Relationship between digital twin and building information modeling: a systematic review and future directions

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Abstract

Purpose – Digital twin (DT) and building information modeling (BIM) are interconnected in some ways. However, there has been some misconception about how DT differs from BIM. As a result, industry professionals reject DT even in BIM-based construction projects due to reluctance to innovate. Furthermore, researchers have repeatedly developed tools and techniques with the same goals using DT and BIM to assist practitioners in construction projects. Therefore, this study aims to assist industry professionals and researchers in understanding the relationship between DT and BIM and synthesize existing works on DT and BIM.

Design/methodology/approach – A systematic review was conducted on published articles related to DT and BIM. A total record of 54 journal articles were identified and analyzed.

Findings – The analysis of the selected journal articles revealed four types of relationships between DT and BIM: BIM is a subset of DT, DT is a subset of BIM, BIM is DT, and no relationship between BIM and DT. The existing research on DT and BIM in construction projects targets improvements in five areas: planning, design, construction, operations and maintenance, and decommissioning. In addition, several areas have emerged, such as developing geo-referencing approaches for infrastructure projects, applying the proposed methodology to other construction geometries and creating 3D visualization using color schemes.

Originality/value – This study contributed to the existing body of knowledge by overviewing existing research related to DT and BIM in construction projects. Also, it reveals research gaps in the body of knowledge to point out directions for future research.

Keywords Digital twin, BIM, Facilities management, Built environment, Literature review, Construction innovation

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1. Introduction

Digital twin (DT) is a concept that involves gathering real-time data to monitor a physical asset and improves operational efficiency enabling predictive maintenance and better decision-making (Khajavi *et al.*, 2019). DT has been launched as the fourth wave of technological advancement (Industry 4.0) continues to evolve. Massive data is generated during the construction project phases, from the conceptual design phase until decommissioning phase (Bilal *et al.*, 2016). However, the huge amounts of data created by each construction project cannot be properly communicated and interpreted by the stakeholders, resulting in confusion and reworks (Gunduz *et al.*, 2013). Therefore, project data must be appropriately handled and communicated to be effectively disseminated to all stakeholders as well as to improve project performance (Bond-Barnard *et al.*, 2013). DT can address those issues by allowing construction project stakeholders to interact more effectively as a team (Pan *et al.*, 2020). In other words, not adopting DT in construction projects may lead to inefficient data communication between project stakeholders (Tao *et al.*, 2018). However, the benefits of DT cannot be exploited in the construction industry unless practitioners have the required knowledge. Therefore, practitioners must grasp the required knowledge to avoid incorrect implementation of DT in construction projects.

Over the past two decades, building information modeling (BIM) has become an essential innovation in the construction industry (Wang and Lu, 2021). By reducing inefficiencies, boosting productivity and increasing communication among project stakeholders, BIM has the potential to revolutionize and improve construction project performance (Abanda *et al.*, 2018). BIM enables design visualizations, rapid creation of design options, automated model reliability analysis, report generation and asset performance predictions (Sacks *et al.*, 2010). In other words, both DT and BIM have the potential to alleviate many construction project issues and enhance project performance (Volk *et al.*, 2014). However, humans often assume DT and BIM to be distinct from one another, although they are interconnected in some ways (Badenko *et al.*, 2021). As a result of these misconceptions, practitioners are hesitant to explore DT if BIM is already present in their construction projects. Furthermore, not understanding the differences can result in inappropriate usage of DT and BIM in construction projects. Therefore, understanding the relationship between DT and BIM is crucial to avoiding inefficiencies and reduced productivity in construction projects.

To understand DT and BIM in construction projects, there has been an increase in publications related to both subjects in the past few years. However, a quick review of prior works illustrates different interpretations of the relationship between DT and BIM. Prior works are also developing tools and techniques with the same goals. These problems arise from a lack of knowledge about what has been developed. In addition, construction industry practitioners are hesitant to adopt DT due to their unfamiliarity with the differences between DT and BIM. Given the significant amount of work that has been done in this field in the past few years, an overall perspective on the direction of prior efforts is required. By overviewing these diverse efforts, researchers can have a more comprehensive knowledge of the relationship between DT and BIM. Researchers can also use the information to identify knowledge gaps on the subject before planning further research. In addition, industry practitioners can use the information to determine appropriate tools and techniques for their projects. Therefore, there is a need to summarize all relevant work related to DT and BIM in the construction industry for industry practitioners and researchers.

This study aims to identify the relationship between DT and BIM, analyze evolution trends in the DT research area and identify the potential outcomes for future directions. To achieve that aim, the study conducts a systematic literature review of published research articles related to DT and BIM in construction projects. As a result, researchers can gain a more thorough understanding of the relationship between DT and BIM. In addition, researchers can also make use of the information to determine knowledge gaps on the subject before embarking on new research. Industry practitioners can use the data to identify whether tools and procedures are appropriate for their projects.

