

Supplementary Section S1. Review Articles of DT in the Construction Industry

This section aims to provide a thorough overview of the previous *literature reviews* pertaining to the practice of DT in the construction industry and a total of 45 published reviews within the last decade are explored. The reviews can be categorized into four clusters based on their scope, including 1) exploration of DT enabling technologies (e.g., AR, AI, and IoT), 2) differentiation of DT from other similar concepts (e.g., digital shadow, BIM, and Cyber-Physical Systems), 3) identification of barriers or challenges associated with DT adoption, and 4) investigation of DT's applications in the construction industry (e.g., sustainability, fault detection, and monitoring). The cluster distribution is illustrated in Figure S1.

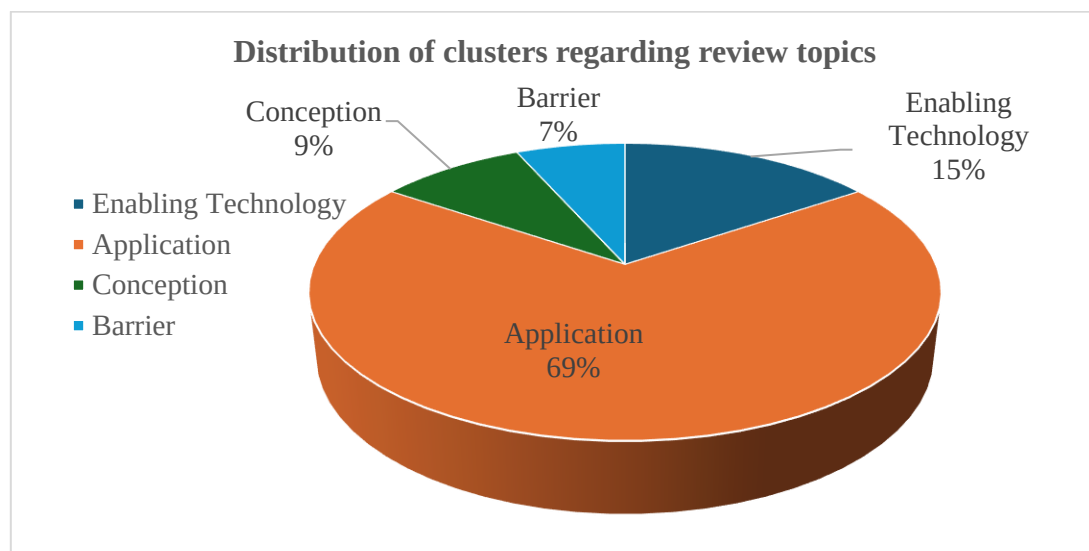


Figure S1. Distribution of clusters regarding review topics

In terms of DT-enabling technologies, each of them plays a role in the functionality of DT. The initial step of implementing DT for a project involves building a virtual representation, which requires a multitude of parameters (e.g., geometry, physical properties, and special locations) of the actual assets [76,80]. The virtual representation in the design stage is quite significant and influences the downstream stages of the construction projects because it cohesively demonstrates the real-time changes of the physical assets and processes. In this case,

technologies related to the virtual model of the DT need to provide abundant data and information including the models, drawings, images, videos, and point clouds. For example, key data acquisition technologies like IoT sensors LiDAR and component-based sensing devices, which facilitate real-time data collection from various resources, enable DTs to perceive the dynamic variations of real-world entities and processes [29,107]. Besides, with the large volumes of data, efficient data processing is also critical to the development of DTs. In this case, data processing technologies, such as Machine Learning (ML) and computer vision, enhance the usage efficiency of data resources [43].

The modeling of the virtual part is accomplished by technologies like Building information modeling (BIM), Geographic Information System (GIS), finite element model, and computer-aided design (CAD) software [43]. Moreover, the visualization capabilities of DTs are improved using virtual reality (VR) and augmented reality (AR). Synchronization is another significant function of DT technology that establishes a reliable connection between virtual and physical objects. Also, the connection between the physical entity and the digital replica ensures the high fidelity and accuracy of the virtual representation [21]. Furthermore, data transmission is the core for establishing such connections. Specifically, technologies for data transmission are divided into wired (e.g., optical fibers, twisted-pair, and cables) and wireless (e.g., Wi-Fi, Bluetooth, ultra-wideband (UWB), and Zig-Bee) ones.

