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From building information modeling to construction digital twin: a conceptual framework

Andrea Revolti[a], Luca Gualtieri[a], Pieter Pauwels[b] and Patrick Dallasega[a]

[a]Faculty of Engineering, Free University of Bozen-Bolzano, Bolzano, Italy; [b]Department of the Built Environment, Eindhoven University of Technology, Eindhoven, Netherlands

ABSTRACT
This article aims to investigate the transition from Building Information Modeling to Digital Twin (DT) technologies in building construction and facility management. The integration of BIM and DT has the potential to enhance decision-making, optimize performance, and improve sustainability throughout the building lifecycle. By conducting a review of the existing literature, this study identifies the current state-of-the-art, as well as key trends, challenges, and opportunities for research and industry 4.0 associated with the adoption and implementation of DT as an extension of BIM. In the Discussion section, issues and gaps for the transition from a static BIM model to a dynamic DT are presented, such as the lack of a framework and protocols for sensor connections. The conclusions will focus on the creation of a protocol for the correct transition of BIM models in the DT environment and the characterization of DT for the construction sector with real use cases.

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Building information modelling; digital twin; construction industry 4.0; operations & maintenance; systematic literature review

1. Introduction and motivation

The contemporary construction industry is constantly evolving and seeking new technologies and practices to improve project delivery, streamline operations and enhance overall efficiency. Over the past few years, the industry has witnessed a paradigm shift from traditional approaches to the adoption of Building Information Modeling (BIM) as a collaborative platform for the design, construction, and management of buildings (Wang et al., 2023). Global BIM adoption has, however, been slow due to the perceived risks and challenges associated with its development (Dallasega et al., 2021). Furthermore, individuals and organizations have misconceptions about the potential of BIM in tackling the challenges of the construction industry and this has resulted in its abandonment and a lack of knowledge and understanding of the technology. Nowadays, BIM is a standard for the construction industry and provides numerous benefits, including improved collaboration, enhanced visualization, clash detection, and accurate quantity takeoffs (Aliakbar et al., 2023; Sawhney et al., 2017). However, as the industry strives for more sophisticated digital solutions, the limitations of BIM have emerged. Due

CONTACT Andrea Revolti andrea.revolti@unibz.it Faculty of Engineering, Free University of Bozen-Bolzano, Piazza Domenicani 3, Bolzano 39100, Italy

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to the static data contained in BIM, although there are numerous articles in the literature dealing with its application in the field of maintenance (Aliakbar et al., 2023; Errandonea et al., 2020; Varela et al., 2022), difficulties can be encountered in its efficient application for the dynamic phases of site operations and maintenance operations of the built environment, even in the case of models realized in a Level of Development (LOD) 500. This leads to the concept of Digital Twin (DT), an emerging technology that extends the capabilities of BIM by expanding its scope of use through the possibility of interaction between the digital model and the real environment. A DT is a virtual replica of a physical asset, such as a building, that incorporates real-time data from sensors, systems, and other sources (Aliakbar et al., 2023). It enables the monitoring, analysis, and bi-directional simulation of various aspects of the asset's performance throughout its life-cycle. A DT, in the construction sector, incorporates various types of information, such as architectural and engineering designs, structural data, sensor data, and building system information (Errandonea et al., 2020). It can be created through a combination of BIM, Internet of Things (IoT) devices, cloud computing, and data analytics (Sacks et al., 2020). The purpose of developing a DT in construction is to gain a deeper understanding of the project, simulate different scenarios, optimize performance, and improve decision-making throughout the construction process (Sacks et al., 2020). During the construction process, it allows stakeholders, including architects, engineers, contractors, and facility managers, to visualize the project, analyze its behavior, detect potential issues, and make informed adjustments to enhance efficiency, sustainability, and safety (Mayer et al., 2023). Furthermore, considering the building management and leveraging on real-time data and advanced analytics, a DT enables predictive maintenance, facilitates the integration of various systems, and supports effective resource management (Mayer et al., 2023). It can also aid in identifying and mitigating occupational risks, optimizing energy consumption, and enhancing overall operational performance (Petri et al., 2023).

By integrating BIM with the concept of DT, stakeholders can access a holistic and dynamic representation of a building, allowing for advanced monitoring, predictive analysis, and optimization of its operations. The motivation behind this research study lies in understanding the drivers and potential benefits of transitioning from BIM to DT in the construction sector. While BIM has already gained significant adoption and recognition as standard in the construction industry, although maintaining limitations as outlined above, the integration of DT presents new opportunities for improved decision-making, operational efficiency, and sustainability. It is crucial to investigate the motivations behind this transition and assess the potential advantages it offers to construction stakeholders (Rics Report, 2022). Issues such as data interoperability, real-time synchronization, hardware limitations, and usability need to be addressed to ensure seamless integration and widespread adoption of BIM combined with DT technologies in the construction industry. This approach does not consider BIM obsolete but intends to promote it, evolving it into a tool that ensures bidirectional data flow, more naturally connected to real events and data with time continuity. To sum up, the purpose of this paper is to address the research gaps by answering the following research questions (RQs):

RQ1: What are the limitations of BIM that motivate the adoption of a Digital Twin to support the construction execution and operation & maintenance (O&M) phase?

RQ2: What are the advantages of the evolution of a BIM model into a Digital Twin to support the construction execution and operation & maintenance (O&M) phase?

RQ3: What are the gaps for the evolution of a BIM model into a Digital Twin in construction?

The following sections of this article are arranged as follows. Section 2 elucidates the fundamental concepts of BIM and DT. Section 2 presents an elaborate description of the research methodology employed. The findings of the systematic literature review are examined in Section 4. This section will report the limitations of the BIM approach during the construction and subsequent operational and maintenance (O&M) phases of the building, as well as the potential strengths and uses for overcoming these issues through the use of a DT. The problems of connecting BIM and DT will also be illustrated. Section 5 will discuss and summarize the strengths and weaknesses of the investigated methodologies, summarized through content analysis. The conclusion Section (6) will summarize the results derived from the initial RQs, suggesting potential developments for further research.

2. Basic concepts and related works

2.1. Building information modeling

The definition of BIM was first published in an Autodesk white paper in 2002 (Autodesk Building Solutions, 2021), its primary purpose being to distinguish architectural 3D parametric modeling from the traditional 2D drawings. BIM is not merely a software but rather a fusion of technology and a process that establishes guidelines on its utilization (Autodesk Building Solutions, 2021). In fact, according to Hardin and McCool (Hardin & McCool, 2015), the true value of BIM lies not in the 3D model itself but in the information and connectivity underlying it. The United States National BIM Standard defines BIM as a digital representation that captures the physical and functional attributes of a facility (construction), while also serving as an approach to design that fosters shared knowledge among all stakeholders involved in creating a building, spanning from conceptual phases to the entire lifecycle. In BIM, each stakeholder has the ability, based on their role, to modify, extract, or update the data and information contained in the model. Different levels of information, known as Levels of Development (LOD), are defined within BIM to differentiate the completeness and accuracy of the model, ranging from LOD 100 (macro concept design) to LOD 500 (as-built element) (National BIM Standard-United States ® NBIMSUS™). BIM encompasses seven dimensions: the three geometric dimensions (3D), scheduling (4D), cost analysis (5D), environmental sustainability (6D), and management/maintenance (7D). These seven dimensions represent the various stages of a building's lifecycle: from the design phase for both architectural/structural and MEP (Mechanical, Electrical, and Plumbing) aspects (3D), to the construction phase (4D), project cash flow (5D), energy analysis and LCA (6D), and operations and maintenance (O&M) (7D).

One of the strengths of BIM lies in the interoperability of the information it contains, facilitated by the use of a standardized format called Industry Foundation Classes (IFC) (American Institute of Architects) or COBie (National BIM Standard-United States ® NBIMSUS™), which ensures the representation and exchange of geometry and object information among different BIM software. The Industry Foundation Classes (IFC) is an open and standardized data format used in the architecture, engineering, and construction (AEC) industry to facilitate the exchange and sharing of information among various software applications and systems. IFC defines a structured schema for representing building and construction data in a digital format, allowing for interoperability between different software tools used at various stages of a building's lifecycle, including design, construction, and operation. The COBie format aims to replace the means by which information is conveyed today, by proposing a standardized digital information structure that can accommodate the contents normally included in product data sheets, user and maintenance manuals, warranty documents, etc. COBie is, therefore, a tool for exchanging information, a means of communication (National BIM Standard-United States ® NBIMSUS™). Like any communication, it requires a sender and a receiver; in the case of COBie the two phases of the building process are involved: on the one hand the construction phase, understood as the entire building process, from planning to delivery of the works, and, on the other hand, the operation phase, i.e. the management and maintenance of the building infrastructure (National BIM Standard-United States ® NBIMSUS™).