2. Background

2.1 Digital twin

The concept of a DT may be applied to a wide range of industries and technology (Daily and Peterson, 2017). A DT is a virtual representation of a physical asset, process, system or service used to understand and predict future difficulties over its life cycle (Qi and Tao, 2018). The physical twin, the digital model and the linkage between them are the three basic components of a DT (Glaessgen and Stargel, 2012). These components work together to provide real-time monitoring, visualization of data, data analysis and "what-if" simulation to anticipate future difficulties, as well as provide beneficial understandings and possibilities. DT was initially introduced in the context of product life cycle management (Grieves, 2011). Since then, it has since been widely used in the aviation and aerospace industries to simulate vehicle conditions, systems and operations (Glaessgen and Stargel, 2012). Consequently, DT is used in different industries, including robotics, health monitoring and manufacturing. In the construction industry, the significant benefits of creating a DT of a constructed facility include acquiring, generating and visualizing the asset's environment, assessing data anomalies and optimizing services (Nasaruddin *et al.*, 2018).

2.2 Building information modeling

BIM is a digital representation of what will be built in a construction project (National BIM Standard, 2022). The architecture, construction, engineering and facility management can benefit from the adoption of BIM in terms of visualization of the design, detection of design clashes, estimation of time and cost and improvement of interoperability among stakeholders (Volk *et al.*, 2014). The industry has embraced BIM because it helps to maintain a good balance in the project management triangle (i.e. scope, cost and time) (Olawumi *et al.*, 2018). In addition, BIM can mimic operations management on a site during construction, which can help to assist and optimize project scheduling (Coraglia *et al.*, 2017). During the design and construction of a project, BIM is used to improve resource efficiency (Volk *et al.*, 2014; Liu *et al.*, 2012), knowledge exchange (Tang *et al.*, 2010) and avoid costly design errors (Tang *et al.*, 2010; Succar, 2009). BIM has evolved over the course of its existence. According to the BIM maturity model, BIM started with Level 0 BIM in 1990 with CAD modeling software, and during the 2000s, BIM evolved to Level 1 BIM and Level 2 BIM. As for now, Level 3 BIM is currently being developed (Khajavi *et al.*, 2019).

2.3 Comparison between digital twin and building information modeling

DT and BIM can be compared in detail based on various aspects. First, DT is defined as a connected and synchronized digital representation of assets, processes and systems to understand and predict potential issues across its life cycle (Qi and Tao, 2018). Meanwhile, BIM is a digital representation of what will be built in a construction project (National BIM Standard, 2022) with no real-time synchronization. Generally, the concept of DT focuses on the interaction of people with built environments. In contrast, BIM is used for visualization in the design phase and construction phase rather than in the operations and maintenance phase. DT and BIM both have separate beginnings. DT originates from NASA's Apollo program to keep a physical twin of the crew module on the ground to recreate scenarios and resolve any difficulties that the spacecraft may encounter in space (Schleich *et al.*, 2017). Meanwhile, Charles M. Eastman pioneered the idea of BIM in the 1970s (Sacks *et al.*, 2018). BIM was initially applied in the RUCAPS CAD system for the design and construction of London Heathrow Airport Terminal 3 (Aish, 1986). DT and BIM are beneficial in the construction industry for many reasons. DT can be used for predictive maintenance, tenant comfort improvement, scenario and risk analysis as well as it can enhance the decision-making process (Qi and Tao, 2018). Meanwhile, BIM is primarily used to eliminate errors in design, enhance stakeholder communication, improve construction efficiency and track the duration and cost of a construction project (Volk *et al.*, 2014). During the operations phase, facility managers use DT to enhance its operation. In addition, architects can design future facilities by using the information from the detected flaws and improvement areas unveiled during operations and maintenance. Meanwhile, architects, engineers and constructors are the users of BIM who use it throughout the design and construction phases (Eastman *et al.*, 2011; Sacks *et al.*, 2018). Moreover, facility managers use BIM for maintenance planning throughout the asset life cycle (Azhar *et al.*, 2012). Table 1 summarizes the similarities and differences between DT and BIM.

2.4 Positioning this study

This subsection summarizes the knowledge gaps that exist in the current literature to support the rationale for conducting the study. Previous works have advanced the current body of knowledge and practice by analyzing the benefits of DT and BIM in construction projects. However, the works were in silos. Thus, the relationship between DT and BIM has not been comprehensively explored. Therefore, the current study addresses that research gap by investigating the relationship between DT and BIM.

3. Methodology

The current body of knowledge still lacks an overview of the relationship between DT and BIM in construction projects. Therefore, this study conducted a systematic literature review (SLR) of prior publications on the subject matter. The main advantage of SLR is its transparency, which allows other researchers to repeat it. SLR is also useful for obtaining a broad overview of an issue, giving researchers and practitioners evidence-based insights into

Table 1.
Differences between DT and BIM

Aspect	DT	BIM
Definition	A connected and synchronized digital representation of assets, processes, systems to understand and predict potential issues across its life cycle	A digital representation of what will be built in a construction project
Simulation of operations	Real-time operational response	No real-time synchronization
Concept	Interaction of people with built environments	Visualization in the design phase and construction phase
Origin	NASA's Apollo program	Charles Eastman
Values	Predictive maintenance; scenario and risk assessment; informed decision support system; occupants' comfort assessment	Cost reduction; increased productivity; stakeholders' interoperability
Phase of life cycle	Operations phase, maintenance phase	Planning phase, design phase, construction phase, decommissioning phase
Users	Architects, facility managers	Architects, engineers, developers and facility managers

