

REVIEW ARTICLE

Implementation of Digital Twins in construction industry: A systematic review

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Abstract

Although Digital Twins have advanced remarkably in many industries, including manufacturing and healthcare, the construction industry faces a significant gap in adopting and implementing Digital Twins. Thus, this paper aims to examine the consequences of implementing Digital Twins technology in the construction sector to provide a comprehensive picture of Digital Twins applications within the construction lifecycle and the technologies employed, in addition to identifying the challenges facing the technology in the construction sector. The study utilized a systematic review methodology to accomplish its objective. The study categorized the applications of Digital Twins into four stages of the construction project lifespan. The four phases encompassed in this process are planning and design, construction, operation and maintenance, and demolition and recovery. The findings indicate that the utilization of Digital Twins in the planning and design phase, as well as the demolition and recovery phase, is not tangible compared to its applications in the construction, operation, and maintenance phases. This study identified the difficulties associated with implementing Digital Twins technology in the building industry. The problems encompass various aspects, including the sector itself, economic and political factors, technical advancements, and social issues. Through the resolution of these obstacles, the construction sector might attain complete integration of Digital Twins technology. Future research is advised to enhance the deployment of Digital Twins by gaining a more profound comprehension of Digital Twins knowledge throughout the lifecycles of construction projects.

1. Introduction

The Digital Twins (DT) is an advanced technology that has transformed the business by replicating every product, process, or service aspect. The technology can recreate all physical objects in a digital environment and offer engineers insights and information from the virtual realm [1]. Consequently, technology empowers firms to rapidly identify and resolve tangible issues, create

and construct superior products, and achieve value and advantages faster than previously attainable. Moreover, DT technology empowers enterprises to enhance their business operations and optimize performance [2]. DT is a notion that consists of three parts: a physical object, which can be either potential or actual; a digital representation of the physical thing; and data and information linkages that link the physical and digital entities [3, 4].

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Michael Grieves first introduced this groundbreaking concept during his product lifecycle management course in 2003 [3]. According to Grieves, DT monitors, manages, and improves from the beginning to the end of their lifecycles [4].

An early and significant application of DT technology occurred in 1970 when NASA engineers utilized a simulator, a replica of the command module, and a separate replica of the module's electrical system, to successfully resolve and save the Apollo 13 mission. NASA engineers successfully executed the procedure in less than two hours, thereby preserving the lives of the three astronauts aboard. While the origins of DT may be traced back to the aerospace industry, the manufacturing industry is currently at the forefront of technological exploration. DT has been identified as the primary facilitator of Industry 4.0 and smart manufacturing [5]. A DT-based system has been presented for the assembly-commissioning of extremely accurate goods. This approach tackled the ongoing difficulties of ineffective assembly and unreliable quality control that are inherent in conventional assembly methods [6]. DT has been efficiently adopted in sectors including healthcare, automotive, smart city, energy, and agriculture.

The construction sector has made significant contributions to both economic progress and social stability [7]. Nevertheless, the construction industry's pervasive nature also imposes significant constraints on its ability to make rapid advancements [8]. In the era of Industry 4.0, there has been a growing focus on the study and application of informatization, digitalization, and intelligent technologies across several sectors [9]. By enabling real-time communication and exact correlation between digital models and the actual objects that correspond to them, DT can extend the useful life of the product [10]. Given the growing digital requirements of the construction industry and the digitization features of DT, it is evident that DT has great potential for implementation in the construction industry [11] throughout the entire life cycle, from initial design to eventual demolition

[12]. Therefore, effective communication and information exchange are essential among various stakeholders, including architects, engineers, contractors, facility managers, and construction workers, at every project lifecycle phase, which can be accomplished by utilizing DT [13].

Building information modeling (BIM) and DT are two crucial technologies in the construction sector, although they have different uses and functions. To provide thorough assessments after construction, BIM focuses on producing detailed models of building systems and components [14, 15]. However, with real-time data integration and multidimensional digital representation of physical assets, systems, and processes, DT speeds up BIM's development and advantages, enabling informed decision-making and live asset monitoring [14, 16]. Although BIM is necessary for thorough evaluations, DT improves this by fusing cloud computing, Internet of Things (IoT), AI, and cyber-physical systems to create a networked virtual environment for planning, directing, and overseeing projects at every stage of their development [17]. Furthermore, BIM focuses on 3D modeling and construction simulation [18] whereas DT provides virtual-reality mapping and real-time interaction between physical and virtual workshops, improving joint management and production efficiency. BIM and DT interoperability are essential to achieve energy savings, environmental initiatives, and general sustainability in the building industry [14]. Additionally, integrating BIM and DT can improve building construction by offering solutions for better design practices and industry efficiency [19].

DT can be utilized to replicate the construction process, enhance design efficiency, identify potential issues, and monitor the functioning of the building throughout its lifespan. For instance, DT can evaluate various construction techniques and forecast their effects on the building's energy usage, structural integrity, and overall sustainability [20]. In addition to evaluating health conditions and organizing maintenance tasks, there are three potential applications of DT: lifecycle management, engineering enhancements, and

numerical analysis for better decision-making [21]. Nevertheless, there remains a deficit in understanding the application of DT in the field of construction. DT is a recently developed technology that demands proficiency in multiple domains, including BIM, data analytics, and software development [22]. The construction sector has not fully adopted the use of DT, in contrast to other sectors [23]. Thus, this study seeks to investigate the utilization of DT technology in various stages of the construction industry's life cycle by conducting a systematic literature review. The paper contributes to the literature by identifying the implementation of DT from the perspective of the construction lifecycle, discussing the technologies employed, and determining the challenges facing DT in more integration and adoption in the construction industry.

2. Methodology

This study utilized a systematic review of the current literature to evaluate the available research within the specified area of the study. A systematic literature review differs from a traditional narrative review by employing a rigorous, transparent, and replicable methodology [24].

The steps of the review process, which include eligibility, identification, screening, and data abstraction and analysis, come next. The authors depend on Scopus's main journal database. One of the most critical sources of citations and abstracts for peer-reviewed literature is the Scopus database, which includes over 22,800 journals from all 5000 publishers globally. Many subject areas are included in this database, such as biological sciences, agricultural, social sciences, and environmental sciences.

The authors chose the four steps that comprise the systematic review process. In May 2024, the

review procedure was carried out. Finding relevant keywords to employ in the search process is the first step in the identification process. Related terms, including DT, digital technologies, and the construction industry were utilized, drawing on prior research and a thesaurus shown in Table 1.