In summary, BIM can be characterized by three fundamental concepts (IFC4, 2018):

• BIM as a PROCESS, involving a series of activities to manage the data and information within information models.

• BIM as a MODEL, serving as a container for data and information that can be read, enriched, and modified throughout the lifecycle of a project.

• BIM as a COLLABORATION TOOL, requiring all stakeholders to collaborate at appropriate stages in the process, following established rules, to ensure that the information models remain up-to-date and usable. It is within this context of collaboration that the concept of DT can be integrated.

2.2. Digital twin in construction

In the construction sector, a DT refers to a virtual replica or representation of a physical building or infrastructure project. It encompasses the use of digital technologies and data to create a comprehensive and dynamic model that mimics the real-world counterpart throughout its entire lifecycle, from design and construction to operation and maintenance till to the dismission and demolition phase (Aliakbar et al., 2023; Honghong et al., 2023). A DT incorporates various types of information, such as architectural and engineering designs, structural data, sensor data, and building system information. It can be created through a combination of BIM, Internet of Things (IoT) devices, cloud computing, and data analytics. The purpose of developing a DT in construction is to gain a deeper understanding of the project, simulate different scenarios, optimize performance, and improve decision-making throughout the construction process. It allows stakeholders, including architects, engineers, contractors, and facility managers, to visualize the project, analyze its behavior, detect potential issues, and make informed adjustments to enhance efficiency, sustainability, and safety (National BIM Standard-United States ® NBIMSUS™). By leveraging real-time data and advanced analytics, a DT enables predictive maintenance, facilitates the integration of various systems, and supports effective resource management. It can also aid in identifying and mitigating risks, optimizing energy consumption, and enhancing overall operational performance (American Institute of Architects, 2023). Overall, a DT applied to the construction sector provides a powerful tool for improving collaboration, reducing costs, minimizing delays, and maximizing the lifecycle value of a building or infrastructure project. Transforming a BIM model into a DT involves augmenting the static design and construction information with real-time data, connectivity, and advanced analytics. The reported use case concerns the construction and management of a bridge. From a lifecycle perspective, the utilization of BIM primarily contributes to the design and construction phases, while DT technology finds its significance during the O&M phases. DT does not represent a standalone technology but it is closely related to the BIM model to which it is applied as an extension. The information generated during the design and construction stages, such as IFC files and 3D models, can be reused and updated for the operation phase. Simultaneously, DT information management relies on BIM during the operation phase of the construction. This is to reiterate that there can be no DT without a BIM model, properly created and properly managed.

To implement a comprehensive DT for a building or infrastructure project, the process begins with the development of a detailed BIM model that encompasses architectural, structural, and system details. Following this, IoT sensors are strategically installed throughout the physical asset to gather real-time data on parameters such as temperature, humidity, occupancy, energy usage, and equipment performance – crucial operational data for the DT. A robust data infrastructure is then established to ensure seamless communication between the IoT sensors, BIM model, and other relevant systems. As the IoT sensors commence capturing real-time data from the physical asset, the next step involves integrating these data with the BIM model, aligning it with corresponding elements to create a synchronized representation of the asset. Visualization tools and analytics platforms are utilized to interpret and analyze the integrated data, enabling stakeholders to monitor and assess asset performance, identify patterns, detect anomalies, and generate actionable insights. The DT is further leveraged for simulations and predictive analysis, allowing stakeholders to evaluate design changes, assess energy efficiency, optimize maintenance schedules, and enhance overall performance. To ensure the DT remains current, a continuous process of monitoring the physical asset is maintained, with updates reflecting the most recent data collected, empowering stakeholders to make informed decisions based on the latest information (Opoku et al., 2021):

3. Research methodology

A Systematic Literature Review (SLR) has been performed in line with the methodology proposed by Booth et al. (Papaioannou et al., 2016) and Boland et al (Boland et al., 2014). The SLR serves as a robust tool for evaluating published research within a scientific domain, possessing qualities that usually are missing in alternative methods such as citation-based approaches. To carry out the SLR, a so-called 'three-step process' has been used (Denyer & Tranfield, 2009). These steps encompass: 1) the initial phase of 'planning the review' (preparation stage), 2) the subsequent stage of 'conducting the review' (operational stage), and 3) the concluding step of 'documenting the review' (reporting stage). In the following, the three steps are summarized considering the context of this work.

3.1. Planning the review

The first step consists of two main activities:

(i) *Refine the research questions and*
(ii) *Establish a protocol for reviewing the research*

Initially, the research questions RQ1, RQ2 and RQ3 based on the identified research gaps have been defined. SCOPUS has been used as the main database for the identification of relevant scientific works through carefully selected keywords, gained from experience in previously conducted research projects (Table 1). Second, a protocol was created to systematically decide which papers were used for content analysis. The conceptual boundaries of the search in Scopus were not fixed in the choice of the specific domains as DT is a cross-cutting technology with respect to many domains. Instead, in order to circumscribe the research, and obtain results with validity and relevance, a significant date leading to standardization of the use of BIM standards in construction was fixed. In fact, 2019 is considered a landmark year for the construction industry and the BIM approach, as this when the UNI EN ISO 19,650 interventional standard was issued. This standard defined the principles and guidelines for managing project information in the asset lifecycle within a BIM workflow and design (ISO 19650–1, 2018). Furthermore, in

Table 1. Keywords, subject area and restrictions criteria keywords string.

Restriction	Restricting Condition	Scopus String
Subject Areas	Engineering, Computer Science, Energy, Physics, Social Sciences, Biochemistry, Management, Environmental Sc., Mathematical, Material Sc.,	Subject_Areas = LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "BIOC") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "CENG") OR LIMIT-TO (SUBJAREA, "CHEM") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "MATH"))
Year	From 2019 to 2023	*Years* = Limit-To (PubYear, 2020) Or Limit-To (PubYear, 2022) Or Limit-To (PubYear, 2021) Or Limit-To (PubYear, 2020) Or Limit-To (PubYear, 2019) Or

(TITLE-ABS-KEY (bim) OR TITLE-ABS-KEY (building AND information AND modelling) OR TITLE-ABS-KEY (building AND information AND management) AND TITLE-ABS-KEY (digital AND twin) OR TITLE-ABS-KEY (dt) AND TITLE-ABS-KEY (construction AND industry) OR TITLE-ABS-KEY (o&m) OR TITLE-ABS-KEY (building AND site AND management)).

2019, there was also an exponential increase in articles containing 'BIM' and 'DT' together in the keywords. Being a transversal literature research, it was decided, by the research team, to not limit the initial research with restrictions on the subject areas. This was to avoid the exclusion of relevant interdisciplinary works relevant to the topics of the review. Table 1 summarizes the subject areas and related restrictions criteria. The research has led to 204 articles.

Initially, out of the total 204 articles, a pre-selection was made using these elements and notions.

Firstly, articles not published in their definitive versions were excluded ($n = 201$), and a filtration process involved also the selection of articles written exclusively in English ($n = 191$). Subsequently, to enhance the overall scientific rigor and quality, the inclusion criteria were refined to encompass only journal articles and conference papers ($n = 157$). Lastly, a more focused review was undertaken by restricting the analysis to articles within the domains of Engineering and Computer Science ($n = 137$). In the subsequent step, the titles and abstracts of these articles were carefully reviewed to ensure alignment with the RQs. Articles focusing, for example, on the restoration of museums and historical buildings, interviews and semi-structured questionnaires, as well as those investigating the topics of aerospace, procurement and tenders were excluded, as they were classified as off-topic in relation to the objective of this work, which focuses on the industrial and construction sector ($n = 41$). However, the topic of 'Digital Shadow' warranted further investigation, necessitating a thorough examination of the entire article (for a detailed analysis, refer to the subsequent section). The following validation sequence with the PRISMA Model (Figure 1) was employed for this SLR (Page et al., 2021).