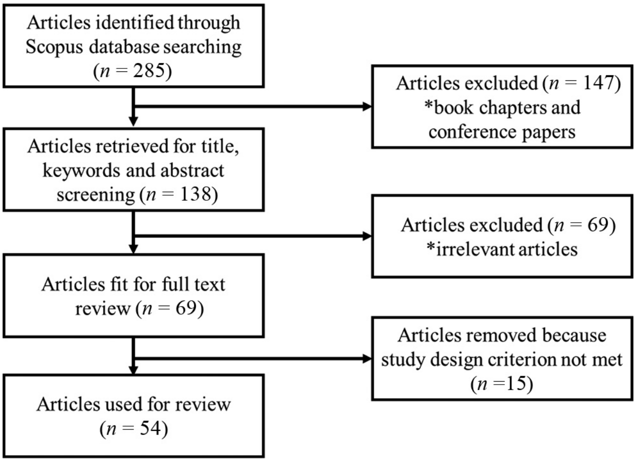

Figure 1.
Summary of SLR procedures

a particular topic or research problem (Helby Petersen, 2019). Figure 1 shows the SLR process that narrows the study from 285 articles to 54 articles over three sequential screenings.

The Scopus database was used to retrieve research articles related to DT and BIM in construction projects published between 2018 and early 2022 (January). Scopus was selected as the search engine because it has a large database of publications from different fields, including management, accounting, engineering, business and construction (Hong and Chan, 2014). Scopus is also the database that contains the most abstracts and citations globally, covering 15,000 journals from 4,000 publishers (Li *et al.*, 2019). A systematic desktop search was conducted by identifying and choosing relevant articles related to DT and BIM in construction projects. After choosing the search keywords, a desktop search was conducted using the "article title/abstract/keywords" field. The search query was designed to include "digital twin," or "digital twins," and "building information modeling," "building information modelling" or "building information model."

Using the search string, 285 articles were retrieved from the Scopus database. Only 138 articles remained after the book chapters, and conference articles were removed. Conference papers and thesis dissertations were excluded due to the possibility of inadequate quality (Abdul Nabi and El-adaway, 2020). Moreover, all the selected articles are peer-reviewed journal articles because journal articles undergo peer review. In contrast, other types of publications do not undergo the same rigorous review before publication (Olawumi and Chan, 2018). Subsequently, the selected articles were screened by reviewing the abstracts, keywords and titles. In total, 69 articles were excluded. Not all of the articles were directly related to DT and BIM in construction projects. Thus, articles that do not meet design criteria were eliminated following a thorough examination of their content. Consequently, a total of 54 articles were found to be valid for further investigation.

4. Overview of existing research related to DT and BIM

Figure 2 illustrates the annual number of publications from the selected journals from 2018 to early 2022. Research in this field has grown slowly, with the increase of only two publications between 2018 and 2019. In 2020, research related to DT and BIM began a noticeable upswing, with the body of literature steadily growing over the following years. It should be noted that the number of publications in 2022 is not shown in the figure since only

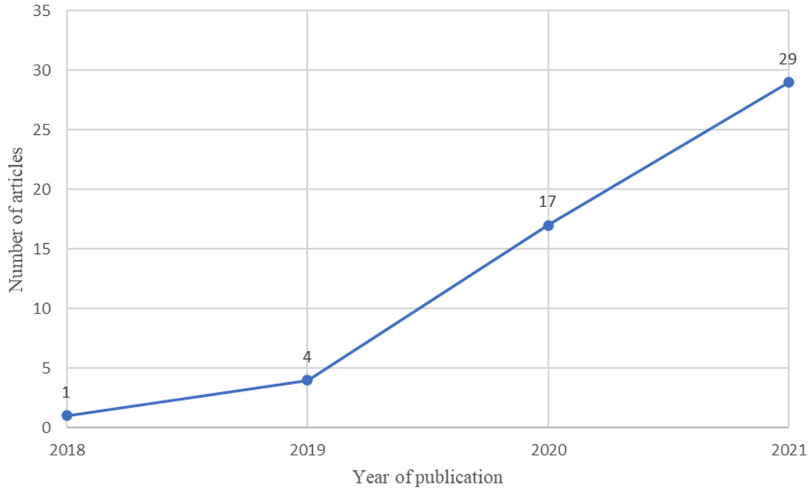

Figure 2.
Publication year of the selected articles

three publications were recorded because the search was finalized in early January 2022. Table 2 shows a summary of the publications from the SLR conducted. Sustainability is the leading publisher with seven publications, followed by *Applied Sciences* (six publications), *Automation in Construction* (five publications), *Journal of Management in Engineering* (three publications) and *Advances in Civil Engineering* (three publications).

5. Results

5.1 Relationships between digital twin and building information modeling

After analyzing the articles based on the search string in the Scopus database, only 40 articles wrote about the relationship between DT and BIM. Consequently, four types of relationships between DT and BIM have been discovered. The relationship can be classified into: BIM is a subset of DT; DT is a subset of BIM; BIM is DT; and no relationship between DT and BIM. Figure 3 summarizes the identified relationship between DT and BIM.