The authors may demand that specific criteria be evaluated and narrowed to prevent prejudice. First, in terms of language selection, only English-language publications are chosen in order to prevent misinterpretation, misunderstanding, and challenging translations. Second, only book chapters, review articles, and article journals were chosen. Thus, excluding the book series, book, letter, abstracts, editorials, and conference proceedings should be discarded. Thirdly, the authors chose multiple timeframes with a 10-year window (between 2015 and 2024). This is due to the authors' belief that, based on comparable papers, this time frame is sufficient to observe how research has evolved. The study's flow diagram is displayed in Fig. 1. After the identification and screening stage, the remaining articles were abstracted to be assessed and analyzed.

3. Analysis and Results

3.1. Bibliometric analysis

The study was comprised of 43 pertinent papers obtained from internationally renowned journals such as Automation in Construction, Buildings, Building Engineering, Sensors, Applied Science, Construction Engineering and Management, and IEEE. Fig. 2 depicts the yearly distribution of the papers included in the period from 2015 to 2024, while Fig. 3 demonstrates the distribution of papers included in this study according to the journals published.

Table 1. Keywords and searching strategy

Database	Search String / Query String
Scopus	TITLE-ABS-KEY (("Digital Twin") AND ("Digital Modelling") AND ("Digital Technologies") AND ("Sustainable Development") AND ("Construction Industry")) OR (("Digital Twin in Construction") OR ("Construction Digital Twin") OR ("Digital Technologies in Construction") OR ("Digital Modelling in Construction") OR ("Sustainable Development in Construction"))

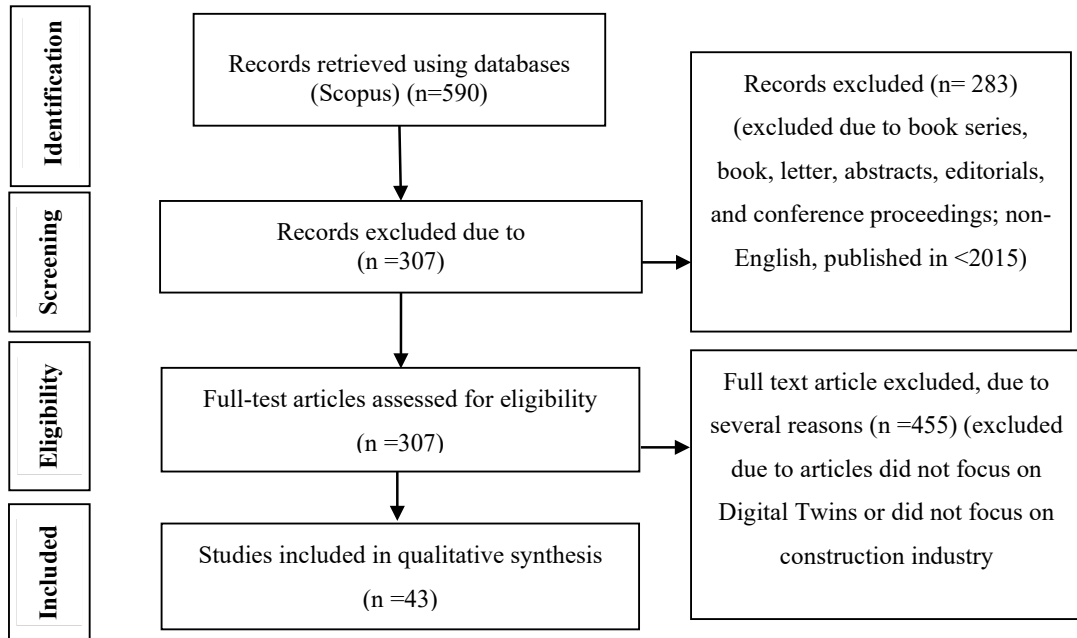


Fig. 1. Flow of the study

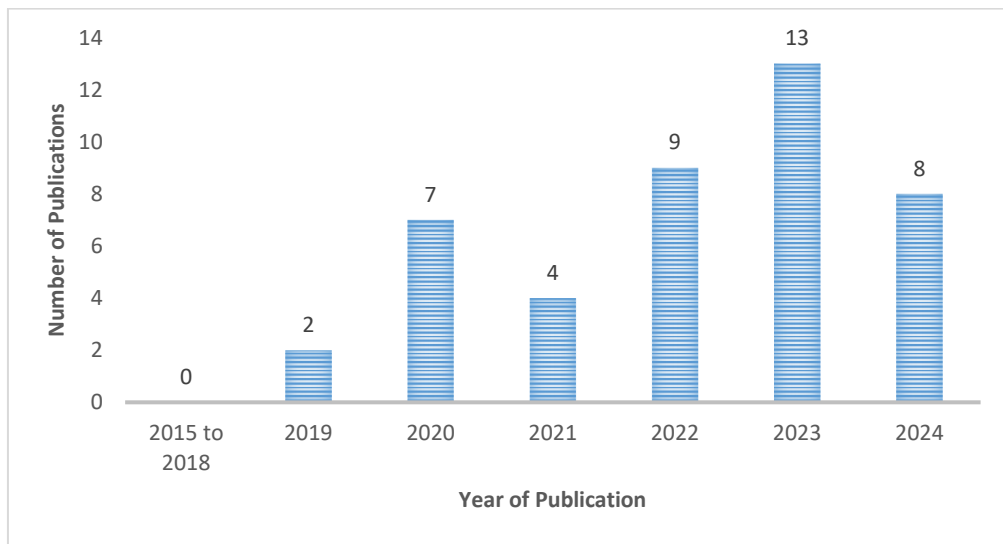


Fig. 2. The annual distribution of the included article

Fig. 4 indicates countries' co-authorship networks. Fig. 4 shows that the United Kingdom was the most published country of DT in construction with 11 publications, followed by the United States with seven papers, and at the third rank were Australia, Hong Kong, and South Korea with five papers each country.

A term co-occurrence analysis was carried out using VOSviewer to analyze the patterns of DT-related publications. This software allows the construction of a keyword network using natural language algorithms and text mining techniques, discovering links between the most frequently repeated terms related to the topic under study and then grouping them into clusters [25].