Considering the distribution of articles per year, it transpires that it is only in recent years (2021–2023) that researchers have begun to explore this area of research to bring the BIM approach and modelling and DT into a direct connection for the construction sector. While DTs have long been utilized in aerospace and robotics for virtual modeling and simulation, it is only in recent years that their transformative capabilities have garnered attention in construction (Madubuike et al., 2022). The decision to include only journal and conference articles is due to the fact that generally these scholarly texts are considered more enduring and citable than other writings (e.g. book chapters or theses) and can, therefore, be considered of greater importance in terms of scientific value.

Before starting the evaluation and shortlisting phase of the papers through an initial reading of the abstracts, some schemes of bibliometric analysis, made with VOSviewer® software, are given. Bibliometric networks provide a quantitative approach to understanding the structure and dynamics of the scientific literature. By analyzing the relationships between publications and their attributes, researchers can then obtain valuable information about scientific collaboration, knowledge diffusion, and research impact (Vosviewer Software Manual). VOSviewer® software was chosen because it is one of the most widely used tools for bibliometric analysis and visualization of bibliographic networks. The software allows researchers to analyze and explore relationships among scientific publications, authors, keywords, and other entities. The first pattern of networks reported here concerns the keyword analysis of the 204 articles selected from the Scopus search. Obviously, the words BIM and DT are among the main connections, but other keywords such as Information Management, Decision-Making, Life-cycle, Project

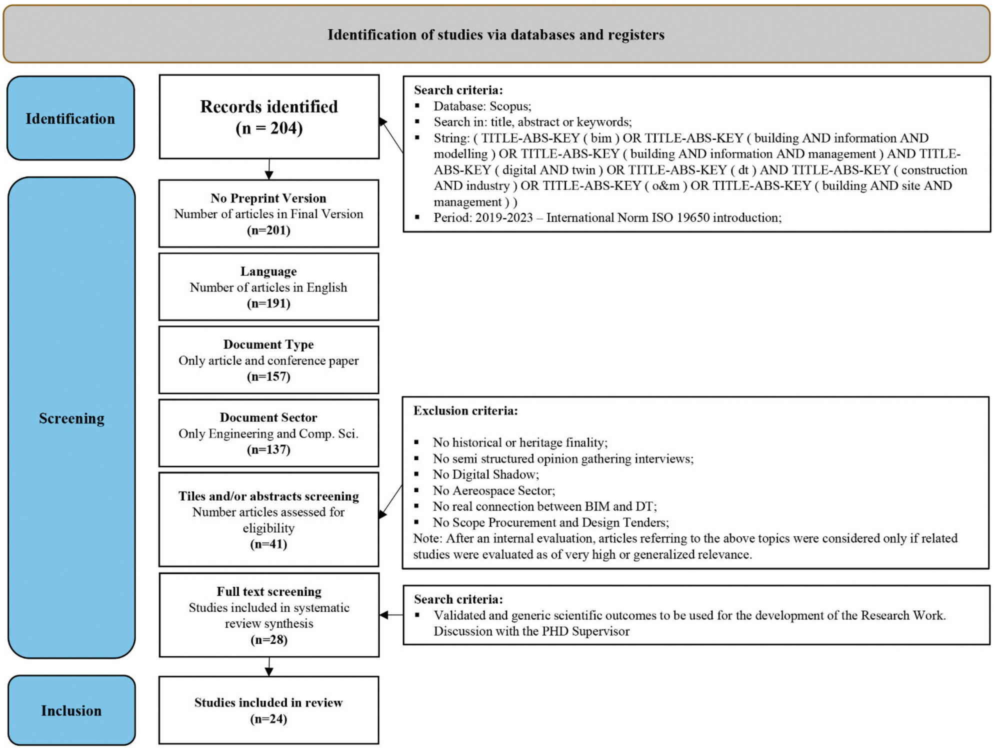

Figure 1. Summary of the SLR (based on the PRISMA model).

Management, Extended Reality, etc., also prove to be important and allow us to further refine the text analysis and literature evaluation in the following paragraphs (Figure 2).

3.2. Documenting the review

The second stage of the SLR consists of two steps:

(i) Compiling the review report
(ii) Validating the report

The review protocol was used for the quantitative and content selection of the analyzed articles. The choices and motivations for the chosen articles were discussed among a team composed of two researchers. This helped to accelerate double-checking needed for the ultimate approval and selection of the works that are included in this SLR. Articles not agreed by both researchers were excluded. For example, one of the exclusion criteria for various articles was not to use in this SLR research papers that mistakenly understood the concept of DT with digital shadow (Figure 3); articles that pointed out the differences were, instead, considered suitable. The DS is a virtual representation of a construction project or built asset that provides real-time insights into its status and performance during the construction and operation phases (Madubuike et al., 2022). Its purpose is to provide immediate, yet static and mono-directional, visibility into the current status,

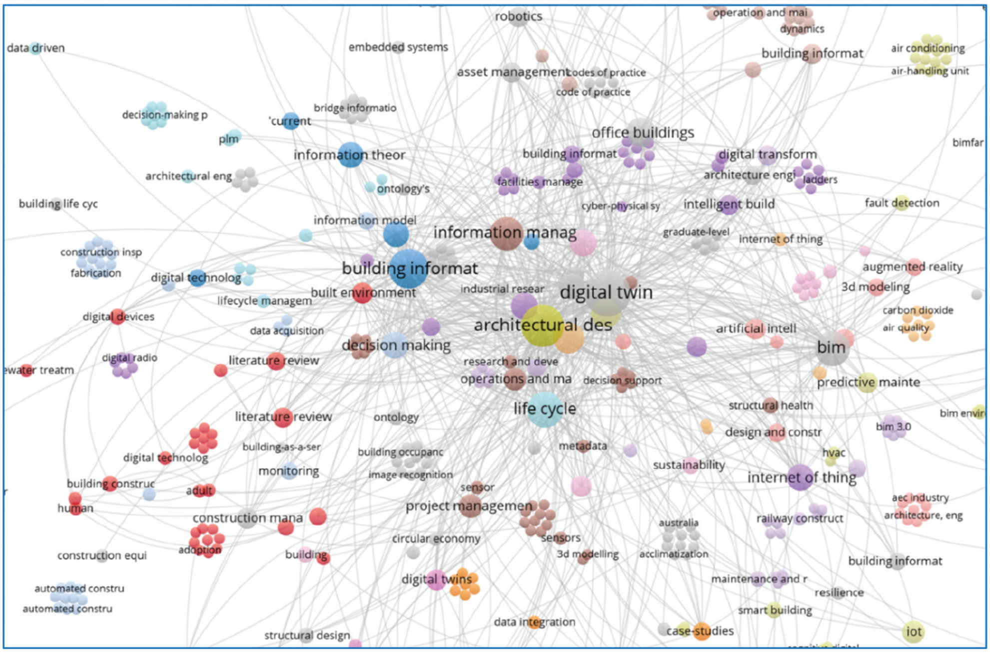

Figure 2. Keywords network scheme.

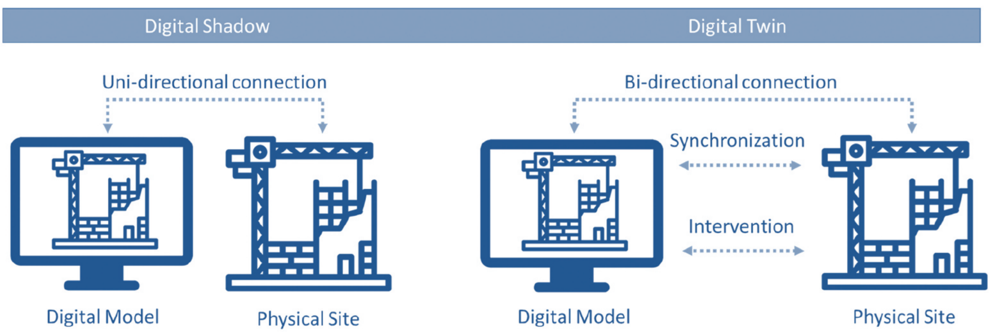

Figure 3. Digital shadow and digital twin in the construction sector.

performance and condition of the construction project or asset (Madubuike et al., 2022). By supporting monitoring, problem identification and decision-making during construction and operation and maintenance activities, it facilitates efficient management (Rafsanjani & Nabizadeh, 2023). The main objective of DS is real-time monitoring, performance tracking, problem identification, and decision support during construction and O&M activities. The DT is a digital replica of a physical construction project or built asset that captures and integrates data from various sources. It enables simulation, analysis, and optimization throughout the entire life cycle of the project or asset, including the design, construction, and O&M phases. It additionally supports design optimization, construction planning, performance monitoring, predictive maintenance, and operational decision-making. It integrates both real-time and historical data to create a comprehensive, bidirectional digital representation. The main goal of DT is to achieve a holistic approach to modeling, simulation, analysis, and optimization throughout the entire lifecycle of the construction project or asset (Wildenauer et al., 2022). It includes various aspects such as design optimization, construction planning, performance monitoring, predictive maintenance, and operational decision-making.