5.1.1 Building information modeling is a subset of digital twin. There are 24 articles that view BIM as a subset of DT. Bastos Porsani *et al.* (2021) stated that BIM is the first step toward Industrial Revolution 4.0, which includes virtual reality and DT as major components. Integrating as-designed and as-built BIM models in DT information systems might improve organizational operations (Gurevich and Sacks, 2020). The construction industry depends on as-built data and 3D geometry from BIM to create DT (Rausch *et al.*, 2021). Antonino *et al.* (2019) demonstrated that DT could be developed by integrating real-time information and BIM. In addition, DT smart cities can be created by combining BIM with large data from Internet of Things (IoT) in smart cities (White *et al.*, 2021) and geographic information system (GIS) (Zhu and Wu, 2021b). Developing a historic building information model (HBIM) may result in an informative DT of heritage architectures (Youn *et al.*, 2021; Jouan and Hallot, 2020).

5.1.2 Digital twin is a subset of building information modeling. Only three articles consider DT as a subset of BIM. DT is a multidimensional and digital representation of physical assets, systems and processes that can speed up the development and benefit of BIM in the construction industry (Moretti *et al.*, 2020). The component information of existing facilities could be mapped and stored using DT, which maintains a high degree of correlation

Journals	No. of articles	Articles
Sustainability	7	Chen *et al.* (2021), Kaewunruen *et al.* (2018); Zaballos *et al.* (2020), Desogus *et al.* (2021); Kaewunruen *et al.* (2020), Kaewunruen *et al.* (2021); Khan *et al.* (2021)
Applied Sciences	6	Moretti *et al.* (2020), Lee and Lee (2021); Bastos Porsani *et al.* (2021); Villa *et al.* (2021), Schimanski *et al.* (2019); Seghezzi *et al.* (2021)
Automation in Construction	5	Pan and Zhang (2021), Rausch and Haas (2021); Moretti *et al.* (2021), Lee *et al.* (2021); Lu *et al.* (2020)
Journal of Management in Engineering	3	Lin and Cheung (2020), Zhang *et al.* (2022); Gurevich and Sacks (2020)
Advances in Civil Engineering	3	Pan *et al.* (2020), Zhao *et al.* (2021); Yu *et al.* (2020)
Journal of Cleaner Production	2	He *et al.* (2021), Kaewunruen and Lian (2019)
Building and Environment	2	Shahinmoghadam *et al.* (2021), Abdelrahman *et al.* (2022)
Energies	2	Demianenko and De Gaetani (2021); O'Grady *et al.* (2021)
Construction Innovation	2	Oti *et al.* (2021), Al-Saeed *et al.* (2020)
Buildings	2	Teisserenc and Sepasgozar (2021), Youn *et al.* (2021)
ISPRS International Journal of Geo-Information	2	Zhu and Wu (2021a); Jouan and Hallot (2020)
Smart and Sustainable Built Environment	2	Alizadehsalehi and Yitmen (2021); Götz *et al.* (2020)
Sensors	2	Liu *et al.* (2020), Liu *et al.* (2021)
Cities	1	White *et al.* (2021)
Computers, Environment and Urban Systems	1	Diakite and Zlatanova (2020)
Data-Centric Engineering	1	Sacks *et al.* (2020)
Direccion y Organizacion	1	Torrecilla-García *et al.* (2021)
Engineering, Construction and Architectural Management	1	Xie *et al.* (2020)
Frontiers in Built Environment	1	Kaewunruen and Xu (2018)
International Journal of Construction Management	1	Rausch *et al.* (2021)
International Journal of Safety and Security Engineering	1	Antonino *et al.* (2019)
Journal of Airport Management	1	Oliveira (2020)
Journal of Building Engineering	1	Moyano *et al.* (2022)
Magazine of Civil Engineering	1	Badenko *et al.* (2021)
Open Engineering	1	Huynh and Nguyen-Ky (2020)
Remote Sensing	1	Zhu and Wu (2021b)
Journal of Digital Landscape Architecture	1	Luka and Guo (2021)
Total	54	

Table 2. Summary of selected articles used for this study

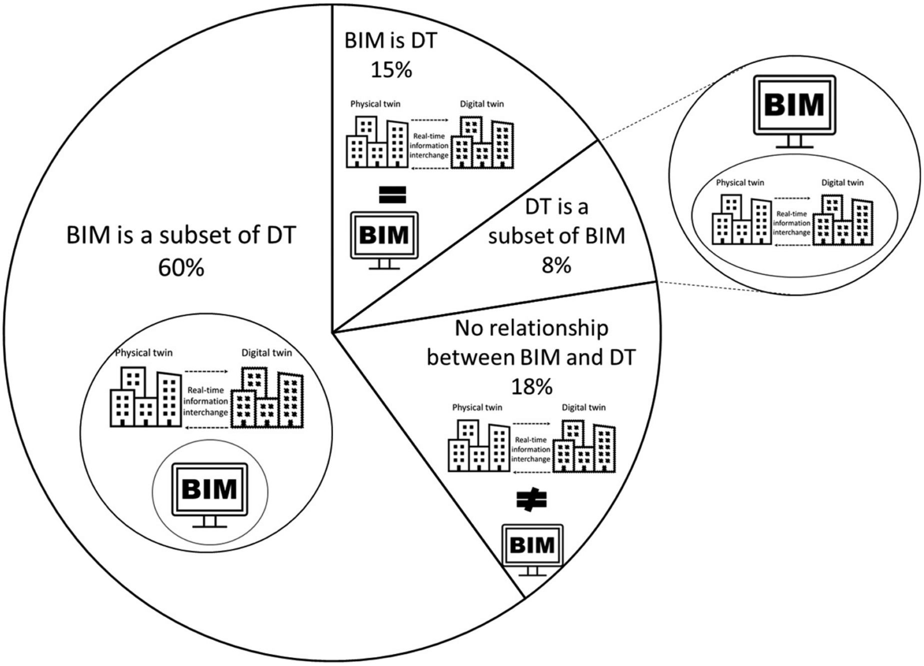

Figure 3.
Summary of the relationship between DT and BIM

and consistency on the facility components in BIM (Zhao *et al.*, 2021). The arrival of the concept of DT in BIM can improve the safety and efficiency of decommissioning nuclear power plants (Oti *et al.*, 2021).