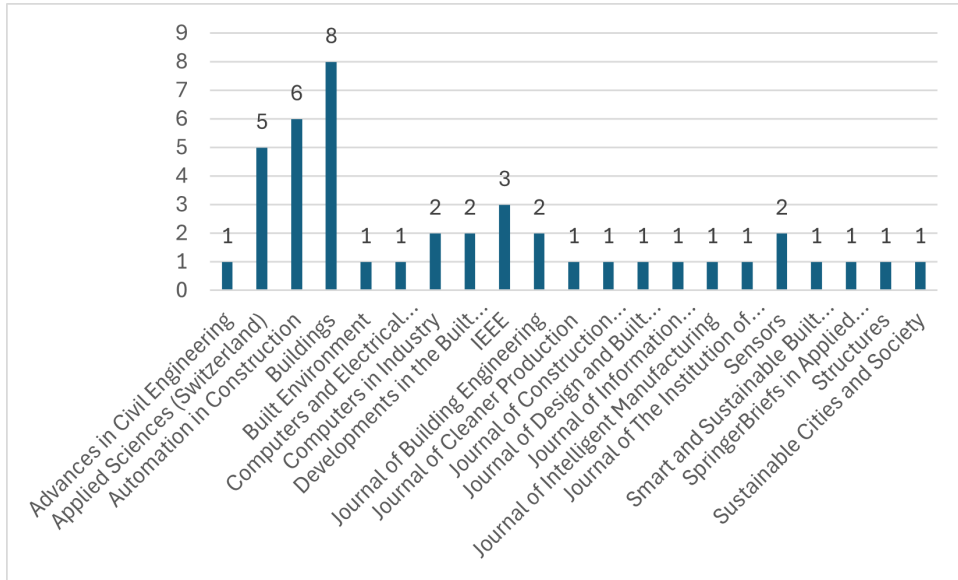


Fig. 3. Number of papers analyzed in journals

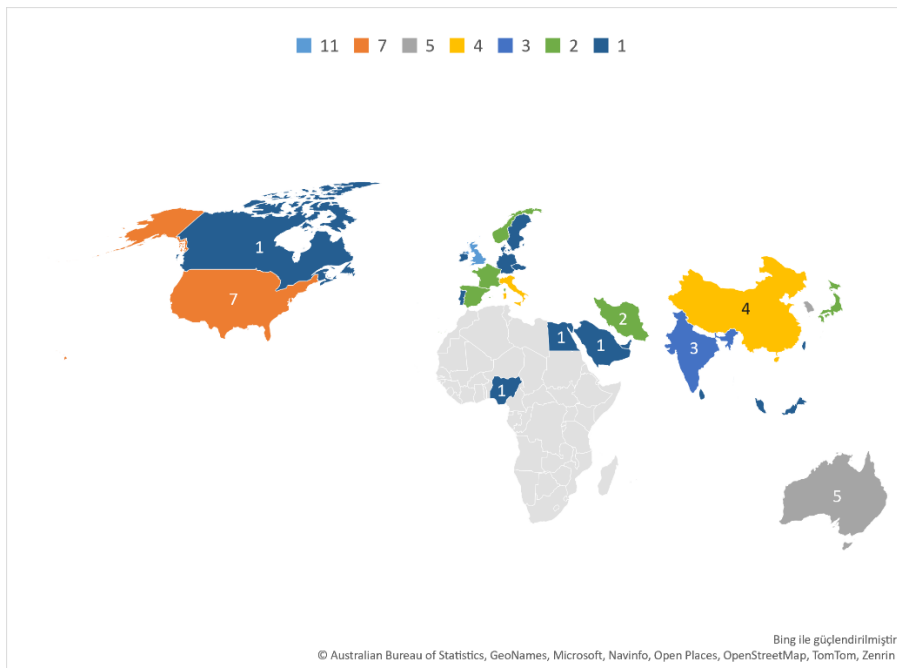


Fig. 4. Countries co-authorship of papers analyzed

A keyword must appear at least twice to be included in a keyword co-occurrence analysis. For this study, co-occurrence was defined as the presence of two or more terms within the title, abstract, or keywords. Before commencing the co-occurrence analysis with VOSviewer, it is necessary to merge keywords with synonymous

meanings. This encompasses the terms "digital twin," "digital twins," and "DT."

Fig. 5 displays the outcomes of the keyword co-occurrence analysis. Specifically, the research showed that of the 367 keywords examined in the evaluated papers, 49 of them met the threshold requirement of having at least two co-occurrences.

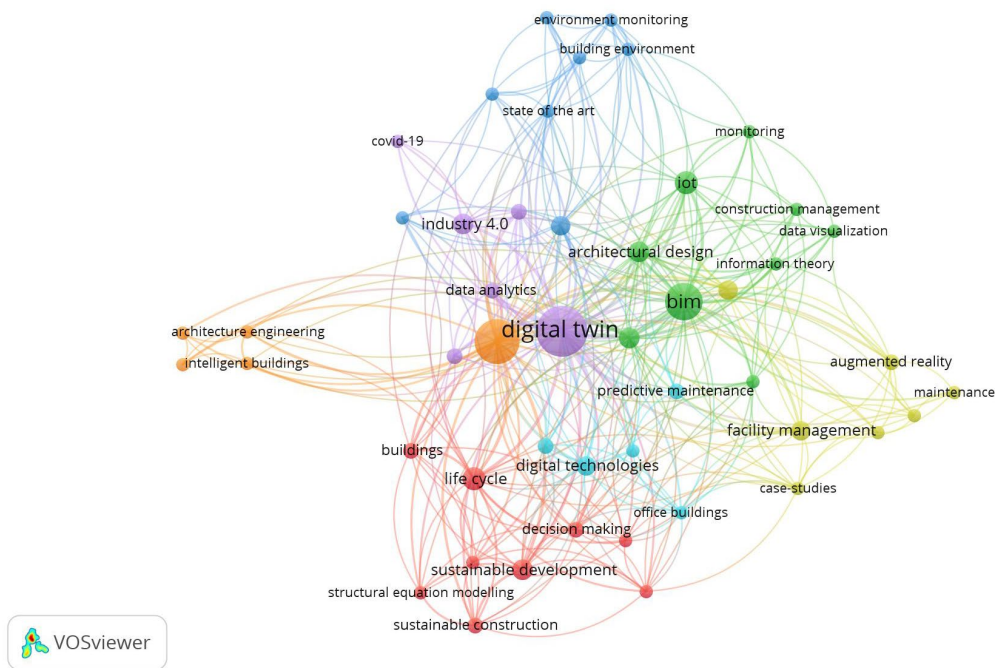


Fig. 5. Keywords co-occurrence analysis

The analysis revealed that the most frequently mentioned keywords in the literature were DT (28 occurrences), construction industry (22 occurrences), BIM (15 occurrences), lifecycle (6 occurrences), and IoT (6 occurrences).