In terms of DT definitions and concepts, within the construction industry, there is a lack of a universally accepted definition of DT. However, numerous researchers are actively working towards proposing a definition of DT specifically tailored to the construction field [17]. To illustrate, Madni et al. [16] defined DT as a virtual model of its physical twin that continually evolves throughout its lifecycle to simulate maintenance, performance, and health status. Kor et al. [18] put forth a definition for DT in construction as a comprehensive engineering model

capable of monitoring construction products through multi-site monitoring systems, utilizing data flow and unique capabilities. Similarly, Inrahim Yitman et al. [19] extended the DT concept to a Construction Digital Twin, which encompasses real-time monitoring, anomaly detection, behavioral learning, and the ability to predict the actions and functions of the physical twin. These definitions primarily address the real-time monitoring function of DT, which is particularly relevant for predictive maintenance in construction projects. Notably, there is no general definition of DT applicable to all industries since each industry has its specific purposes and requirements when utilizing DT technology.

Several review studies have been conducted to examine the barriers and challenges associated with the implementation of DT. For example, Opoku et al. [32] identified the barriers to DT implementation in construction and classified them into four categories: stakeholder-oriented, industry-oriented, construction-company-related, and technology-related barriers, among which the most prominent barrier was the low knowledge level of the stakeholders. Similarly, Lei et al. [33] identified nine non-technical and fourteen technical challenges, and the most significant challenges were interoperability and practice value. In the context of sustainable structural design, Farouk et al. [34] identified and categorized forty-five barriers into six groups, determining that the most significant obstacles to DT are related to “performance” and “security”. By figuring out the potential challenges and barriers to DT implementation, researchers attempt to provide insights into the risks that hinder the successful implementation of DT.

When it comes to the DT’s application, most of the review articles have examined the application of DT in the operation and management (O&M) phase, such as asset management, defect detection, diagnostics, facility management (FM), and decision-making [86]. Although it’s more convenient to adopt DTs after the handover of the assets, the data and information

generated before the handover are also significant for the whole lifecycle of the projects. Therefore, it's recommended to use DT throughout the lifecycle of the projects [21]. In fact, many studies (e.g., [5,57,76]) have explored the potential of utilizing DT throughout the entire life of construction projects. In the design stage, DTs assist the designers in virtual modeling, simulating, and detailed design. Being capable of integrating data from various sources, DTs enable the designers to conduct what-if scenarios thus reducing the inconsistencies between the design and the physical asset [5]. Furthermore, DTs can integrate the historic data to facilitate performance-led design, thus improving the efficiency of the subsequent phases of the projects. In the construction stage, based on the large volumes of real-time data, DTs can facilitate construction management by monitoring safety, progress, quality, workers, and materials [5].

In summary, the reviewed literature provides a thorough overview of the current research landscape surrounding DT in the construction industry. With powerful capabilities such as real-time monitoring and analytics, predictive maintenance and optimization, and the simulation of “what-if” scenarios, DT is widely acknowledged as a highly potential technology in improving the digitization level of the construction industry. Nonetheless, there exist risks in the practice of DT within the construction context. To improve the probability of successful implementation, it's necessary to identify the potential risks (opportunities and threats) and correlate them with the DT maturity levels. In this way, the stakeholders can have insights into the risks they may face in achieving their desired level of DT adoption. Therefore, this study is about to extract a comprehensive list of risks associated with DT implementation from the literature and align them with the adopted five-level DT maturity model. The summary of the reviewed articles is shown in Section S2, which outlines their key information such as context, method, aim, and key findings

Supplementary Section S2. Summary of the previous *review* articles related to DT