5.1.3 Building information modeling is digital twin. Six articles used DT as a synonym for BIM. Schimanski *et al.* (2019) stated that BIM is DT and is the main factor that allows better processes in the construction industry. Kaewunruen *et al.* (2020) suggested that DT, or so-called BIM, has brought a great revolution to the construction industry. The same first author (Kaewunruen) also used similar definitions in other publications (Kaewunruen and Xu, 2018; Kaewunruen and Lian, 2019; Kaewunruen *et al.*, 2018; Kaewunruen *et al.*, 2021). Kaewunruen and Xu (2018) stated that DT or BIM is in great demand and is not only a tool but also a process that can aid in transforming the construction industry. For example, integrating BIM or DT with sensors allows for real-time monitoring of bridge operations (Kaewunruen *et al.*, 2021). In addition, developing DT or BIM can enhance collaboration among project participants and accurately estimate costs and technical issues encountered by producing net zero energy buildings (NZEB) in predetermined locations (Kaewunruen *et al.*, 2018).

5.1.4 No relationship between building information modeling and digital twin. Seven articles view DT and BIM as two separate subject matter (i.e. no relationship between DT and BIM). Sacks *et al.* (2020) stated that DT is different from BIM as BIM only replicates the physical twin, but DT is also connected and automatically updated to the physical twin. Lee *et al.* (2021a) and Xie *et al.* (2020) also suggested that compared to BIM, DT is an up-to-current modeling with a broader concept in terms of information richness and decision-making capability. Alizadehsalehi and Yitmen (2021) suggested that DT is helping BIM processes by automatically updating and creating the digital model of a construction project. Badenko *et al.* (2021) stated that although DT and BIM focus on creating and linking a digital model to its physical twin, DT and BIM have different development paths (Badenko *et al.*, 2021). Liu *et al.* (2021) stated that DT and BIM could be combined to enhance the efficiency of safety management.

O'grady *et al.* (2021) suggested the integration of DT in virtual reality environments through the facilitation of BIM to enhance the applicability of circular economy strategies.

5.2 Existing studies

Numerous prior works have been conducted related to DT and BIM. After collecting and analyzing the 54 articles, five subthemes have been established. As shown in Figure 4, the subthemes can be further classified into five phases of facility life cycle, which are planning, design, construction, operations and maintenance, and decommissioning.

5.2.1 Planning phase. The integration of BIM and GIS can help solve multiple issues in the phase of planning, designing and analyzing construction projects (Ninić *et al.*, 2017). One of the challenges in integrating BIM and GIS is storage inefficiency which can lead to burdens in