The study revealed that the 49 keywords have been categorized into seven clusters, which are connected by a total of 542 linkages. The initial cluster (highlighted in red) contains keywords such as life cycle, building operations, sustainable construction, and sustainable development. The second cluster, shown by the color green, has keywords such as BIM, IoT, architectural design, construction management, and information management. The third cluster, shown in the color blue, has keywords such as blockchain, built environment, and environment monitoring. The fourth cluster, highlighted in yellow, comprises phrases such as artificial intelligence (AI), augmented reality (AR), mixed reality (MR), facilities management, and maintenance. The fifth cluster, represented by the color purple, encompasses phrases such as DT, industry 4.0, cyber-physical systems, and data analytics. The

sixth cluster, depicted in light blue, has keywords such as digital technologies, project management, and risk management. The seventh cluster, highlighted in orange, has phrases such as architecture engineering, construction, and intelligent buildings.

3.2. Results

This section offers a thorough description and analysis of the DT's implementation in all stages of construction. It aims to provide significant insights into how DT may improve intelligence for operational purposes in the sector. Hence, the utilization of DT in various stages of the lifetime will be categorized into four phases: planning and design, construction, operation and maintenance, and ultimately, demolition and recovery.

3.2.1. Planning and design phase

When it comes to construction projects, the initial phase of planning and design [26] is considered to be of utmost importance and is mainly influenced by financial factors [27, 28]. At this stage, doing a feasibility study is crucial. The submission of the completed drawing, along with any relevant

specifications, is required, as well as the dimensions and material specifications for the building must be determined [11]. The design quality, which serves as the basis for the entire construction project, will significantly impact subsequent construction-related activities [29], including safety [30], efficiency [31], cost [32], and so on. Therefore, employing DT at this point can offer several benefits, such as accelerating the design process, minimizing the requirement for revisions, and allowing designers to incorporate the acquired data into subsequent endeavors [33].

DT facilitates the iterative optimization of both the physical model and the information model by merging them [34]. Iteratively optimizing the models reduces the requirement for additional labor during rework and streamlines the whole design process [35]. Nevertheless, there is a divergence of opinion among academics and professionals regarding the potential enhancements that DT could bring to building project planning and design [36–38]. Nevertheless, DT has proven to be quite beneficial in some design and planning scenarios. Implementing DT during a project's design and planning phase has been made more accessible by BIM, a method for creating and managing a model that includes digital information on a specific asset [34]. A digital BIM model is created using data that has been collaboratively collected and regularly updated at essential stages of the project. To improve the project's overall outcome, BIM collects and shares feedback from stakeholders throughout the design stages [39]. However, a practical and up-to-date model that serves as an implementation of DT in the construction industry is created by integrating BIM with wireless sensor networks [40]. This integration provides project designers with valuable information to aid them in the development of the project.

As a result, DT enables designers to make educated judgments by providing them with a comprehensive digital model of the project [41]. Designers can utilize data collected through DT by saving it in a database [42]. This data can then be used to facilitate decision-making in several domains, such as energy management, supplier

selection, procurement, and material selection. In addition, BIM may provide knowledge on early design decisions on project viability, sustainability considerations, energy analysis, and other factors, serving as pre-construction guidelines [43].

Ning et al. [44] demonstrated the impact of construction site design on noise pollution by employing a hybrid genetic algorithm and ant colony model. The result could assist the management in strategizing the layout of construction sites and substantially reduce noise pollution. Tao et al. [45] addressed the problem of scheduling in the presence of workspace interference. It is suggested that workspace interference be categorized into two distinct classes and that a two-stage metaheuristic model be developed to enhance the interference issue. The paper discussed the application of semi-automatic geometric digital twinning for pre-existing structures using photographs and computer-aided design (CAD) models [46]. A case study conducted on a section of an office building found that utilizing maintenance and operations aided by DT is a practical approach during the building's operational phase. It also examined the distinctions between geometric digital twinning and existing structures.

Latifah et al. [47] did a study on predicting workplace design to effectively handle different forms of uncertainty and detect design modifications through the use of DT. The researchers analyzed the architectural components of DT at the building level, which include data acquisition, data/model integration, digital modeling, transmission, and service layers. A DT-based decision support system was developed [48]. For instance, individuals could be provided with a viable approach for selecting suitable locations for sports facilities through the utilization of visual data analysis. Experiments were performed to validate the precision and computational efficiency of the proposed methodology.

With the help of DT, Shao and Wang [49] collaborated to develop a systematic planning strategy that considered various features of subsurface space. The outcome was a distinct

separation of the planning process and systematic architecture. Furthermore, DT has been employed to predict energy usage during the initial planning phase [50]. The results were successful when the DT model was used to optimize building-integrated solar chimneys [51]. Compared to iterative physical models, this strategy saved significant computational costs.

Furthermore, Tarik et al. [52] used DT to quantify the energy storage effects of a double-skin solar façade system. Kalantari et al. [53] described a toolset that allows users to duplicate and analyze changes made to a physical prototype using DT. Almusaed and Yitmen [54] investigated the feasibility of using AI and DT models to simulate and analyze different architectural design solutions and predict their impact on safety, comfort, and efficiency.

Buildings that employ DT applications enhance user comfort, maximize resource utilization, analyze potential situations, and avoid design iterations in the building operating process [55]. Design iterations are used to repeatedly modify or adjust a design in response to testing, requirements change, or feedback. A product must be designed, assessed, and refined repeatedly during these iterations to get the intended result. Every iteration cycle usually consists of the following steps: designing, developing a prototype, testing it, assessing the outcomes, and making any required adjustments. To refine and improve a product based on user feedback and performance evaluations, design iterations are crucial in engineering product design [56]. Designers can solve problems, improve functionality, maximize performance, and ensure the finished product satisfies requirements by going through several design iterations.

Tagliabue et al. [57] suggested a methodology that used a DT-based IoT-enabled dynamic approach to allow for real-time sustainability assessment from a user's perspective during design. The study's proposed system can reliably support the control and monitoring of the built environment toward a green and sustainable environment. With a substantial improvement over the manual method, Lu and Brilakis [58] devised a slicing-based object

fitting method that produced geometric DT of existing bridges and obtained an average modeling distance of 7.05 cm and a modeling duration of 37.8 s.

3.2.2. Construction phase

Construction is the most arduous, resource-intensive, and intricate phase of a building project. In addition to having the highest number of employment opportunities, this stage also encompasses the development of vital infrastructures [59], foundation construction [60], and land surveying [61]. Moreover, the bulk of construction necessitates the establishment of infrastructure to facilitate heating, ventilation, water supply, and power. To enhance the degree of automation in the construction process, it is necessary to systematically include DT at every phase of building construction projects. As per Wang et al. [62], this application aids in improving the supervision of construction activities, boosting construction efficiency, reducing construction-related risks, and ensuring the overall quality of building projects.