Considering the construction sector and BIM, the DS primarily focuses on monitoring and analyzing project data to optimize construction processes, while the DT focuses on simulating and analyzing the behavior and performance of physical assets for better operation and maintenance. Both concepts leverage real-time data, but their scope and application differ, with the DS centered around project management and the DT centered around asset performance and optimization (Coupry et al., 2021).

4. Content analysis of the SLR

This section summarizes the content analysis and is structured in four paragraphs. The first section will list the main shortcomings and limitations of BIM in the Construction and O&M phases of the building, while the second paragraph will mention the advantages and potential uses of DT to the construction industry. On the other hand, the third paragraph will discuss the gaps and problems encountered for the transition from static BIM model to DT.

4.1. Limitations of BIM in supporting the construction execution and O&M

The reviewed articles highlight a notable absence of emphasis on delineating the potential of the BIM approach during the design and creation phases of building projects. Given the standardization of BIM in numerous countries, this aspect is now considered established knowledge rather than a subject of ongoing research. Instead, the focus of the literature revolves around investigating potential issues or deficiencies in the BIM approach and modeling throughout the lifecycle phases of a building, from construction to demolition. 'IFC' and 'COBie' files are reported as standardized information interchange formats in the articles (American Institute of Architects, 2023; National BIM Standard-United States ® NBIMSUS™ 2023). This interoperability is vital in achieving BIM objectives, as it enables the sharing of accurate and comprehensive building data throughout the entire lifecycle of a project (IFC4, 2018). Assuming, therefore, that the BIM model was correctly created, with the level of detail LOD 500 and the databases within it are consistent with the IFC or COBie archiving standard, various limitations and problems can be found in the literature on the usability of these databases (Honghong et al. (Honghong et al., 2023)). Rafsanjani et al. (Rafsanjani & Nabizadeh, 2023) report in their research that the BIM approach finds its main application in the planning, design and construction phases. However, according to Honghong et al (Honghong et al., 2023), in the later stages of maintenance, building lifecycle management and O&M, it has some limitations that need to be recognized. First of all, the BIM framework does not allow for a complete digital lifecycle of a building project because the data and information collected are often incomplete, outdated or fragmented. Deng et al. (Deng et al., 2021) indicate that, even if the information is correctly entered, if BIM models are not regularly updated this may provide inaccurate or obsolete information, impeding effective decision-making and not providing additional value for the maintenance phase. In terms of data format, despite its widespread use, the IFC standard also has certain limitations when it comes to handling real-time data. According to Radzi et al (Radzi et al., 2023), one of the main limitations is the lack of support for real-time updates and synchronization of data across multiple software platforms. The IFC standard is primarily designed for exchanging static information of a project, rather than supporting dynamic and real-time data exchange. This limitation hinders the ability to have up-to-date and synchronized information across all stakeholders involved in a project, which is crucial for efficient decision-making and collaboration. Additionally, as related by Hosamo et al. (Hosamo, Imran, et al., 2022) the IFC standard does not provide a standardized approach for incorporating sensor data or real-time monitoring systems, which are increasingly utilized in modern construction projects. Moreover, Coupry et al. (Coupry et al., 2021) find BIM's effectiveness for predictive maintenance to be limited, as the models primarily focus on the physical aspects of the building rather than capturing dynamic factors and real-time data required for predictive maintenance analysis. Additionally, inadequate standards for facility management within BIM frameworks can hinder seamless integration between BIM models and facility management systems, impacting the overall efficiency of maintenance operations (Lu, Xie, Parlikad, et al., 2020)). Furthermore, as reported by Zhao et al (2022), the lack of interoperability among different BIM software and tools can limit the exchange of information and collaboration between stakeholders involved in building lifecycle management. Other limitations on interaction problems, as highlighted by Villa et al (Villa et al., 2021), are between 3D building models and IoT building facilities data. While BIM provides a comprehensive virtual model of a building, it often fails to fully integrate with the data generated by IoT devices embedded in the building's infrastructure. This disconnection prevents the seamless exchange of information between the physical building and its digital representation, limiting the effectiveness of BIM in optimizing building performance and maintenance.

Finally, according to Radzi et al (Radzi et al., 2023), BIM's reliance on a static database can restrict its adaptability to changing maintenance requirements, making it challenging to address evolving operational needs effectively. Addressing these limitations is crucial for leveraging BIM's full potential in maintenance, building lifecycle management, and the O&M phase and trying to transform a static parametric 3D model into a DT. Table 2 shows the quotations extrapolated from the articles read.

4.2. Advantages of digital in supporting construction execution and O&M

According to Giorgadze et al (Giorgadze et al., 2022), by creating a virtual replica of a physical building, DT enables facility managers to monitor and control various aspects of the building in real-time, leveraging connections to Internet of Things (IoT) sensors. Moreover, Wildenauer et al. (Wildenauer et al., 2022) state that one key advantage is also the ability to optimize maintenance operations by analyzing real-time data directly from the building. This allows for proactive identification and prediction of maintenance needs, leading to reduced downtime, improved asset performance, and enhanced cost-efficiency (Laghari et al., 2021). As reported by Hosamo et al (Hosamo, Nielsen, et al., 2022), DT facilitates energy-saving initiatives by providing insights into energy

Table 2. Shortcomings and limitations of BIM in view of a DT in construction.

Shortcomings Clusters	Stated facts
BIM is only used for the design phase and not in the construction and management phases	"BIM is predominantly utilized in the design and construction phase while IoT mainly manages the operation and maintenance process." (Rafsanjani & Nabizadeh, 2023)
	"BIM is commonly applied in capital delivery: planning, design and construction phases, but is not used effectively over the whole lifecycle, especially in the operations phase where the Facility Management (FM) falls." (Wildenauer et al., 2022)
	"The current 3D building models do not fully interact with IoT building facilities data. Data integration in BIM is challenging." (Villa et al., 2021)
	"BIM is much more widely used in the design phase, while in the FM phase it is still underutilized." (Villa et al., 2021)
	"BIM projects have mainly focused on technologies and less on various aspects of management." (Deng et al., 2021)
	"BIM is not always enough in delivering effective and efficientasset management, especially in operation and maintenance phase." (Lu, Xie, Parlikad, et al., 2020)
	"[. . .] BIM is used for the design and construction phases. However, BIM still has limited adoption within asset management." (Lu, Xie, Parlikad, et al., 2020)
	"BIM is not always enough in whole-life cycle asset management, especially in the O&M phase." (Lu, Xie, Heaton, et al., 2020)
	"While BIM has been widely adopted within the design and construction phase, its adoption within the operation and maintenance phase is limited." (Lu, Xie, Heaton, et al., 2020)
	"BIM is used for visualization in the design phase and construction phase rather than in the operations and maintenance phase." (Radzi et al., 2023)
	"The main limitation of BIM methodology is its static information: data are provided during the design phase but not updated during the building's life cycle." (Mannino et al., 2021)
	"Although BIM is widely used in the building design phase, there isstill much to do for its use in Facility Management." (Mannino et al., 2021)
	"According to British Standards Institution (BSI), the (BIM) standards are still inadequate to address the core FM processes, data types, entities, and parameters mapping with FM systems." (Zhao et al., 2022)
	"However, originally, BIM is mainly constructed to provide static data, such as documentation and ontological and geometrical information." (Coupry et al., 2021)
BIM does not allow interaction with work processes and organisation	"BIM only provides the building elements of a Virtual Design and Construction model and does not include the interaction among building, organization, and work process." (Rafsanjani & Nabizadeh, 2023)
	"[. . .] BIM is limited extent or barely with real-time data. Moreover, the necessary data governance in construction does not exist and is mainly reinvented for every project but not applied holistically on a life cycle basis." (Wildenauer et al., 2022)
	"BIM Data is not only incompletely available or inaccurate; thus, it is not beneficial in achieving core business service outcomes as there is no comprehensive alignment of information between the built asset integrating the facility, people and core processes." (Wildenauer et al., 2022)
	"BIM for O&M was still in its early stage and there were some challenges that need to be addressed. Examples include data interoperability, O&M principles for BIM implementation, and justification of the financial value of BIM-O&M applications in a building's life cycle." (Deng et al., 2021)
	"BIM models can only provide static raw information, while sometimes it is necessary or useful to evaluate projects in different aspects such as the integration of building design and construction schedules, which lead to the next level of BIM

(*Continued*)

Table 2. (Continued).

