J. Innovative Eng. Nat. Sci., vol. 5, no. 1, pp. 399-435, 2025.
http://doi.org/10.61112/jiens.1572660

Original Paper

Journal of Innovative Engineering and Natural Science
(Yenilikçi Mühendislik ve Doğa Bilimleri Dergisi)
https://dergipark.org.tr/en/pub/jiens

From blueprint to reality: how digital twins are shaping the architecture, engineering, and construction landscape

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ARTICLE INFO

Article history:
Received 23 September 2024
Received in revised form 16 December 2024
Accepted 30 January 2025

Available online

Keywords:
Digital Twin
Building Information Modelling
Architecture Engineering and Construction
Smart Building System
Digital Technologies

ABSTRACT

Digital Twin (DT) technologies are reshaping the Architecture, Engineering, and Construction (AEC) industry by bridging physical and digital domains to enable real-time data integration, advanced simulations, and predictive analytics. This study systematically investigates the role of DT technologies in addressing persistent industry challenges such as inefficiencies, cost overruns, and sustainability goals. Through a detailed literature review of 95 publications spanning 2019 to 2024, the research identifies key contributions, barriers, and gaps in DT applications across lifecycle phases and scales, ranging from individual buildings to urban infrastructure. The findings emphasize DT's transformative potential in enhancing operational efficiency, predictive maintenance, energy optimization, and sustainability. A comprehensive framework is proposed to guide the integration of DTs, addressing technical, economic, and knowledge-based challenges while highlighting opportunities to leverage complementary technologies such as IoT, BIM, AI, and blockchain. The study concludes with actionable recommendations for advancing DT adoption in the AEC industry, paving the way for smarter, more sustainable built environments.

I. INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry faces persistent challenges like cost overruns, project management inefficiencies, sustainability issues, and complex data handling, which demand more advanced technological solutions. While Building Information Modeling (BIM) and data-driven tools have streamlined many workflows, they struggle to manage real-time dynamic data effectively. Recent studies emphasize that Digital Twin (DT) technology can address these limitations by enhancing multiple lifecycle phases, such as BIM and facilities management, and supporting decision-making with real-time insights [1]. Moreover, a state-of-the-art review highlights how integrating DT into construction lifecycle management offers a framework for addressing key industry needs and improving efficiency, innovation, and sustainability [2]. Notably, research trends point to emerging challenges in data interoperability and the integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies during the design and construction phases, suggesting that broader adoption of DT could further optimize processes and outcomes across the AEC industry [3,4].

The concept of DT has evolved significantly since its introduction by Michael Grieves in 2002 [5], where it was first described as a comprehensive virtual counterpart to a physical product, capturing all its properties from microscopic to macroscopic levels. Initially applied in aerospace and aeronautics by NASA and the U.S. Air Force to optimize vehicle performance and predict maintenance needs [6], DT technology has since expanded into various industries. In manufacturing, DTs are integral to Industry 4.0, facilitating design validation, process

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optimization, predictive maintenance, and lifecycle management [7], helping detect early design flaws and saving time and cost in production.

AEC industry has also started leveraging DT technology to address challenges like data overload and project management inefficiencies. DTs streamline communication among stakeholders such as architects, engineers, and contractors, improving collaboration throughout the lifecycle of construction projects-from design to demolition. By enabling real-time monitoring, simulation, and predictive analysis, they enhance decision-making and efficiency across different construction phases, making the industry more agile and connected [8].

Beyond construction, DT technology is expanding into sectors like healthcare, energy, and smart cities [9]. In smart cities, DTs are used for urban planning, infrastructure management, and disaster response, simulating real-world scenarios to help evaluate risks and improve sustainability. They are a key tool for improving city infrastructure and services, contributing to the creation of more resilient and efficient urban environments [10]. As DT continues to evolve, its cross-industry applications will drive innovation, collaboration, and sustainability, transforming industries undergoing digital transformation [11].

Despite their wide applicability, DTs face challenges such as system interoperability and real-time data synchronization, particularly in industries like AEC [12]. However, the consensus remains that this technology is essential for reducing costs and time, increasing productivity, improving maintenance, supporting decision-making, and promoting sustainability across multiple sectors [13]. Research has highlighted their transformative potential in improving operational efficiency, sustainability, and stakeholder collaboration. However, despite their advantages, DT implementations are often hindered by interoperability issues, high costs, and knowledge gaps among AEC professionals. Addressing these challenges requires a structured, industry-specific approach that aligns technological innovation with practical needs.