DT can assist in several management duties throughout the building phase, such as scheduling, quality control, materials handling, resource allocation, and sequence coordination. Various technologies are currently being utilized, including tag identification systems for tracking the whereabouts of materials and workers, smart sensors and sensor networks for monitoring the quality of construction, and GPS for detecting and measuring job progress as well as tracking production advancement [34]. With rare exceptions, these technologies are not combined to fulfill various administrative roles [63].

Presently, DT is being employed to address a diverse array of construction-related problems, including information exchange [64], human-robot interaction [65], quality assessment [66], construction safety [67], and site monitoring [68]. However, the majority of research using DT technology during the construction phase of a project mainly concentrated on evaluating the structural integrity of the object's systems. The notion of DT is utilized for assessing historic brick

buildings' structural system integrity [69]. The authors developed a simulation model designed explicitly for the deployment of DT technology in historical brick construction. The study shows that DT technology can accurately comprehend structural behaviors at various stages of development.

Shi and Wang [70] presented an application in the initial stages of construction in their study on constructing DT systems for subsurface geological models. The study included a combination of restricted, location-specific boreholes and photographs into a 3D geological model. This model was constructed utilizing advanced deep-learning techniques to obtain previous geological information about the building site. A study was conducted on the optimization approach of camera placement on the building site using BIM [71]. The comparison between the technique and the experience-based camera layout method highlights notable benefits. The parallel modified genetic algorithm is used in this study's BIM-based optimization framework to put cameras in construction projects in a way that is both economically and practically sound. The time dimension is considered to determine and meet the requirements for the maximum covering area. The findings demonstrate that, in comparison to experience-based camera placement, the temporal average of the entire coverage was enhanced by 12% upon using the optimal camera placement produced by the suggested framework. The authors also contrast the performance of the suggested strategy with approaches from previous studies that did not take the temporal component into account. According to the experiment's findings, the suggested camera placement achieves an effective coverage rate that is comparable to static-based camera placement. Incorporating the DT into this technique has the potential to enhance its accuracy and efficiency in the future. This can be accomplished by integrating historical data, empirical data, on-site data, and a theoretical foundation.

Furthermore, the substantial amount of data generated and stored by the DT has the potential to

aid in future endeavors, such as organizing and strategizing construction projects. The automated monitoring of building progress is performed by constructing flexible DT-based frameworks and integrating IoT and BIM technologies [72, 73]. The virtual position of building components offers valuable information for tracking development [74, 75].

The timely delivery of construction materials is a critical factor that impacts the advancement of a project. The construction site logistics department conducted a study to determine the practicality of using DT for large storage containers called bulk silos [76]. This study was done in collaboration with a reputable construction supplier. Sun et al. [77] introduced an enhanced platform for effectively overseeing clever dispatching systems. They successfully tackled several challenges, including decision-making, resource dispatching, demand analysis, and identification of resource shortages. Jiang et al. [64] implemented a cooperative platform that utilizes DT and blockchain technology to automate the management of modular integrated construction fit-out processes on and offsite. An innovative DT framework was proposed to address the issue of supply chain coordination in modular construction. This framework enables forecasting the anticipated arrival dates for modular components [74, 75]. Furthermore, Zhao et al. [78] informed an innovative hoisting management system that utilizes DT to perform several functions, including real-time data collection, meticulous lifting route planning, and accurate positioning of prefabricated components.

Risk management is a further helpful use of DT in construction project management. In response to this pressing requirement, Sun et al. [79] devised a sophisticated approach that utilizes DT technology to accurately forecast and handle hazards, ensuring the safety of construction workers and the successful execution of foundation pit excavation. Furthermore, a vital field of study involves evaluating prestressed steel structural safety. DT can assist in achieving structural security performance analysis by enabling the integration of

time and location through virtual interaction [80]. Liu et al. [81] introduced a method that uses DT and support vector machines to anticipate safety concerns in hoisting operations. Gathering real-time hoisting data can help predict potential hazards in the hoisting procedures. Subsequent research will further investigate the incorporation of autonomous control of the physical layer by the service layer. Yitmen et al. [12] proposed a framework combining BIM, DT, and extended reality (XR) technologies to create an automated construction progress monitoring system.

Another area of research is the use of DT technology to monitor workers' movements and activities on building sites. The goal is to enable fast detection of safety issues and timely intervention when they are recognized. Wu et al. [82] created a real-time visual warning system using DT, deep learning, and MR technologies in this context. The suggested solution provides construction workers with quick and up-to-date information about safety circumstances, thereby preventing accidents. Furthermore, the study evaluated the system in three field-like settings, confirming its ability to synchronize construction activities across a vast area and graphically present hazard signs. The test scenarios used to develop the system provided noteworthy evidence of its effectiveness in improving workers' ability to accurately assess risks, strengthening their compliance with safety protocols, and providing construction safety managers with a new perspective on analyzing the safety of construction projects. Chellappa and Chauhan [83] created DT with video recordings and digital human modeling software. DT was used to duplicate working postures and evaluate ergonomic problems. Shariatfar et al. [84] used 4D BIM models, sensor data, AI models, and cloud computing databases to create visual representations of potential risks, affected body parts, and event characteristics during various site activities such as scaffolding, excavation, and welding.

3.2.3. Operation and maintenance phase

Construction contractors typically transfer the responsibility of managing buildings to other

stakeholders throughout the operation and maintenance phase, which complicates the task of managing and accessing the data associated with the facility. The degree of digitalization observed in the construction industry's operation and maintenance phase is comparatively modest compared to other sectors or even the design and construction phases [85]. The involvement of several parties in various processes associated with building projects poses a challenge to the smooth integration of data across dissimilar stages and among diverse stakeholders [86]. Despite the virtual model being an exact duplicate of the object, it has no connection to the actual project [87].

DT has the potential to enhance the flow of information among different stakeholders. The project's operation and maintenance phase utilizes DT technology for facilities management, maintenance management, monitoring, logistics, and energy simulation. DT can assist facility managers in making critical decisions such as building performance management, optimizing energy consumption, and building operation and maintenance. Collecting live data enhances the operational effectiveness of the project and enables proactive maintenance and well-informed decision-making [88]. Facility managers and researchers in related sectors should consider the most effective utilization of data and information to enhance facility management operations [89].