Shortcomings Clusters	Stated facts
	implementation." (Deng et al., 2021) "The fact that no program can use the modeled information is the third obstacle to adopting BIM in maintenance." (Hosamo, Imran, et al., 2022) "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 [. . .] not for comfort improvement, scenario, risk analysis and decision-making process." (Radzi et al., 2023) "The current major use of BIM [. . .] focuses on storing and visualizing operation data, it lacks means to go deeper for data and knowledge mining for a better decision to provide additional value for bridge maintenance." (Honghong et al., 2023) "The current 3D building models do not fully interact with IoT building facilities data." (Beetz, 2021) "Since the introduction of BIM, the industry's awareness of the importance of adopting digital models for FM is increasing. [. . .] There is a need for faster, more efficient, and possibly error-free real-time visualization and analysis of collected data." (Villa et al., 2021)
BIM is not 'error free' and does not provide updated data in real time	"BIM is basically a repository for project information, with the major limitation of not transferring all this information to the facility management phase and not being able to handle real-time data." (Villa et al., 2021) "BIM framework not fully enable whole life cycle digital construction. [. . .] intensive data and information have been collected, but often are incomplete, outdated, or fragmented." (Honghong et al., 2023) "BIM can generally only provide static data of the built environment and cannot update real-time information in the models automatically without additional data sources." (Deng et al., 2021) "BIM attempts to store and represent all the relevant information of a project's lifecycle in an object-oriented 3D model. However, time-consuming and error-prone manual work is required for the generation, maintenance, and upkeep of the information in BIM." (Giorgadze et al., 2022) "BIM is a digital representation of what will be built in a construction project with no real-time synchronization." (Radzi et al., 2023) "BIM will not satisfy the need for an automation solution in the AEC-FM industry alone." (Hosamo, Imran, et al., 2022) "Using BIM alone, there is no automatic condition monitoring to allow facility managers to make quick maintenance decisions." (Hosamo, Imran, et al., 2022) "[. . .] The second issue with maintenance modeling is updating BIM models during maintenance. It is unknown who would be responsible for updating the model following major renovations or additions to the building." (Hosamo, Imran, et al., 2022) "[. . .] An implementation framework to match Asset Information Requirements (AIR), which lowers the value of Construction-Operations Building information exchange (COBie) data generated during this phase, is unavailable in the literature." (Zhao et al., 2022)
BIM is often managed by personnel without precise training	"Person who places the order is frequently unaware of the appropriate use of the BIM models and the degree to which they should require modeling. Because of this, models can sometimes be too precise or leave out necessary information entirely." (Hosamo, Imran, et al., 2022) "[. . .] No one who could keep the model and its data up to date is available. In addition, the upkeep of the model would need the expertise of the maintenance staff, which is typically unavailable." (Hosamo, Imran, et al., 2022) "[. . .] A BIM model encompassing all the information required for fire safety, electro-technical repairs, and regulating potentially damaging situations would be too complicated for most users to implement effectively." (Hosamo, Imran, et al., 2022)

consumption patterns, allowing for better energy management and optimization strategies. Zhao et al. (Zhao et al., 2022) tested the predictive maintenance capabilities of DT to enable facility managers to schedule maintenance tasks based on actual asset conditions, reducing the risk of equipment failure and avoiding unnecessary maintenance. Decision-making processes are also enhanced, as facility managers can access comprehensive and up-to-date information from the DT to make informed choices regarding resource allocation, energy usage, and occupant comfort (Honghong et al. (Honghong et al., 2023)). Automation is another benefit of DT, as reported by Radzi et al. [40], as it enables the automatic detection of problems and their localization within the building, streamlining the maintenance process. Real-time data provided by DT enable facility managers to monitor performance indicators, detect anomalies, and take prompt action, ensuring efficient problem resolution. Using a virtual replica of the construction site, DT allows stakeholders to digitally simulate and visualize the assembly process of construction elements. This enables them to identify any clashes or issues beforehand, optimizing resource allocation and minimizing costly errors during construction (Hosamo et al. (Hosamo, Nielsen, et al., 2022)). Zhao et al. (2022) studied the real-time visualization capability of DT to enhance communication and coordination among project teams, improving overall efficiency (storage space management, sequence of activities, routes) and reducing rework. DT can also be utilized for measuring exact real-time occupancy data using image recognition sensors and computer vision. Radzi et al. [40] found that, by analyzing visual data from cameras and sensors, DT can accurately detect and monitor the occupancy of indoor spaces. This information is invaluable for optimizing space utilization, improving energy efficiency, and enhancing occupant comfort in buildings. Moreover, DT extends its benefits beyond individual buildings, allowing for urban-scale monitoring of multiple buildings, communities, and cities. By integrating data from various sources, such as IoT devices, smart infrastructure, and environmental sensors, DT enables comprehensive monitoring and analysis of urban environments (Villa et al., 2021)). According to Alizadehsalehi et al (Alizadehsalehi & Yitmen, 2021), this holistic view supports urban planning, infrastructure management, and sustainability initiatives, fostering smarter cities. Villa et al. (2021) reported that DT enables real-time collaboration, leading to faster problem-solving, improved project outcomes, and enhanced overall productivity. In conclusion, DT technology brings a multitude of advantages to the construction industry. From automating construction progress monitoring to providing a platform for real-time visualization, measuring occupancy data, enabling urban-scale monitoring, and facilitating collaborative work, DT enhances project management, decision-making, and overall efficiency (Lee et al., 2023). Embracing DT has the potential to transform the construction sector, unlocking new levels of innovation, productivity, and sustainability. Table 3 shows the quotations extrapolated from the articles read.

4.3. Current gaps for the transition from BIM to DT

The transition from BIM to DT technology in the construction sector faces several challenges and problems that need to be addressed. For Villa et al (2021), one significant issue is the lack of established standards and protocols for the integration of BIM and DT. The absence of clear frameworks hampers the seamless transition and interoperability between these two technologies, impeding the effective utilization of DT for facility management purposes (Hosamo, Nielsen, et al., 2022)). Therefore, Beetz (2021) states that there is a crucial need for semantic lifting of legacy data models, involving the systematic conversion and enhancement of existing structures to align with contemporary standard formats. Simultaneously, addressing the integration of vast domain vocabularies is paramount, requiring a comprehensive strategy to harmonize diverse terminologies within the DT ecosystem. Furthermore, Beetz (2021) argues that the DT must be able to adeptly handle multi-modal integration of heterogeneous status information, including sensor data, images, and measurements. This demands the design of a flexible architecture and the implementation of data fusion techniques to ensure a coherent representation of varied data sources. Additionally, Rafsanjani & Nabizadeh (2023) highlighted the lack of a human-centered vision in the development of DT, often resulting in a focus solely on technical aspects rather than considering user needs and requirements. Another challenge to solve is, according to Deng et al (2021), the absence of a robust connection between the 3D model derived from BIM and the integration of Internet of Things (IoT) sensors in the DT. This connection is essential for real-time data exchange and monitoring, which is crucial for accurate representation and control of the physical building. Moreover, Camposano et al. (2021) stated that there is a shortage of trained personnel with the necessary expertise to structure and establish these connections between the DT and IoT sensors effectively. Another technological hurdle encountered is related to the location and coverage of the sensors network, as well as the signal strength of the router or hotspot. Ensuring a robust and reliable network infrastructure is crucial for seamless communication and data transfer within the DT ecosystem (Mannino et al., 2021)). Despite advancements in IoT techniques, data loss during the transfer process remains a concern. Mannino et al. (2021) reported that factors like software incompatibility and external environment interferences can lead to data fading or loss, impacting the reliability and accuracy of the DT. Furthermore, for Deng et al (2021), the heterogeneity of data collected by different IoT sensors, both in terms of type and format, poses difficulties in the data analysis process, requiring additional efforts for data harmonization and integration. In terms of management, according to Alizadehsalehi & Yitmen (2021), human involvement is still essential for decision-making and feedback in the DT environment. While automation and AI algorithms can assist in certain tasks, human expertise and judgment are crucial for complex decisions and nuanced understanding of the construction process and, to meet growing expectations of users, the architecture of a DT becomes more complex, encompassing a broader range of components and scope. The increasing complexity inevitably brings additional challenges in terms of system design, integration, and scalability (Hosamo, Nielsen, et al., 2022)). Additionally, the working hypotheses and knowledge about DT are still fragmented and limited to single case studies, lacking comprehensive research and generalizability. This element was found in all the articles analyzed. And the few concrete cases involved semantically simple constructions such as bridges or roads and not complex buildings. To overcome these challenges, it is crucial to develop standardized protocols, establish clear frameworks, adopt a human-centered approach, strengthen the connection between BIM and DT, invest in training and education programs for personnel, and conduct further research to consolidate working hypotheses and expand the

Table 3. Advantages of DT in construction.