This study aims to systematically explore the role of DT technologies in the AEC industry by analyzing their applications, benefits, and limitations. It examines how these technologies enhance lifecycle management, operational efficiency, and sustainability while addressing key barriers to adoption, such as interoperability and cost challenges. Furthermore, the study proposes a conceptual framework to guide the integration of DTs across various scales and lifecycle phases, ultimately offering a roadmap to foster innovation and sustainability in the built environment.

II. METHOD

This section outlines the systematic approach adopted to explore and analyze the role of DT technologies in the AEC industry. The methodology employed ensures a comprehensive and rigorous synthesis of the existing literature, enabling actionable insights into key contributions, barriers, and gaps associated with these applications.

2.1 Research Approach

This study employs a systematic review methodology, concentrating on peer-reviewed journal articles and selected conference proceedings. The objective is to highlight the key contributions of twin technologies in the buildings, identify barriers and gaps in the existing body of knowledge, and propose a conceptual framework to guide future DT implementations.

2.2 Data Collection

2.2.1. Literature Search

A targeted search was conducted on established academic databases, including Web of Science, Scopus, and Google Scholar, to gather relevant literature. Keywords such as “Digital Twin”, “AEC”, “BIM” and “digital technologies” were utilized to ensure a broad yet focused retrieval of articles.

2.2.2. Criteria for Inclusion and Exclusion

To ensure a rigorous and relevant literature selection process, clearly defined inclusion and exclusion criteria were applied. Articles eligible for inclusion were those published between 2019 and 2024, focusing specifically on DT applications within AEC industry or closely related fields. Only peer-reviewed journal articles, conference proceedings, and review papers were considered. Studies that did not explicitly address DT technologies or related advancements were excluded, as were non-peer-reviewed sources such as blog posts, white papers, and editorials. Additionally, articles published in languages other than English were omitted to maintain consistency and accessibility.

The selection process began with a broad search of abstracts, keywords, and titles to identify potentially relevant studies. This was followed by a more detailed review of the full texts to confirm their alignment with the study’s objectives. After applying these criteria, a total of 95 articles were identified as meeting the inclusion requirements and were subsequently analyzed in depth for their contributions, challenges, and gaps in DT applications.

2.3 Data Analysis

2.3.1. Categorization and Coding

To gain a thorough understanding of the contributions made by each selected article, a systematic approach was employed to analyze and categorize the literature across multiple dimensions. These included the primary research objectives of each study, the methodologies utilized, and the specific technologies explored, such as BIM, IoT, and AI. Particular attention was given to the lifecycle phase addressed by each article whether in design, operation, or maintenance, and the scale of application, which ranged from individual buildings to urban scale projects. Furthermore, the analysis identified each study’s key contributions to the existing body of knowledge, alongside the barriers and challenges encountered in implementing twin technologies. The research also highlighted significant gaps in literature, offering a foundation for addressing these shortcomings. Finally, the relevance of each article to the present study and its primary outcomes was critically assessed to extract actionable insights that would inform the development of a robust and forward-looking conceptual framework.

2.3.2 Quantitative and Qualitative Analysis with Visualization

The data extracted from the selected literature was subjected to both quantitative and qualitative analysis to ensure a comprehensive understanding of trends, contributions, and gaps in digital twin research within the AEC. Statistical methods were employed to quantify key patterns, such as the frequency of lifecycle phases addressed (e.g. design, operation, maintenance), the distribution of technologies mentioned (e.g. BIM, IoT, AI), and temporal trends in DT research and applications over the past decade. Additionally, a thematic analysis was conducted to identify recurring themes across the extracted data, focusing on "Key Contributions", "Barriers/Challenges" and "Gaps Identified". These thematic insights informed us about the development of actionable recommendations and the conceptual framework presented in this study. To enhance clarity and facilitate interpretation, key findings were visualized using graphs. These visualizations provide a clear representation of statistical trends and thematic patterns, offering an evidence-based foundation for the study's conclusions and proposed framework.