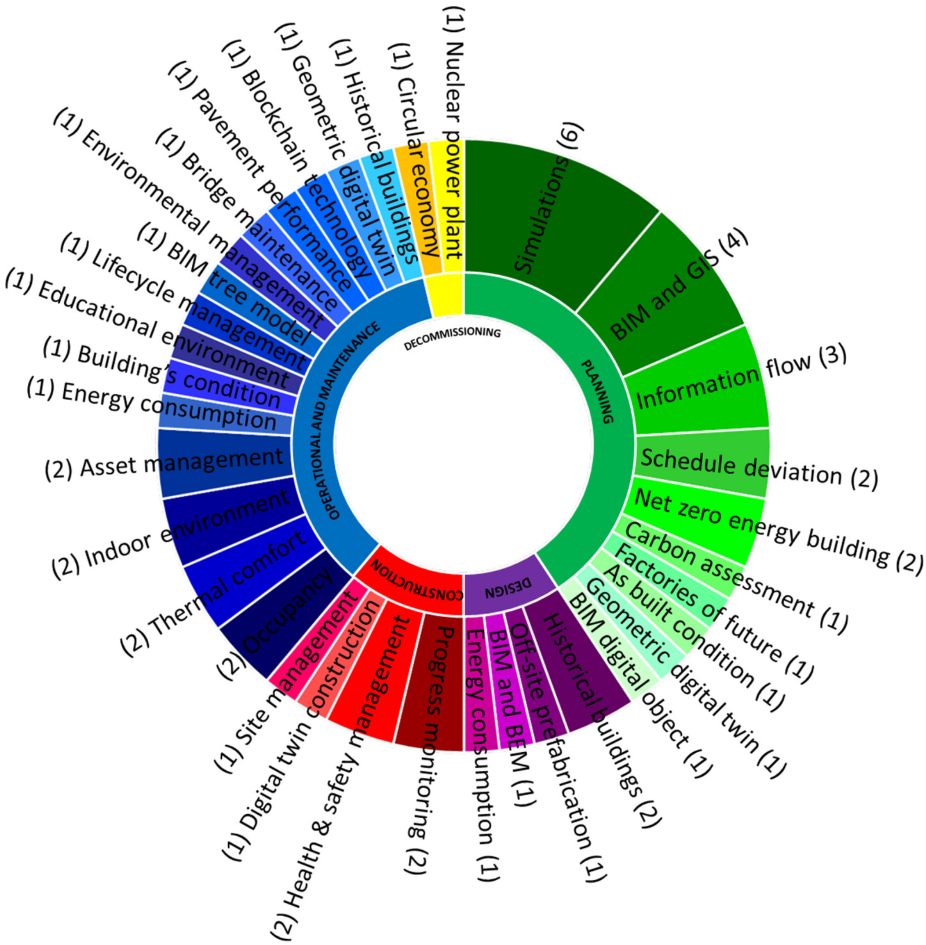

Figure 4.
Themes of the selected articles with number of publications

data exchange and analysis (Deng *et al.*, 2016). To solve storage issues, Pan *et al.* (2020) developed a hierarchical data format based data compression and integration approach to support BIM-GIS applications. Another obstacle is the issue of geo-referencing digital models in a GIS environment. Thus, Diakite and Zlatanova (2020) proposed an automated framework to convert local coordinates of digital models into real-world geographic coordinates. In addition, Zhu and Wu (2021a) developed a standard geo-referencing technique that can be used with current and future industry foundation classes (IFC). Another issue is the problem of converting BIM data to GIS data due to the intrinsic differences between BIM and GIS. To solve the problem, an approach for converting IFC to shapefile using computer graphics technology was developed by Zhu and Wu (2021b).

In prefabricated construction, information flow is an important factor in planning and controlling production. Thus, Teisserenc and Sepasgozar (2021) developed a conceptual model involving implementing blockchain with DT, BIM and IoT to enhance trust, cyber security, efficiencies, information management, information sharing and sustainability. There is still a lack of research on the information management of a DT, including data storage, security and sharing. Thus, Lee *et al.* (2021) integrated DT and blockchain to develop a framework that can selectively store and share relevant project information as well as trace that information back to its source. Occupational health and safety management in construction projects is complex. Thus, Torrecilla-García *et al.* (2021) presented a framework to improve strategic developments of solutions for safety planning and management of construction projects.

As schedule deviation in the logistics of prefabricated construction can hinder its advantages and prevent its widespread use, Lee and Lee (2021) developed a framework that integrates DT with BIM and GIS for real-time logistics monitoring and simulation. Schimanski *et al.* (2019) use computational design and digital fabrication techniques to develop a digital process flow that can help save time during the bid estimation phase and the preparation of work. The absence of a reliable approach for assessing embodied carbon in the AEC industry has hampered the advancement of low-carbon design in the sector. Therefore, Chen *et al.* (2021) proposed a DT-based life cycle assessment (LCA) approach to measure embodied carbons of constructed facilities, consequently expanding the current LCA from a partial life cycle to a whole-life cycle. In addition, Badenko *et al.* (2021) developed a framework called “Factories of the Future” to investigate the integration methods, develop appropriate principles and methods and assess the interpenetration effectiveness of DT and BIM.

NZEB is one method for reducing energy usage in constructed facilities, which involves fulfilling energy demands entirely through renewable energy sources. Hence, NZEB is one of the critical components for a more sustainable future. Therefore, Kaewunruen *et al.* (2018) proposed a new hierarchy flow chart for a digital model to emphasize the technical and financial viability of NZEB for existing facilities. In addition, Zhao *et al.* (2021) proposed a technique that uses scan-to-BIM and DT to evaluate NZEB retrofitting schemes by analyzing energy consumption and carbon emission indicators of existing facilities using scan-to-BIM and DT.

Urban planning and policy decisions can be modeled using the data generated by DT. In 2021, White *et al.* used a publicly released model of an area in Dublin to create its DT. The information from the DT can be used in the planning of the urban area and policy decisions. Besides, DT of airports can improve performance and efficiently obtain data (Oliveira, 2020). In addition, Kaewunruen *et al.* (2020) created a DT of subway stations to simulate their design, construction and operations and maintenance processes and assess the LCA of the stations. Furthermore, Kaewunruen and Lian (2019) analyzed the world-first 6D BIM for the life cycle management of a railway turnout system. The government and other public procurement bodies are requiring the use of BIM, consequently driving its adoption. To guide construction stakeholders on BIM adoption, Kaewunruen and Xu (2018) used a Revit-based simulation to discuss BIM application within the context of railway stations.

5.2.2 Design phase. There is still a lack of basic knowledge of the linkages between design, detailed modeling and fabrication automation. Therefore, He *et al.* (2021) developed a customized application that works with BIM authoring tool to generate the precise geometry models of the 3D-printed modules, allowing users to check and resolve interferences at the early stage. Data loss while transferring data between BIM and BEM is a major issue leading to reworks. Thus, Bastos Porsani *et al.* (2021) proposed a semi-automated workflow from BIM to BEM that could improve the design process. In addition, Demianenko and De Gaetani (2021) proposed a system for simulating renovation scenarios that incorporated BIM and artificial neural networks-based models to predict the total energy consumption, life cycle cost and LCA.