Advantages Clusters	Stated facts
DT can handle real-time data	"The concept of DT was developed to supplement static BIM in the asset lifecycle by providing opportunities to handle realtime data." (Wildenauer et al., 2022)
	"[. . .] DT technologies enable efficient and responsive planning and control of FM activities by providing real-time status of the building assets." (Zhao et al., 2022)
	"A DT is intended to supplement BIM with real-time enabling technologies." (Wildenauer et al., 2022)
	"During the Construction phase, DT provides facility owners with real-time information, allowing owners to make more informed decisions based on facts rather than assumptions." [40]
	"Developing DT frameworks often involves integrating the Internet of Things (IoT), BIM, and finite element models. These DT frameworks provide updates that are practically real-time to improve construction management." (Lee et al., 2023)
DT can optimise the construction and maintenance phase (also predictive)	"DT can be used for predictive maintenance, tenant com-fort improvement, scenario and risk analysis as well as it can enhance the decision-making process." [40]
	"[. . .] DT technologies have their hotspots in real-time data collection and monitoring, decision making, and predictive maintenance." (Zhao et al., 2022)
	"DT has been increasingly applied for maintenance and asset management in the construction industry. In particular, abnormal situations [. . .] fire detection, spatial object displacement, earthquake disaster, and flooding." (Lee et al., 2023)
	"[. . .] The main application of DT is considered in the operation and maintenance phase, [. . .] the researchers can extend this topic to the other life cycle phases." (Rafsanjani & Nabizadeh, 2023)
	"The DT can be used to replicate [. . .] in the operation and maintenance phase (O&M) into their virtual twin models, constructing and updating these models based on multiple sources of data, and adding new functions to simulate different operation scenarios." (Honghong et al., 2023)
	"Predictive capabilities of DT are very promising in the building sector." (Hosamo, Nielsen, et al., 2022)
	With such prediction capabilities (of the DT), the operators and managers can use the results to plan the maintenance early enough to prevent any equipment failure, helping them to move from reactive maintenance to proactive maintenance, such as preventive maintenance solution." (Coupry et al., 2021)
	"DT in Construction (DTC), [. . .] providing accurate status information and proactively analysing and optimizing ongoing design, planning and production." (Wang et al., 2023)
	"DT technology is frequently used for problem detection and maintenance savings despite a relatively new concept." (Hosamo, Nielsen, et al., 2022)
	"Combined with predictive maintenance to perform automatic planning, these DT can be used to propose the best maintenance procedures to be performed to the operator, providing a prescriptive version of the maintenance." (Coupry et al., 2021)
DT can optimise building obsolescence	"DT is a tool for saving energy consumption in built environments. However, the automation resulted from DT can also save other resources (e.g. manpower) and increase safety." (Rafsanjani & Nabizadeh, 2023)
	"DT identifies the shortage of resources, analyzes requirements, performs decisions, dispatches the resources, and updates all the processes in the database with the support of AI." (Honghong et al., 2023)

(*Continued*)

Table 3. (Continued).

Advantages Clusters	Stated facts
	"[. . .] DT can predict the building components' health, their useful life, failures and, in general, the building performance." (Villa et al., 2021) "DT can be used at Urban Scale monitoring multiple buildings such as communities and cities." (Alizadehsalehi & Yitmen, 2021)
DT can optimise/regulate the use of constructed spaces	"[. . .] DT for detecting human motions in crowded environments and measuring exact real-time occupancy data using image recognition sensors and computer vision." [40] "[. . .] Global monitoring of the building and its equipment. Thanks to the centralised database pro-vided by the DT, the different stakeholders obtain easier access to data related to the equipment they want to monitor." (Coupry et al., 2021) "[. . .] DT using sensors to track dynamic onsite conditions, with which reminders can be sent to its inhabitants to allow immediate actions." (Zhao et al., 2022)
DT can increase site/ builiding safety	"[. . .] great potential of digital twinning processes for improving fault prediction and detection accuracy while also lowering cost and risk to human life." (Hosamo, Nielsen, et al., 2022) "DT is necessary for facility management since they can be employed in "What-if" analysis in decision making relating to the building's operation and maintenance activities." (Opoku et al., 2021)

knowledge base surrounding DT in facility management. Table 4 shows the quotations extrapolated from the articles read.

5. Discussion

Responding to the first of the RQs, it is reported that many articles have listed that a significant limitation of the BIM approach is the static nature of its data and information. Thus, even though it is very often reported that BIM can also be a tool that can be used for process and activity management (construction or maintenance), in reality it is often information that is not updated over time. In fact, the updating of data, must be done manually and is often not structured with rules and time systematicity, also because this requires high time effort. This dimension goes beyond the physical and material aspects of the model and focuses on the long-term management and maintenance strategies to ensure optimal performance of the building and sustainability during the service life. Within the management dimension of BIM, various activities, such as facility management, operations planning, asset tracking, environmental well-being and maintenance scheduling, have to be managed only manually (Hosamo, Imran, et al., 2022). The current BIM approach, while remaining an industry standard and a crucial foundation for up-to-date information visualization and data management, cannot fully address these needs automatically. RQ2 was focused on understanding what advantages the DT could bring to the construction sector. As the Internet of Things (IoT), Machine Learning (ML), and Artificial Intelligence (AI) sectors continue to advance, the utilization of DT can provide substantial benefits and decision support for the above-mentioned activities (Table 3) that require up-to-date data collection and classification (Hosamo, Nielsen, et al., 2022). In Section 4.2, five main clusters have been identified that group together the benefits of using DT in the construction sector, i) *DT can handle real-time data, ii)*

Table 4. Problems and gaps related to the transition between BIM and DT.

Gaps Clusters	Stated facts
Lack of a standard framework for data transfer	"The definition of a common model of web-based protocols for data exchange allows transferring this data between objects, making the various network parts interactive." (Villa et al., 2021) "[. . .] Absence of a logical implementation framework and the integration of empower-ing technologies and instruments. This subject requires additional researchs." (Hosamo, Nielsen, et al., 2022) "[.] Semantic lifting of legacy data models, the alignment and integration of vast domain vocabularies, multi-modal integration of heterogeneous status information (sensor, images, measurements) and ongoing efforts to create reference frameworks for semantically rich DT in the built environment." (Beetz, 2021) "National and international norms and standards may apply to DT. If these restrictions are unclear or difficult to follow, DT adoption may be hampered." (Bandara et al., 2023) "Because of The lack of a completed framework application case, it is difficult to clarify the improvement degree of the overall performance in the validation stage." (Zhang et al., 2022) "[. . .] lack of up-to-date data, usually caused by incorrectly anticipating the need of later phases and by a lack of communication between the different actors in these phases." (Coupry et al., 2021)
Lack of a sensor connection	"[. . .] No clear insight about such a holistic and life-cycle DT concept. Especially, there is very little under-standing about how various sensory and non-sensory data from con-struction and operation phases can be seamlessly integrated into the 3D BIM models." (Giorgadze et al., 2022) "[. . .] many types of IoT sensors collect either the same or different environment data, while their data type may not be homogenous, which can present several difficulties in the data analysis process." (Deng et al., 2021)
Lack of network stability	"The main technological challenges found are related to the location and coverage of the sensors network and the signal strength of the router/hotspot." (Mannino et al., 2021) "A significant problem that could arise is the stability of networks for communicating information." (Mannino et al., 2021)
Lack of functional platforms for management	"Future research may include improvement of systems and platforms by incorporating more functions related to the PM sub-competencies and productive analysis." (Mannino et al., 2021)
Risk of data loss	"[. . .] Data loss during the transfer process is still a problem due to various reasons such as software incompatibility and data fading due to external environment interferences." (Deng et al., 2021)
Complexity of the DT model	"[. . .] DT are complex software ecosystems that emerge from the increased expectations that AEC/FM stakeholders place upon BIM and other related technologies. To cope with those user demands, the architecture, components, and scope of DTs are generally more complex than those found in the existing software solutions." (Camposano et al., 2021)
Human contribution difficult to discard	"In terms of decision-making, most of the relevant studies still involve human in the control loop to make the final decisions based on the collected real-time data (e.g. construction progress, indoor tem-perature, humidity) or gleaned insights from the predicted results (e.g. energy consumption, thermal comfort)." (Deng et al., 2021) "In terms of control strategy, humans still play an important role for decision and feedback." (Deng et al., 2021) "In the DT, Human-centric scenarios should thereby be developed through artificial intelligence which let integrate human decision-making real-time data into the information utilized." (Alizadehsalehi & Yitmen, 2021)

(*Continued*)

Table 4. (Continued).