2.4 Framework Development Process

The insights gained from the literature analysis were synthesized to develop a conceptual framework aimed at advancing the adoption of DT technologies in buildings. This framework provides a phased roadmap for integrating these significant technologies across the various stages of the building lifecycle, from design and construction to operation and maintenance. It also includes practical recommendations for overcoming critical challenges such as interoperability issues, data privacy concerns, and the high implementation costs associated with DT adoption. Furthermore, the framework outlines strategies for leveraging emerging technologies, including AI, IoT, and blockchain to enhance the functionality and effectiveness of these systems. This comprehensive framework is intended to guide practitioners and researchers in implementing DT solutions more efficiently and sustainably.

2.5 Research Limitations and Future Validation Opportunities

The findings and insights presented in this study were derived from a comprehensive analysis of the selected literature, ensuring a systematic and robust synthesis of existing knowledge. While efforts were made to align the results with established trends and challenges in the AEC industry, this study relies primarily on academic literature, which may not fully capture emerging technologies or undocumented practices in the field. The proposed framework has not yet undergone empirical testing or external validation, leaving its practical application open for further research. Future work could involve collaborating with industry practitioners and integrating feedback to refine and validate the framework in real world scenarios.

III. LITERATURE REVIEW: DIGITAL TWIN TECHNOLOGIES AND THEIR IMPACT ON THE AEC INDUSTRY

This section reviews the current state of DT technologies in the buildings and construction. It explores their conceptual foundations, applications across lifecycle phases, and the challenges and gaps hindering widespread adoption. Synthesizing insights from the literature, this review highlights the transformative potential of these technologies and establishes the foundation for the proposed framework. The section is organized into four subsections: an overview of digital twin technologies (Section 3.1), their applications in AEC (Section 3.2), barriers and gaps in the literature (Section 3.3), and findings from a systematic review of 95 research articles (Section 3.4).

3.1 Overview of Digital Twin Technologies

DT technologies bridge the gap between the physical and digital worlds by creating dynamic, real-time models of physical entities and systems. These digital replicas are continuously synchronized with their real-world counterparts through real-time data streams [14]. By enabling enhanced visualization, real-time monitoring, and predictive analytics, DT technologies empower data-driven decision-making across a building's lifecycle.

Expanding on standard DTs, virtual twins offer advanced simulation capabilities to predict future scenarios and assess outcomes prior to physical implementation. Originally developed for industries such as aerospace, manufacturing, and healthcare, DT technologies have gained significant traction in the AEC industry. Their ability to optimize workflows improving design coordination, construction efficiency, and decision-making—makes them a transformative tool for modern projects. By delivering actionable insights, DTs enable stakeholders to make informed decisions, enhancing performance and sustainability throughout a project’s lifecycle [15].

While DT technologies have broad applications across multiple industries, their implementation in the AEC industry presents unique opportunities and challenges. The following section examines how DTs are applied in building design, construction, and lifecycle management, with specific examples illustrated in Figures 1 and 2.

3.2 Applications of Digital Twin Technologies in AEC

DT technologies are transforming the building and construction industry by enabling seamless interaction between the physical and digital realms throughout the building lifecycle. These systems are structured around three interconnected zones: the physical zone, the digital zone, and the connection/integration zone (Figure 1) [16]. The physical zone represents the real-world building, where IoT sensors and devices continuously track environmental conditions, energy consumption, and system performance. The data collected forms the basis for creating accurate digital representations. The digital zone comprises a highly detailed virtual model that mirrors the physical asset, leveraging real-time data to simulate, predict, and optimize building operations. Connecting these two zones is the integration zone, which ensures continuous data exchange and feedback, enabling dynamic monitoring, simulation, and optimization across the building’s lifecycle [17, 18].