The existing digital model of historical assets is a theoretical model often built by facility managers using basic geometries and does not take into account structural transformations induced by time or natural events. Therefore, Moyano *et al.* (2022) developed a new technique to review visual recordings and analyze structural deviations. Besides, Youn *et al.* (2021) determined the critical factors in converting 3D scan data of Korean traditional wooden architectures into HBIM data by investigating the modeling processes of wooden bracket sets. Hence, HBIM models can be used as a DT to comprehend deformation and damage in wooden joints.

5.2.3 Construction phase. DT provides facility owners with real-time information, allowing owners to make more informed decisions based on facts rather than assumptions. A new mode, "Digital twin construction (DTC)," was formulated by Sacks *et al.* (2020) for managing production in construction by providing accurate status information and proactively analyzing and optimizing ongoing design, planning and production. Pan and Zhang (2021) developed a framework by integrating BIM, IoT and data mining techniques for controlling and optimizing complex construction processes under a high degree of automation and intelligence. Alizadehsalehi and Yitmen (2021) developed a framework for automating construction progress monitoring through reality capture to extended reality allowing digital construction progress monitoring. Zhang *et al.* (2022) enhance the DT concept as well as extend the existing level of details of BIM for construction site management by presenting a framework that integrates BIM, IoT and data storage. Particulate matters exposure has been linked to major health issues, including inherited genetic damage (Morakinyo *et al.*, 2017). Therefore, Khan *et al.* (2021) integrated low-cost dust sensors with BIM to generate a DT for automated dust control techniques on the construction site. The most common accidents for hoisting activities during construction include falling and suffering from mechanical or component collisions (Fard *et al.*, 2017). Thus, Liu *et al.* (2021) proposed a model that integrates IoT, BIM and a security risk analysis method to complete the information fusion process between the hoisting site of a physical twin and its digital model.

5.2.4 Operations and maintenance phase. According to Christensen *et al.* (2014), occupancy data can be used to optimize the energy usage of systems and equipment. Therefore, Antonino *et al.* (2019) proposed a technique for detecting human motions in crowded environments and measuring exact real-time occupancy data using image recognition sensors and computer vision. Also, Seghezzi *et al.* (2021) discussed the stages of IoT system calibration, which include preliminary analyses to optimize the design of IoT camera-based sensors systems and test campaigns to verify system efficiency and accuracy in monitoring occupancy. Desogus *et al.* (2021) presented a method for integrating IoT sensors with BIM processes to create a single data platform for the visualization of indoor conditions and energy consumption metrics.

Existing digital models do not fully connect with the IoT data of their physical twins. Therefore, Villa *et al.* (2021) developed a framework composed of IoT sensors, dashboard, IoT and BIM for monitoring and visualizing the conditions of constructed facilities throughout operations and maintenance virtually. Educational environment comfort is a critical factor in learning success and social progress (Zomorodian *et al.*, 2016). Thus, Zaballos *et al.* (2020) developed a smart campus concept involving BIM and IoT-based wireless sensor networks that allows environmental monitoring and emotion detection systems to provide insights into indoor comfort. The indoor environment is a critical aspect of human life, health and well-being (Asadi *et al.*, 2017). Therefore, Xie *et al.* (2020) developed an AR-supported automated environmental anomaly detection and fault isolation method to address problems that affect indoor thermal comfort. Integrating BIM and IoT can lead to more immersive virtual reality environments, intuitive visualizations and higher levels of interactivity during indoor comfort assessment. Thus, Shahinmoghadam *et al.* (2021) proposed a virtual reality application to identify the benefits of virtual reality, BIM and IoT for real-time monitoring of indoor thermal comfort. In addition, Liu *et al.* (2020) proposed a framework that integrates BIM, IoT and support vector machines to enhance the level of intelligence of indoor safety management. Furthermore, Abdelrahman *et al.* (2022) developed Build2Vec, which is a prediction model that predicts spatial-temporal indoor environmental preferences.

5.2.5 Decommissioning phase. Nuclear power plants have continued to be constructed and operated worldwide due to their low capital costs and benefits to global warming mitigation. Decommissioning is a critical phase in nuclear plant operation for assuring the safety and security of radioactive products and by-products. Thus, Oti *et al.* (2021) proposed a framework for a more regulation-aware and safer decommissioning of nuclear power plants. The circular economy (CE) is an approach to optimize the recycling process of construction materials. CE allows construction material transition from a conventional model to a model involving the life extension of resources as well as enabling materials to stay in the loop. Therefore, O'Grady *et al.* (2021) proposed the application of CE principles to construction projects by integrating the related principles with BIM and virtual reality tools.