Gaps Clusters	Stated facts
Lack of an AI connection	"DT can simultaneously be utilized with artificial intelligence. Considering current challenges of artificial intelligence (e.g. machine-centric vs human-centric), the parallel usage of this intelligence with VDC and DT can raise more challenges." (Rafsanjani & Nabizadeh, 2023)
Lack of complete working use cases	"Lack of use cases and usage in building management shows that there is still a need to show the added value of using DT to professionals in the construction sector. [. . .] Few papers related to the application of a BIM-based DT combined with XR technologies for building maintenance." (Coupry et al., 2021)

optimise the construction and (predictive) maintenance phase, iii) counteract building obsolescence, iv) regulate the use of constructed spaces and v) increase site/builiding safety. Specifically, it was confirmed that DT can bring enhanced decision-making and real-time monitoring by leveraging real-time data from sensors and IoT devices embedded in construction sites and buildings. This provides a continuous feedback loop that enables immediate responses to emerging issues; for example, in an office building, temperature and humidity sensors can detect non optimal working conditions, prompting immediate adjustments to e.g. time plans and further breaks to ensure worker comfort. Considering the second cluster (*optimise the construction and (predictive) maintenance phase) DT* can enable project managers to make informed decisions quickly, thereby reducing delays, optimizing resource allocation, and improving project timelines. As a practical example, vibration sensors on cranes that can predict potential bearing failures, enabling maintenance teams to replace bearings before they fail, avoiding asset breakdowns and delays. DTs could also support principles of minimizing waste and maximizing resource utilization. For example, real-time monitoring of the heating system's energy consumption can allow changes to be made that optimize boiler efficiency. In addition, DTs support circular building principles by facilitating the reuse and recycling of materials, thus contributing to a more sustainable built environment. For example, a DT could provide information on materials and make predictions of new functions for existing spaces prior to adaptive reuse of existing buildings. As practical example in the case of an old warehouse being converted into a school, the DT could analyze the structural integrity of existing beams and predict how they would support loads in the new building, while also simulating various layout options to optimize natural lighting for the building functions. In addition, the use of standardized data formats and protocols could ensure interoperability between different systems and tools, which is essential for data exchange and integration. To achieve these results, it is essential to develop a precise protocol, which is currently lacking in the construction sector. This protocol would focus on data standardization and interoperability, which is the primary subject of our team's research.

As reported in the result section, DTs can also predict when maintenance is needed, thus preventing unexpected failures and extending the life of assets. This predictive capability is particularly valuable in cases where maintaining operational efficiency and minimizing downtime are critical such as in hospital complexes or schools. Unfortunately, these facilities are among the most complex and articulated to manage, given the amount of environments, pathways, sensors and possible uses of the spaces.

Considering the cluster *'DTs can enhance worksite/building safety'* (Table 3), DTs can improve workplace safety by offering a detailed and accurate representation of the worksite and tracking the routes and locations of workers and trucks using geofencing sensors and fisheye cameras.

Finally, the adoption of DT technology can lead to substantial cost savings throughout the construction process. For example, DT can be used to monitor real-time data from sensors embedded in concrete to ensure optimal curing conditions, a voiding wasted waiting time or rework on the structure.

RQ3 made it possible the exploration of potential gaps hindering the evolution of BIM model within a DT context. The content analysis led to the determination of macro clusters of barriers and gaps for BIM/DT evolution, some of which are predominantly technological, while others relate to the human component such as low level of technology acceptance, lack of clear DT value propositions, project complexity, and the static nature of building data (Table 4).

Chief among these obstacles is the absence of a clearly defined minimum framework that encompasses the preparation of a BIM, including its databases, for subsequent transformation into a DT. Additionally, the absence of established protocols for managing diverse sensors and real-time data collection poses a significant hurdle. Unstable networks, particularly in the context of construction site criticality, further compound the challenges. The full automation of the process without human intervention remains elusive. Lastly, there is a distinct lack of tools designed for on-site consumption of information extracted from the DT, adding another layer to the existing barriers. To facilitate the successful integration of BIM and DT, it is crucial to standardize the processes involved in connecting and updating data. Defining a codified sequence of steps for the BIM/DT connection will improve the efficiency and effectiveness of data utilization, ensuring seamless integration and synchronization between the two models (Figure 4). This standardization effort is essential to maximize the value and potential of DT in combination with BIM. The BIM/DT connection therefore requires targeted efforts on ontologies, semantics and recognized standards. This is because the DT that succeeds traditional BIM is based on a semantic-based model and a linked data approach. These methodologies have the remarkable ability to integrate data from diverse and fragmented sources, leading to more informed decision-making processes 47 (Khajavi et al., 2019). To make on-site use of a DT and maximize the advantage provided by real-time data, it is possible to leverage Extended Reality (XR). Some of the reviewed articles highlight the efficacy of Augmented Reality (AR) and Mixed Reality (MR) technologies and hardware as valuable tools for real-time data utilization directly in the field (Alizadehsalehi et al., 2020). By leveraging these technologies, users can access and interact with data in real-time, leading to improved situational awareness and more effective decision-making processes. AR and MR technologies offer enhanced visualization capabilities, allowing users to overlay virtual data onto physical spaces and objects, thereby facilitating better understanding and interpretation of information (Shishehgarkhaneh 2022). In reviewing the articles, it becomes also evident that a significant majority, approximately three-quarters of the cited case studies, within the DT used in the civil engineering field focus on infrastructural works such as bridges, railways, and tunnels, rather than buildings (Giorgadze et al., 2022; Mannino et al., 2021; Papaioannou et al., 2016; Rafsanjani & Nabizadeh, 2023). Both the operational phase of construction and the operation and maintenance phases are covered in these articles. A plausible hypothesis for this observation is that these infrastructural works are often

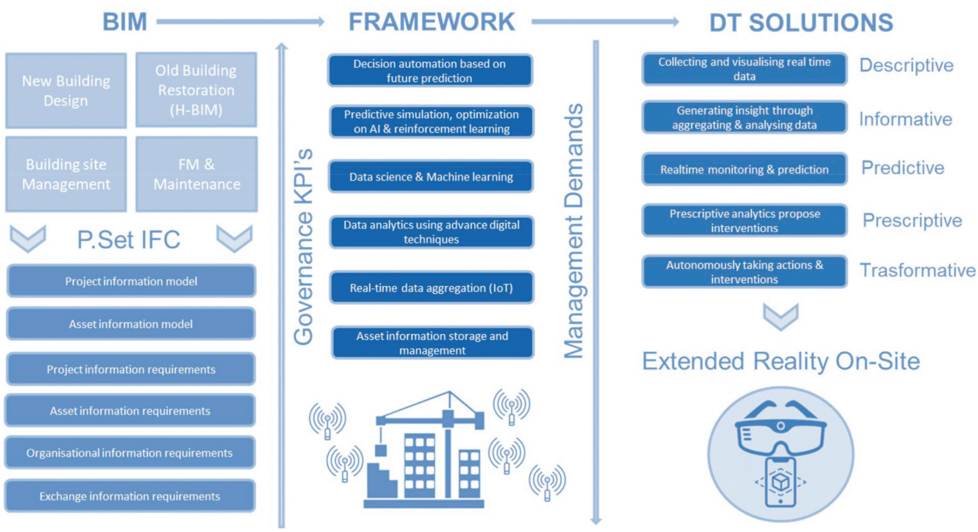

Figure 4. BIM to DT minimal framework.