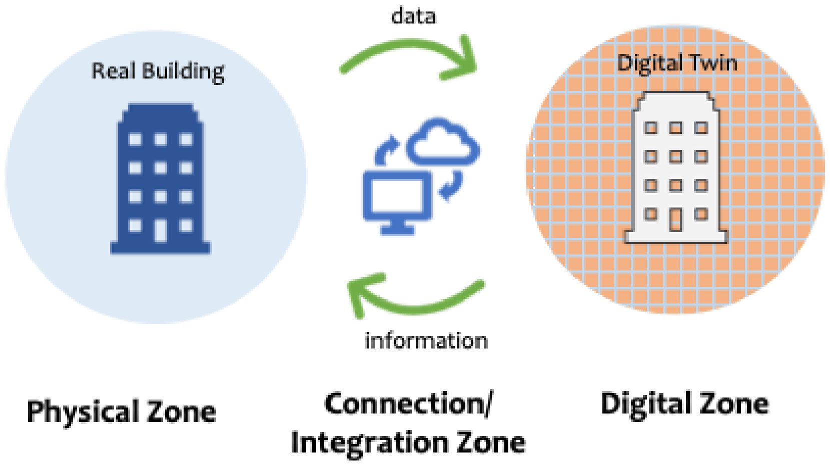


Figure 1. General framework of DTs in AEC (developed by the author)

As illustrated in Figure 1, DT systems enable a continuous, bidirectional flow of information between physical assets and their digital counterparts. By leveraging IoT enabled data collection and cloud-based platforms, DTs ensure real-time synchronization, facilitating enhanced monitoring, predictive analytics, and data-driven decision-making across the design, construction, and operational phases of the building lifecycle. Building on this, Figure 2 provides a detailed perspective of the layered architecture of DT systems, highlighting the core components involved in data collection, processing, and interaction. These interconnected layers form the backbone of DT functionality, empowering stakeholders to collaborate effectively and optimize building performance at every stage of the lifecycle.

DT technologies have significantly impacted architecture and building design, offering a structured, multi layered framework to enhance the entire building lifecycle. Each layer builds upon foundational technologies, enabling seamless integration and functionality. At their core, DTs merge physical models and real-time information flows to create a dynamic, iterative process of optimization. This approach reduces design time, minimizes errors, and helps avoid costly rework. In the construction phase, twins provide real-time progress tracking, while in the design and engineering stages, they enhance inception, briefing, design development, and technical planning. Figure 2 outlines the key layers of this framework, illustrating how data is collected, processed, and applied to continuously refine building performance.

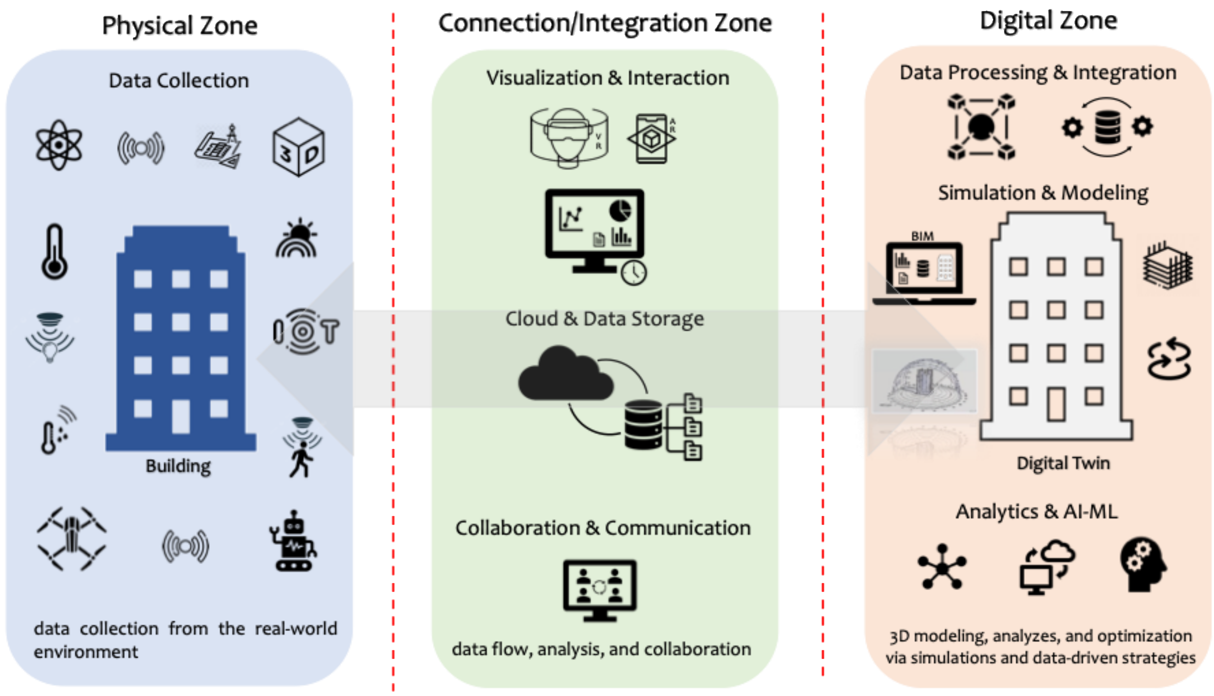


Figure 2. Layers of DT architecture in the context of building design and lifecycle management (developed by the author based on insights from the literature)