A study conducted by Antonino et al. [90] demonstrated that utilizing both historical and real-time data on building occupancy can provide substantial advantages for building management. They can enhance building services and maintenance. In a case study, the authors employed image recognition to monitor users' movements within an office building and deliver up-to-the-minute occupancy figures. They discovered that including real-time data on individuals' activities inside a monitored area can enhance the definition of smart contracts. Nevertheless, the authors encountered no difficulties merging the BIM model with real data obtained by image sensors. In addition, the authors did not validate their proposed technique through extensive case studies to enhance

its practicality in the field of facilities management. An innovative DT system architecture specifically suited for building-level operations was introduced [91].

Ni et al. [92, 93] conducted two studies on the use of DT in conserving and repairing old Swedish buildings. The first study used sensors, historical data, and machine learning algorithms to improve energy efficiency, building conservation, and human comfort in three historic buildings in Sweden [93]. A second study offered IoT-enabled DT to improve the preventive protection of a Swedish theatre. Multiple studies [88, 94] have demonstrated that the conventional method of gathering data for DT often involves the laborious process of reading sensor instances. However, Lu et al. [46] introduced a new semi-automatic technique that utilizes CAD drawings and photographs to develop a well-structured, precise, and user-friendly DT system. Therefore, Heritage BIM is used by Jouan et al. [95] to demonstrate how the DT principle can be applied. A methodology for integrating DT into management planning was put forth to enhance the proactive protection of heritage monuments.

Lu et al. [96] developed an anomaly detection system that utilizes DT technology. The system utilizes a dataset to monitor data, which contains diagnostic information regarding the operational state of assets. Based on the study, a DT-enabled anomaly detection system has the potential to consistently monitor the condition of building assets. The purpose of an anomaly detection system is to find anomalous patterns or behaviors in data that differ from typical, anticipated behavior. During the operation and maintenance phase of a building, it is essential to monitor the state of its assets. Point anomalies and contextual anomalies are the two primary categories into which anomaly detection systems can categorize abnormalities. Individual data instances that deviate from the normal state are referred to as point anomalies, whereas contextual anomalies happen in particular context settings. By identifying irregularities in assets like mechanical, electrical, and plumbing systems, these systems are essential in guaranteeing

the security, effectiveness, and caliber of building operation procedures. Through the analysis of data sources such as vibration measurements and external asset operating information from building management systems, they aid in the early identification of possible issues such as damaged bearings, sealing problems, or cavitation in equipment like pumps. Building operation and maintenance concerns can be monitored, detected, recorded, and communicated via a DT-enabled anomaly detection system, which applies DT concepts. To retrieve monitoring data from building DT that contains diagnostic information on asset operational situations, it combines expanded industry foundation classes. To find and filter contextual abnormalities, the system uses a Bayesian change point detection methodology that considers the shifting loads on assets that are determined by human demands. Continuous anomaly identification of assets, such as centrifugal pumps in the heating, ventilation, and air conditioning (HVAC) systems, is made possible by the DT-based anomaly detection process flow, which improves automated and efficient asset monitoring in operation and maintenance.

DT applications facilitate diverse decision-making throughout various stages of a project's lifespan [97]. Furthermore, DT plays a crucial role in facilitating informed decision-making to maximize the efficiency of building energy use [98]. Seghezzi et al. [99] implemented DT with an occupancy focus to assess and fine-tune a system for monitoring occupancy. This system utilizes IoT camera-based sensors to manage building facilities. Their approach incorporated a post-occupancy evaluation using BIM to enhance the planning of sensor systems and assess the quality of data and effectiveness of the system. Shim et al. [100] suggested using BIM and 3D scanning to create a DT bridge maintenance system to increase the accuracy of bridge decision-making. Omer et al. [101] created a lidar-based DT model that included every flaw in the structure to assess the health of a concrete bridge structure. The bridge was inspected using virtual reality in a fully immersive 3D environment.

Efficient real-time control of electrical equipment is crucial for achieving low-carbon operations, particularly for regulated loads and energy storage devices [102]. In this context, one study used the DT technique to create a complex system that automates and optimizes energy management in a residential building [103]. The design of ideal interior spaces is crucial because it has a substantial influence on multiple elements of human existence, encompassing the promotion of health and general welfare. Clausen et al. [104] developed a model predictive control technique using DT to successfully regulate the HVAC system. This approach resulted in significant improvements in energy efficiency and the personal experience of thermal comfort. This method enhanced the accuracy of forecasting individual thermal comfort preferences. Subjectivity, time-consuming protocols, and arduous record-keeping plague the traditional process of building inspections. It is possible to deal with and get past these problems by using DT to organize the inspection process [105].

The majority of long-term applications of digital transformation occurred during the operational phase. Examples of this application include the use of DT to analyze energy in zero-energy buildings by scanning models into BIM [106] and the integration of wireless sensor networks and BIM to improve safety, environmental monitoring, and control management in underground garages. This includes detecting and controlling gas leaks, humidity, and temperature [40]. Moreover, integrating user behavior tracking with BIM models to evaluate indoor comfort, energy consumption, and air quality in educational institutions [57]. Furthermore, the DT model can be utilized to improve cities' environmental performance using a variety of methodologies, including city energy mapping and modeling [107, 108]. Wang et al. [109] introduced a DT system that improves the maintenance and management of green buildings. The system employs Bentley Systems software and incorporates 3D laser scanning and sensors to monitor a multitude of parameters, including

equipment performance, energy use, temperature, security, humidity, air quality, and water consumption.

The primary objective of using DT in building maintenance is the maintenance of building structures and facilities. In building structure maintenance, Loverdos and Sarhosis [110] developed a geometric digital tomography method for automatically detecting structural defects in masonry and masonry units. Angjeliu et al. [69] developed a DT approach to investigate the structural performance of aging masonry structures, emphasizing the importance of retrofit strategies and preventive maintenance. Lu et al. [91] developed a new data structure based on industrial foundation classes to simplify anomaly detection for building facility maintenance. This data structure is capable of extracting various types of detection data, including diagnostic information about the health of the facilities. DT has been researched as a means of anomaly detection in HVAC systems to optimize the monitoring of building assets [111, 112]. A system architecture for creating DT at the building level was proposed by Vivi et al. [113] to give people a platform to interact with buildings through sustainable and intelligent channels. Real-world development was used to investigate the research further and demonstrate DT's capacity for tracking, predicting, and enhancing asset maintenance.

Deng et al. [114] examined the evolutionary shift from BIM to DT in the field of architecture, engineering, and construction for building representations. DT study was divided into six groups: monitoring the building process, managing energy use, keeping an eye on the indoor environment, managing space, keeping an eye on risks, and keeping an eye on the community. The researchers also investigated the utilization of DT in combination with BIM and IoT for instantaneous forecasts during the building and operational stages. In their study, Couprie et al. [115] examined the integration of BIM-based DT with XR technologies to enhance building maintenance operations. The advantages of BIM-based DT were observed in terms of deployment, building lifecycle

management, data management, monitoring, inspection, and planning. Additionally, XR technologies enhanced data visualization and interaction with models in DT.