characterized by a simpler and more limited set of elements, functions, and maintenance operations compared to complex building systems. The variables and potential variations associated with buildings are considerably more intricate and challenging to define, making them inherently more complex to study and analyze. In contrast, infrastructural works present a more controlled and standardized environment, allowing for more straightforward identification and examination of relevant factors. This emphasis on infrastructural works in the available literature may suggest that the civil engineering field has primarily directed its attention toward these areas as a means to establish foundational knowledge and methodologies before delving into the intricacies of building systems. Further research and investigation into the complexities of building structures are essential to enhance the understanding and develop comprehensive strategies for maintenance and management within the entire built environment. Another notable observation is the absence of any study that comprehensively addresses the 'building system' in its entirety. While there are case studies exploring various aspects of building systems, such as structural analysis, energy efficiency, HVAC systems, or occupant comfort, none have provided a holistic examination of the entire building system as an integrated entity (Beetz, 2021; Hosamo, Imran, et al., 2022). By proposing a specific scope of application, the management of variable components is effectively constrained and limited. This lack of comprehensive research on the building system as a whole is a significant gap in the existing literature. The complexity and interconnectedness of different components within a building system, including architectural, structural, mechanical, and electrical aspects, pose a substantial challenge for researchers and practitioners alike. The absence of studies focusing on the entire building system limits our understanding of how these different components interact, influence each other, and collectively impact building performance and maintenance. Addressing this gap in research would require interdisciplinary collaboration, integration of various expertise, and a systems-based approach to comprehensively analyze and optimize the building system. A holistic understanding of the building system is crucial for developing effective strategies and solutions that can maximize building performance, energy efficiency, occupant satisfaction, and overall sustainability. In summary, transitioning from BIM to DTs involves overcoming substantial technical, organizational, and cultural barriers.

The static nature of BIM data must evolve into an open, dynamic platform capable of real-time data integration and advanced analytics. Addressing these challenges is essential for leveraging the full potential of DTs in enhancing construction processes and lifecycle management. Figure 4 outlines a minimal framework to extend BIM into a DT, including new buildings, heritage BIM for historic structures, and phases of construction and maintenance. The first step of the framework, involves constructing the BIM model using specific classes and property sets (P.Set IFC) in accordance with Building Smart Consortium standards [50]. This approach ensures a verified dataset of information and data structures that will form the foundation for managing Key Performance Indicators (KPIs) to support the project operational control. The second phase describes the creation of a semantic middleware, facilitating the integration of IoT sensors to perform data analytics and predictive simulations through AI, along with secure and up-to-date data storage. This involves developing APIs that enable data exchange and integration with external IoT solutions. Protocol translation mechanisms may be needed to bridge differences between proprietary and open standard protocols. The third proposed phase involves the implementation of a fully semantic DT, which analyses datasets from the BIM model and other IoT sensors by using ML and AI. Those steps will enable the BIM model to evolve into a Digital Twin (DT) to support the construction sector.

Summarizing the discussion paragraph presented in this paper, the original contributions of the working group are as follows:

(i) The main weaknesses of the BIM approach have been researched and analyzed;
(ii) The characteristics of DTs for the construction industry, encompassing both the construction and O&M phases, were summarized and discussed;
(iii) The key technological and domain gaps hindering the large-scale implementation of DTs in the construction sector were identified and analyzed;
(iv) A conceptual framework was proposed to enable the transition from a BIM model to DT.

5.1. Limitations of the review

One of the limitations of this research is that only Scopus has been considered as scientific reference database. Another limitation is that works not written in English language were excluded from the content analysis. The search period was restricted to focus on recent/up-to-date data and only included publications from 2011 onwards. This timeframe has been chosen to focus on recent findings and to limit the content to be analyzed. Another limitation is that our work includes only scientific publications in the form of journal and conference papers, while books, reports, manuscripts, and trade journals were excluded. Journal papers were considered because of their usually peer-reviewed content and conference papers because of potential new findings. Another limitation of our work is that we considered only works published in the scientific literature; practical works published in online magazines, newspapers, and reports were not considered.

6. Conclusion and future research

The objective of this paper was to investigate the limitations of the BIM approach, potential improvements and areas of use of DT with regard to construction, building sites and building operations and find the gaps and barriers that exist today for the evolution of a BIM into a DT. The SLR tool was used to answer three research questions using the Scopus database. Once the research string was defined, the articles initially found (204) were skimmed using both objective criteria and by reading and analyzing the abstracts and discussion within the working group. The results of the article analysis were then reported and discussed.

The first contribution of this article is to highlight the limitations of the BIM approach in the construction site operations management and maintenance (O&M) phase, emphasizing the need to address these limitations to leverage BIM's full potential evolving it in a DT. In fact many articles pointed out that a BIM model, the intensive data and information collected can be incomplete, outdated, or fragmented. This hinders effective decision-making and fails to provide additional value for the maintenance phase. Regular updating of the BIM models with real data will be essential to ensure accurate and up-to-date information, but this operation couldn't be undertaken manually since it would cause excessive effort and problems of handovers between different operators (Opoku et al., 2021). Furthermore, BIM's effectiveness for predictive maintenance is not related since it primarily focuses on the design and construction phase of the building and lacks the ability to capture dynamic factors and real-time data necessary for predictive maintenance analysis. Interoperability issues among different BIM software and tools further limit the exchange of information and collaboration between stakeholders involved in building lifecycle management. The second contribution is to point out which advantages could come from enhancing interoperability with a DT. In fact promote effective communication and information sharing (Xie et al., 2022), transforming the static parametric 3D model into a dynamic DT can overcome this limitation by enabling real-time data integration and facilitating adaptive maintenance strategies. Last contribution reported in the article was the study of the limitations and barriers that exist today for the evolution of BIM in a DT. BIM operates with a file-based, object-oriented information construct, whereas DTs use object-based graph networks stored in cloud services. This fundamental difference in data handling and storage means that current BIM systems are not designed to support the continuous, bidirectional data flows between physical and virtual models required by DTs (Boje et al., 2020). Consequently, the transition to DTs demands a rethinking of data management practices to accommodate the real-time data exchange and processing needs of DTs. Although BIM standards like IFC facilitate some level of collaboration, they do not adequately address the dynamic, real-time needs of DTs. Achieving interoperability and standardization across various platforms, devices, and stakeholders is crucial for deploying DTs effectively at scale.

Without standardized protocols and frameworks, integrating diverse data sources and ensuring consistent data quality remains a daunting task. Integrating BIM with IoT devices and AI-driven analytics is another major challenge. While BIM models are comprehensive in their 3D representations, they often lack the semantic depth and real-time data processing capabilities necessary for DTs to utilize real-time data for predictive analytics, diagnostics, and automated decision-making. This lack of integration capability limits the effectiveness of DTs in providing accurate and timely insights, which are crucial for efficient project management and decision-making (Tuhaise et al., 2023).

Therefore, future fields of research in BIM-DT integration could be:

(i) Requirement Analysis for the Transition: This field of research should focus on identifying and analyzing the specific requirements and challenges involved in transitioning from a BIM model to a DT with the integration of IoT sensors (Khajavi et al., 2019). It involves investigating the necessary data and information exchange protocols, interoperability standards (like IFC or COBie), data collection methods, and overall system architecture to enable a seamless transition and effective utilization of the DT in the context of the construction and facility management domains.

(ii) Comparative Analysis of DTs: This research area focuses on comparing DTs used in the construction field with those utilized in the industrial field. By examining the similarities and differences, researchers can identify commonalities, transferable practices, and unique characteristics of DTs in each domain. This analysis can contribute to cross-disciplinary knowledge sharing, fostering innovation, and identifying best practices for specific applications of DT technology (Boyes & Watson, 2022).

(iii) Specific Use Cases of DTs in Construction: This field of research involves breaking down the DT concept into specific use cases or environments to study their potential uses, benefits, and requirements. Two scenarios can be explored: the first focuses on the utilization of DT during the construction phase of a building, examining how they can enhance project planning, coordination, and monitoring. The second emphasizes the application of DTs for O&M and FM activities throughout the building's lifecycle, addressing predictive maintenance, energy optimization, asset management, and occupant comfort. Finally, specific solutions could be investigated/realized in AR/MR for the use of DT directly in-field (Laghari et al., 2021).

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Highlights

- Systematic literature review of BIM evolution to DT in the construction sector.
- Analysis of the shortcomings of BIM in the construction and O&M phases.
- Analysis of the advantages of DT in the construction and O&M phases.
- Analysis of the existing gaps for the evolution of a BIM into a DT.
- Critical discussion of the results of the SLR and possible solution and research focus.

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