Ref.	Country of affiliation	Scope	Method	Aim	Key findings
[122]	China	The AECO industry	Mixed review method	To provide a thorough understanding of research on utilizing emerging DTs in the AECO industry	10 emerging DTs in literature: BIM, IoT, RFID, 3D printing, AI, big data, cloud computing, blockchain, Virtual Reality (VR)/AR/MR, DT.
[106]	China	Bridge engineering	SLR	To eliminate the conceptual and technical confusion of DT adoption in bridge engineering.	DT-enhanced BIM has the potential to facilitate connectivity throughout the entire life cycle of construction projects and across various sectors of digital construction.
[123]	USA	Construction industry	SLR	To synthesize the expertise in the field and identify the forthcoming requirements of blockchain technology	The future research directions of blockchain technology should focus on the quantification of the cost-benefits, incorporation into digital project delivery, and the fusion of digital technologies for managing construction
[86]	China	Construction industry	Literature review	To identify the trends in technology development and methodological advancements of DT by systematically assessing research progress, evolution, research focal points, and future directions.	DT is an interdisciplinary information technology that has shown significant advancement particularly in the production of construction materials and components.
[124]	Canada	Offsite construction industry	Literature review	To ascertain the present state of employing digital technologies in offsite construction	There are clear disparities in the usage and advancement stages of various technologies across different years
[84]	Portugal	The AEC industry	SLR	To clarify the progression of digital twins within the AEC industry through an	DTs are viewed as a progression from BIM concerning their extent, communication, and structure

				analysis of its current status and conceptual evolution	
[125]	Russia	“Digital twin” in all industries	Review based on text mining and machine learning	To establish a proper approach for visualizing the academic landscape of DT	The trending topics about DT in the literature include digital twins of assembly lines and robots; DT and BIM in construction; digital twins of power grids and energy distribution.
[107]	Norway	Civil engineering	Mixed review method	To evaluate the adoption of DT for fault detection in buildings.	DT is an effective tool for detecting and correcting, which should be used in computation, analysis, optimization, and decision-making.
[104]	Netherlands	City management	Literature review	To find out how DT technology serves city needs	The integration of GIS and BIM data for urban DTs facilitates collaborative creation, management, and data sharing among diverse stakeholders.
[126]	Iran	The AEC industry	Bibliometric and systematic literature review method	To gather diverse perspectives on user experiences, identify emerging trends, present research findings, and suggest potential future research paths for leveraging BIM, IoT, and DT to improve construction process management and service delivery.	The primary subjects addressed in the literature encompass BIM, IoT, and DT in construction, along with Heritage BIM, Smart Contracts, BIM, VR, AR, and Ontology.
[127]	Malaysia	Construction project management	SLR	To investigate the current status and future trends of BIM in literature.	The findings provide academics with comprehensive and systematic insights into the subject, while also encouraging construction practitioners to evaluate the conclusions of the review and assess the performance.
[113]	China	Disaster prevention in infrastructure	Literature review	To boost intelligent disaster prevention and mitigation for infrastructure frame systematically.	The application of DT throughout the lifecycle of infrastructure can be categorized into five main areas: design and optimization, manufacturing and installation, usage and maintenance, emergency management, and recycling and dismantling
[99]	Spain	Safety management in the	Literature review	To examine the integration of BIM and DT technologies within decision-making processes concerning safety management	This proposed framework can capture the stakeholders’ requirements in design stage and facilitate the decision-making processes at all organizational levels.

		construction industry			
[80]	USA	The construction industry	SLR	To conduct a systematic review of DT applications, analyze the themes present in the literature using a thematic analysis approach, assess the degree of DT integration, and collect recommendations from industries outside other industries.	DT is a potent tool that is leaving its imprint across diverse industry sectors and is attracting interest from scholars and companies both domestically and internationally.
[65]	France	The AEC industry	Literature review	To analyze the latest applications of AR and VR in AEC projects, as well as identify the current trends in their utilization.	Technologies are applied variably across project phases: VR during the design stage, AR and VR during construction, and AR during the FM phase.
[11]	Italy	Construction asset management	Literature review	To identify the most researched areas of asset management in which AI techniques are applied.	Identified three main trends: Digital Twin, Generative Adversarial Networks (with synthetic images) for data augmentation, and Deep Reinforcement Learning.
[66]	Australia	The building, engineering, construction, operations, and mining (BECOM) industries	Literature review	To create an innovative conceptual framework for integrating blockchain technology (BCT) into DTs within the context of the BECOM industry 4.0. The aim is to enhance trust, cybersecurity, operational efficiencies, information management, and sharing, as well as sustainability	The paper offered a specialized examination of the industry and proposed a technological strategy that enables the adoption of BCT through DT to tackle primary challenges and enhance sustainability within the BECOM sector in the context of Industry 4.0
[57]	Australia	The construction industry	Literature review	To analyze the current state of DT application	DT is highly potential to provide solutions to the numerous challenges in the construction industry.
[24]	Turkey	The AECO-FM industry	Bibliometric and scientometric analysis	To analyze and deliberate on the existing patterns, discrepancies, and trends in DT research within the AECO-FM sector.	This paper examines the research patterns, discrepancies, and trends of Digital Twin studies within the AECO-FM sector through a scientometric analysis and mapping using bibliometric data.

