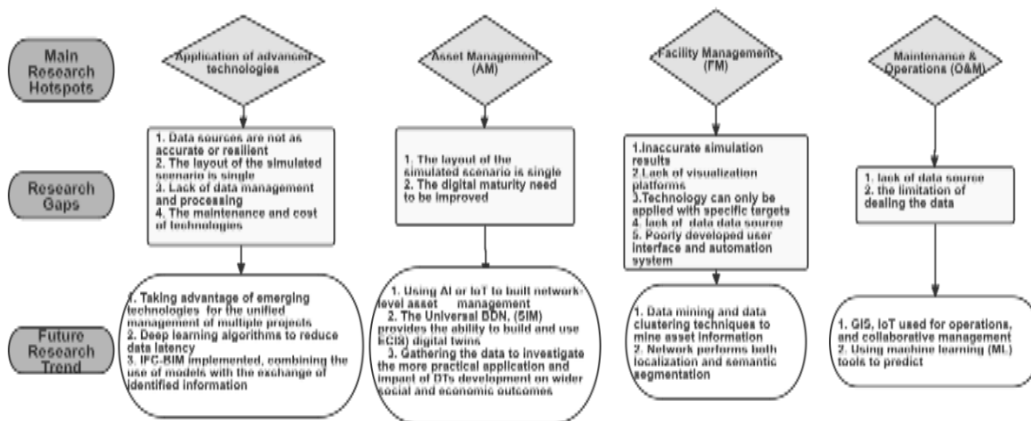


Figure 2. Research framework of hot topics, research gaps, and future research directions

CONCLUSIONS

This paper aims to present a state-of-the-art review and future research directions for BIM-based DT applications in construction safety management. It combines bibliometric, scientometric, and systematic analyses to conduct a thorough assessment of BIM-based DT applications in construction safety. Keyword analysis revealed dominant themes in the field, including DT, BIM, IoT, and FM. In addition, four main current hot topics were identified. They include the application of advanced technologies, asset management, facility management, and operation and maintenance. Future research directions should focus on dealing with data capture using new algorithms or integration with other technologies like AI, ML for prediction and detection. The results of this study fill this gap by supporting the current state of understanding and BIM-based DT adoption in the construction sector. It also calls for further research on BIM and DT to overcome their limitations, reduce their development and maintenance costs, and enable the widespread use of digital technology for construction safety management. The findings would help construction practitioners to understand and improve real-time resource monitoring,

risk management and enhance digital transformation in construction. Despite these contributions, this paper has some limitations that should be considered when analysing the results. Since only one database (i.e., Scopus) was used for retrieving articles, the coverage of papers in the scientific field may have been impacted. Additionally, only journal publications were included in this study. Future studies should consider other datasets and documents to enhance this study.

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