A DT-based guiding system was suggested by Han et al. [116] to improve evacuation effectiveness in thin-shape infrastructure, such as tunnels or small passageways. As the DT model, a cellular automata-based model was developed. The system was designed to generate guidance instructions using both competent guidance and traditional fixed guidance. Park et al. [117] highlighted the significant role that DT would play in the field of intelligent building security in the future by proposing the use of sensors, actuators, and AR to guide building occupants and rescue workers.

3.2.4. Demolition and recovery phase

Researchers typically disregard retirement as a legitimate phase [118]. Additionally overlooked while utilizing DT technology in the building industry is the demolition and recovery phase, which is comparable to the retirement period. Waste is abundant in the demolition sector [119], both quantity and kind [120]. Furthermore, the demolition industry might affect other variables such as public health [121], the economy [122], and profits [123].

Given the magnitude and importance of the demolition industry, several parties, such as the government, contractors, and demolition waste

processing facilities, are seeking a cost-effective, environmentally friendly, and efficient disposal approach [124]. The comprehension of an object's behavior is commonly forfeited during the stages of deconstruction and recuperation. Grieves and Vickers [125] proposed that knowledge about the predecessor of an object's future generation can be used to address comparable challenges that may arise. Liu et al. [118] stated that by studying the demolition and recovery phase, one can gain insights into all stages of the lifespan while keeping costs low in the virtual world.

Züst et al. [126] used graph-based Monte Carlo simulation to show how DT can efficiently manage material flow during excavation and demolition. DT can produce highly realistic multi-stage models before and after building collapse events in the field of collapse investigation. This enables a more comprehensive understanding of potential causes and solutions for future structural failures [127]. It is essential to use data from previous buildings to address similar issues in the next generation of structures [34].

4. Discussion

The preceding section concentrated on the implementation of DT in the construction business, to investigate their thorough comprehension, framework, uses, and difficulties. Fig. 6 shows the type of the documents analyzed in this study.

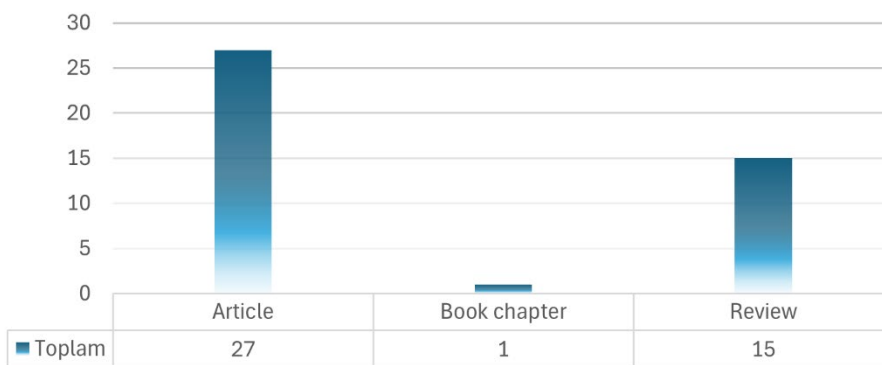


Fig. 6. Document type of papers analysed

Researchers have acknowledged the crucial significance of DT in resolving intricate problems in the building construction business, leading to substantial advancements in this field. Although there have been significant advancements, there is still a substantial disparity in the successful implementation of DT in the building construction sector. There is currently an outstanding increase in interest in researching DT in the construction business. The considerable increase in research activity can be attributed to technological advances that have made DT solutions more accessible and adaptable to construction projects. The rapid adoption of sensor technologies, IoT devices, and cloud computing infrastructure has facilitated the collection and analysis of copious amounts of real-time data, which is critical to the development and maintenance of DT. In addition, as scientists and industry personnel become increasingly aware of the potential benefits of DT, they are delving deeper into their discovery and study. Although there is growing interest in DT, the extent to which they have been implemented in the construction industry is primarily unclear and may be pretty low. Thus, this systematic literature review has determined three fundamental research gaps that provide significant insights to practitioners and researchers to direct their future work.

4.1. Lifecycle perspective

Building projects can be made more productive, high-quality, and efficient by gathering information early in the process. Therefore, it is critical to manage customer needs throughout the whole project lifetime to avoid delays, overspending, and disagreements. Furthermore, to efficiently manage the variety of information created during building phases, a construction information database system must be developed due to the growing complexity of the construction sector. Throughout the construction lifecycle, DT is essential for gathering information because it facilitates real-time data integration and visualization, improves decision-making, and maximizes project planning, execution, and management. Although it has great potential, the use of DT in the construction lifecycle is still in its infancy. To fully achieve its revolutionary potential, standards, reliable data management, and scalable solutions are required to traverse the intricacies involved.

A significant portion of the studies discovered in the investigation were primarily theoretical or focused on offering solutions for DT rather than discussing the actual implementation of DT. Fig. 7 shows the distribution of the use of DT from the papers investigated in the literature through the different phases of the construction lifecycle.

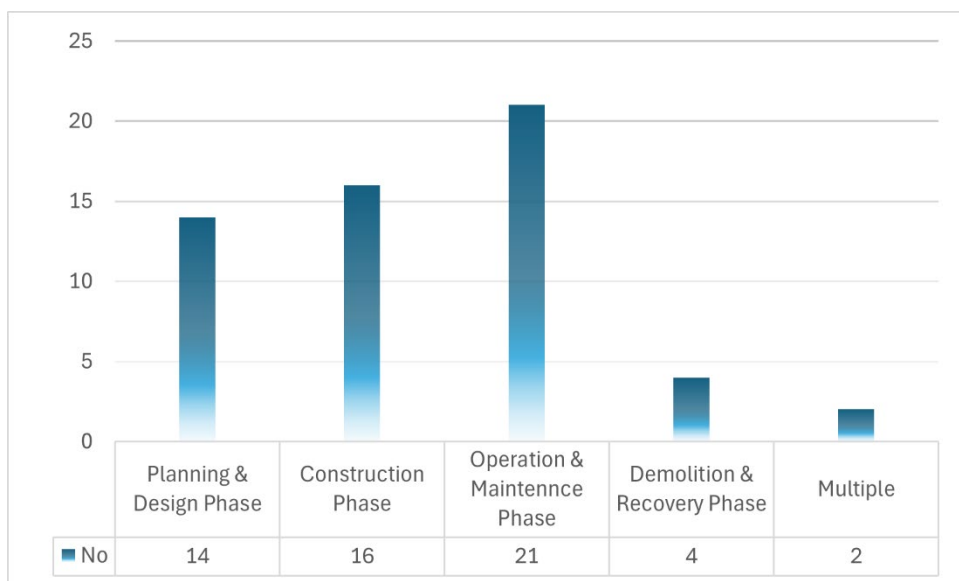


Fig. 7. Distribution use of DT in divergent phases

Regarding the project's phases, it was determined that DT was suitable for every step. However, their use in demolition, deconstruction, and material reuse operations has been largely overlooked, even in conceptual studies and reviews. This opens up the possibility for further research into the potential of DT to improve sustainability practices and resource management throughout the life cycle of construction projects by concentrating on bringing together a variety of stakeholders in one building project to establish DT to optimize the intelligent transformation of building lifecycle management.