				Additionally, it suggests future pathways for stakeholders in the industry.	
[47]	Singapore	Construction engineering and management (CEM)	SLR	To provide a more comprehensive understanding of AI-based applications to the CEM industry.	Multiple AI-related methodologies can adeptly serve three core functions: modeling and pattern recognition, prediction, and optimization. These functions offer numerous advantages to CEM, such as automation, risk reduction, enhanced efficiency, digitization, and computer vision
[59]	USA	Buildings	SLR	To recognize the progress of the emerging technologies that enable the transformation of BIM to DTs in built environment applications.	Introduced a hierarchical classification system, termed the ladder classification system, to categorize the evolution of technologies from BIM to DT.
[62]	UK	Construction industry	Literature review	To identify new challenges of digital construction innovations, yielding a set of research topics with the potential to unlock a range of future applications that apply AI.	This study highlights two key research challenges related to the development of foundational information processing methods for digital building information model: 1. Finding an optimal combination of topological rule inferencing and ML modules to achieve semantic enrichment. 2. Encoding representations of building information in formats suitable for ML applications.
[30]	USA	Construction industry	Literature review	To investigate the adoptions, capabilities, and barriers of DT in delivering value throughout the project lifecycle and understand the point of construction practitioners regarding its potential benefits.	Through the analysis of collected data on interviewees' perceptions of challenges related to DTs, 34 challenges were identified and ground into six themes. Among them, Data Understanding, Preparation, and Usage emerged as the most concerning for the interviewees.
[76]	Thailand	Construction industry	Literature review	To provide comprehensive reviews of BIM, simulation modeling, and DT.	By conducting comprehensive evaluations of BIM, simulation modelling, and DT technologies, this research establishes a clear framework that identifies the direction and potential of DT in the construction industry.

[94]	Australia	Construction industry	Literature review	To assess the present state of 3D concrete printing within the construction industry and examine the integration of DT technology into 3D concrete printing processes	DT serves as an information platform that enhances communication, cooperation, and construction management. It allows targeted monitoring and observation of the project's development at all stages, enabling early response decision-making.
[85]	Malaysia	Built environment	SLR	To help industry professionals and researchers understand the relationship between DT and BIM	The examination of the chosen articles uncovered four types of relationships between DT and BIM: BIM is a subset of DT, DT is a subset of BIM, BIM equals DT, and absence of a relationship between BIM and DT
[74]	Singapore	Construction industry	SLR	To guide both industry and academia on the utilization of DT systems as a key factor in achieving the Construction 4.0 paradigm.	Initially, a cohesive framework is created to incorporate Industry 4.0 technologies into the structure of DT. Subsequently, a Six M methodology, consisting of Machine, Manpower, Material, Measurement, Milieu, and Method, inspired by Ishikawa's Diagram, is introduced. This methodology incorporates factors relevant to the entire lifecycle of buildings. It underscores the advantages of DT in guaranteeing the accomplishment of construction projects
[5]	UK	Civil engineering	Literature review	1) To put forward a new definition for DT. 2) To identify clusters of DT-related research topics within construction industry. 3) To explore the development of each of the research topics about DT.	Proposed a DT definition and its constituents in civil engineering and compared it with BIM and CPS.
[42]	UK	Asset management	Literature review	To develop an innovative model for measuring DT maturity in asset management	The DT maturity model proves to be an efficient method for qualitatively assessing and comparing the level of DT implementation on a project basis. Additionally, it can serve as a starting point for outlining a roadmap aimed at enhancing the effectiveness of asset management supported by DT.