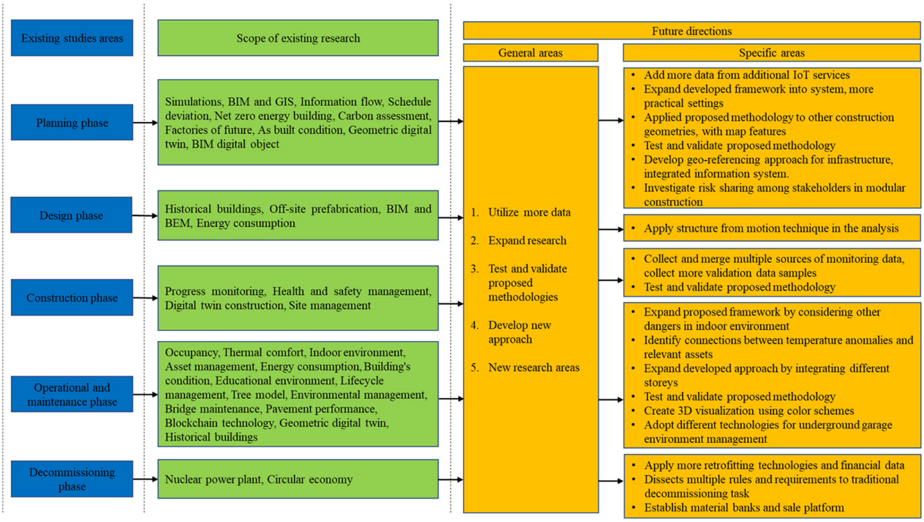

Figure 5.
Framework to link existing research areas to future directions

6. Future directions

Based on the systematic review of the selected articles, several areas that need further research have been revealed (Figure 5). However, these future areas are only suggestions or compilations from the identified research articles in this study. Therefore, these findings should not be limited to other future explorations in the construction domain.

Several works suggest adding additional data as well as specific information in future research. For instance, White *et al.* (2021) suggested that the public data used for the DT simulations can be supplemented with data from additional IoT services in the area. Along with more data, the simulation will be more realistic with real-time information about noise pollution, traffic and crowds. Pan and Zhang (2021) recommend future researchers use information fusion by collecting and merging multiple sources of monitoring data. Moreover, Zhao *et al.* (2021) suggested that researchers should apply more retrofitting technologies to existing buildings and provide more financial data as well as more data integration into the established BIM. Liu *et al.* (2021) recommended that more validation data samples should be collected.

There are researchers that suggest future scholars expand their current research. Oti *et al.* (2021) proposed to appropriately classify and map all traditional decommissioning tasks by dissecting the multiple rules and requirements. Furthermore, Chen *et al.* (2021) suggested that the developed framework can be expanded into a system for estimating embodied carbon in buildings. According to Liu *et al.* (2020), the proposed framework can be expanded by focusing more on risk assistant treatment, as well as considering other dangers in the indoor environment. Moyano *et al.* (2022) recommended focusing on applying the structure from motion technique in the analysis, behavior and diagnosis of humidities, as well as in experimentation linked to architectural elements.

Some prior works also suggested future scholars test and validate the developed framework and methodology. For instance, Moretti *et al.* (2020) suggested that future scholars should test the proposed methodology's robustness by conducting case studies. Al-Saeed *et al.* (2020) suggested future research to validate their work by analyzing feedback from BDO users and nonconformance reports. Shahinmoghadam *et al.* (2021) suggest validating the consistency of the proposed system by involving more people with different backgrounds and individual characteristics. Alizadehsalehi and Yitmen (2021) suggested future research to validate their framework by implementing it on multiple construction projects using objective data to evaluate the long-term impact of DRX in construction operations. Also, Villa *et al.* (2021) recommended future research to use the data acquired from the proposed system for predictive maintenance management of building facilities.

Several studies recommended new approaches that should be developed by future scholars. For example, Zhu and Wu (2021a) suggested that scholars should develop a proper geo-referencing approach for the infrastructure domain. In addition, Desogus *et al.* (2021) proposed creating a 3D visualization of the parameters to quickly identify problematic areas of a building by highlighting using color schemes of the building areas where comfort conditions are not met or exceeded the time limit, as well as any areas where the sensor detects a misuse or excess of energy usage. Schimanski *et al.* (2019) suggested integrating lean management approaches with BIM at the data-processing level to create new integrated information systems.

In addition, some studies highlighted new topics and areas related to their work that is worth investigating. O'grady *et al.* (2021) suggested future research to look into how to link live energy data with building energy management systems and display it in the model so that high-consumption appliances can be identified and targeted reduction schemes can be implemented.

Lee and Lee (2021) also suggested several research ideas for future scholars, such as creating a DT of offsite as well as onsite module manufacturing processes, obtaining various IoT sensor data and investigating how risks in modular construction can be shared among stakeholders. Besides, Kaewunruen *et al.* (2021) suggested future research to investigate on automation of data analysis using Dynamo Script and the development of DTs for infrastructure maintenance and monitoring.

7. Conclusions

There has been growing research related to DT and BIM in the construction industry. Understanding the relationship between DT and BIM may benefit construction projects. However, most industry practitioners lack an understanding of the relationship between DT and BIM. Lack of information on the relationship and differences between DT and BIM lead to these issues. Therefore, this systematic review focused on synthesizing the findings of all relevant research related to DT and BIM in construction projects, thereby making it available and accessible to industry practitioners and researchers.

This study presents a systematic review of published articles on DT and BIM in construction projects. This study examines research articles published to give industry practitioners and researchers a comprehensive overview of the related topic. A total of 54 journal articles were carefully chosen and thoroughly reviewed. The articles were classified and analyzed based on the building construction life cycle: planning phase, design phase, construction phase, operation and maintenance phase, and decommissioning phase. Furthermore, several areas have emerged as requiring further investigation. This study is critical in ensuring that industry practitioners are capable of using DT and BIM correctly to ensure the success of their construction projects. In academia, the overview could be used to identify knowledge gaps before performing further research.

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