4.2. Technologies perspective

A review of literature cases has shown that DT can be constructed using a variety of technologies. There is no fixed framework for developing a DT system that uses only one technology or adheres to a single data format. Alternatively, the structure may be determined by the specific objectives and analytical requirements of the DT system. In the research reviewed in the literature, IoT techniques such as sensors, long-range radio, picture scanning with an unmanned aerial vehicle, laser scanning cloud data, mobile scanners, drones, and robots are employed as essential technologies for data gathering in DT in the construction industry. Some studies have shown the use of the Geographic Information System (GIS) as a technique to collect data for DT in construction projects. Moreover, BIM is considered one of the most important sources of data acquisition and integration in many papers analyzed in the literature.

Hybrid genetic algorithms, simulated annealing algorithms, Bayesian networks, multilayer perception artificial neural networks, deep learning algorithms, support vector machines, regression algorithms, machine learning algorithms, model predictive control algorithms, and others as AI tools and algorithms used in the analyzed studies to anticipate possible problems, optimize workflows, and decision-making capabilities in DT frameworks established in the consultation industry. XR technologies such as VR, AR, and MR have been implemented to enhance the sense of reality by fusing the actual and virtual worlds.

Additionally, they were utilized to produce digital representations of items in which real-world and digital objects coexist and communicate in real-time. Furthermore, the technique for order preference by similarity to ideal solution (TOPSIS) has been utilized in some studies for multi-criteria-based decision-making.

In terms of the software employed, MATLAB, Bentley, CAD software, Revit, GIS-based routing applications, industry foundation classes, Leica's Cyclone version 9.1, and Unity 2017.2 are examples of the software employed to implement DT in construction.

4.3. Challenges perspective

The application of DT in various stages of construction projects has revealed numerous obstacles that hinder the efficient implementation of DT in the construction sector. Some of these issues are inherent to the construction business, such as projects' intricate nature and fragmented structure. The absence of cooperation and transparency among stakeholders and the failure to utilize new technologies such as AI and IoT, which are crucial for implementing a DT system in the construction industry, are inherent to the industry. Additionally, the delayed introduction of DT in the construction industry, the absence of expertise and standardized protocols, and the limited understanding of the DT concept, where numerous studies still employ the same definition for both DT and BIM, are recognized as significant obstacles to the successful implementation of DT in the construction industry. The lack of official support, numerous building rules, high deployment costs, and rising need for power and storage are political and economic constraints that hinder the growth of DT applications in the construction industry. Additional hurdles that could be enumerated encompass the necessity to modernize outdated IT infrastructure, the obstacles related to connectivity, privacy, and security of sensitive data, the difficulties in integrating with current systems or proprietary software, and the intricacy of its architecture.

5. Conclusions

Although still in its nascent stages of development within the construction sector, DT exhibits considerable potential for future growth, as evidenced by a multitude of applications and studies in both academic literature and industry. The study investigated the implementations and applications of DT in the construction lifecycle, discussed the technologies employed, and determined the challenges facing DT in the construction industry. To achieve that, the study employed a systematic literature review methodology by analyzing several forms of literature, including review articles, scholarly articles, and book chapters between 2015 and 2024. The research adds to the body of literature by defining the use of DT from the standpoint of the construction lifecycle, going over the technologies used, and figuring out the obstacles DT faces to further integration and acceptance in the sector. The research derives its distinctiveness from the methodology employed to explore the utilization of DT in the construction industry by analyzing various literature sources. This approach aids in scrutinizing a multitude of studies to address the deficiency in understanding the applications of DT throughout the construction lifecycle.

The analysis revealed a pronounced emphasis on research about the building, operation, and maintenance phases, with comparatively limited attention directed towards the planning and design phases, as well as the demolition and cleanup phases. Furthermore, the study showed that IoT, BIM, and AI were the leading technologies used for data acquisition, integration, and modeling in DT for the construction industry. The authors discussed numerous obstacles that may arise during the development and implementation of DT applications in the construction industry. Nevertheless, the findings of this study were broad in scope as the investigation did not specifically

target any particular geographic region. Furthermore, the study may undergo modifications in the future as the concept of DT in the building continues to evolve.

In terms of research future recommendations, there is a necessity for research to assess the adoption of DT technology throughout distinct stages of the project life cycle. These investigations should cover a comprehensive evaluation, incorporating assessments of the levels of awareness, comprehension, and approval of DT among stakeholders in the industry. Scholars have the opportunity to examine how varying levels of DT integration impact a wide range of performance indicators, including but not limited to productivity, profitability, safety practices and outcomes, and sustainability efforts. This situation creates a potential avenue for upcoming studies to delve into the possibilities offered by DT in enhancing the efficiency of sustainability strategies and the management of resources across the complete duration of construction projects within the built environment. This avenue for research could shed light on the transformative potential of DT in revolutionizing the way sustainability is approached in the construction industry.

The analysis of the case studies provided illuminated the fact that a sizable proportion of research was conducted in affluent areas, including but not limited to the United Kingdom, the United States, and various countries in Western Europe, highlighting a geographical bias towards developed regions in academic investigations. Finally, the outcomes of this research will provide valuable contributions to the academic community by enhancing comprehension of the current state of DT within the construction sector. This will lead to a heightened emphasis on implementing and assimilating DT practices within the industry, consequently fostering innovation and growth.

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Author Contributions

M. Yıldırım: Conceptualization, Methodology, Data curation, Writing - Original draft preparation, Visualization, Investigation, Validation, Writing-Reviewing and Editing; O. Giran: Conceptualization, Supervision, Writing-Reviewing and Editing.

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Not applicable.

Data Availability Statement

The data presented in this study are available in Scopus database.

Ethics Committee Permission

Not applicable.

Conflict of Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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