At the core of DT architecture is the Data Collection Layer, which gathers real-time information from IoT sensors, RFID tags, drones, and robotics. These tools capture critical data such as temperature, energy usage, and site conditions, which can be unstructured, semi-structured, or structured. This raw data is processed in the Data

Processing & Integration Layer, where edge computing pre-processes large data volumes before transmitting them to cloud servers via 5G technology. This approach ensures seamless system integration, real-time responsiveness, and minimized data leakage [19]. The Simulation & Modeling Layer lies at the heart of the DT, where static and dynamic data merge to create detailed virtual models. These models facilitate scenario testing, enabling architects and engineers to refine designs and optimize performance before implementation. Advanced tools within the Analytics & AI Layer support predictive maintenance and energy optimization, while real-time construction data enhances progress monitoring and resource management, driving building efficiency and sustainability. The Visualization & Interaction Layer provides users with immersive AR/VR tools, enabling real-time interaction with DT. This facilitates continuous monitoring and lifecycle management, ensuring structures remain efficient and sustainable. Supporting these layers are the Cloud & Data Storage Layer, which offers infrastructure for processing and storing data, and the Collaboration & Communication Layer, which fosters real-time cooperation among stakeholders. Together, these interconnected layers empower DTs to simulate, monitor, and optimize building performance throughout the lifecycle.

DTs play a critical role throughout the building lifecycle, providing customized applications for each phase. (Figure 3). In the Conceptual Design phase, twins enable the simulation of design concepts and predictive analysis of energy efficiency. By creating virtual prototypes, architects can test various design alternatives early, ensuring alignment with sustainability goals and performance requirements. During the Detailed Design phase, these technologies integrate with structural systems and advanced tools such as Building Information Modeling (BIM). This integration helps optimize structural performance, refine designs, and improve constructability. Digital twins also provide real-time data for iterative design processes, reducing overall design time and avoiding costly rework. In the Construction Planning phase, they simulate project phases and optimize resource allocation, resulting in efficient scheduling. By providing a comprehensive digital representation of the construction process, they enhance planning accuracy and help identify potential risks before physical work begins. Throughout the Construction phase, real-time monitoring enabled by twins allows for tracking progress, identifying deviations, and facilitating effective project management. IoT enabled sensors integrated with these twins provide data on equipment usage, environmental conditions, and worker safety, helping to maintain project timelines and reduce waste. As projects transition to the Operation and Maintenance phase, managing and integrating data from multiple stakeholders become increasingly complex. Although virtual models may accurately represent physical assets, they often lack seamless connectivity [20]. DTs address this challenge by streamlining information flow, enhancing facilities management, predictive maintenance, and energy simulations. Facility managers can leverage twin data to make informed decisions, improving operational efficiency and optimizing energy use [21]. During Renovation and Retrofitting**,** they simulate proposed modifications and assess their sustainability impacts. These simulations provide cost-effective strategies for upgrades, ensuring compliance with modern standards while minimizing environmental impact. Additionally, DTs allow for scenario testing to evaluate the long-term benefits of retrofitting strategies.

DTs significantly enhance lifecycle management, relying on technologies such as BIM and Wireless Sensor Networks (WSN) [22]. BIM consolidates data into a unified model, improving collaboration and enabling real-time updates, though workflow adjustments are often necessary. When combined with WSN, DTs provide real-time feedback to optimize design, construction, and energy management [23]. While BIM primarily relies on static data, twins utilize real-time information, further enhanced by data analytics and machine learning, to improve lifecycle decision-making [18]. Despite challenges such as stakeholder integration and research gaps, particularly in demolition and recovery phases, they are driving smarter, more efficient practices in architecture, paving the way for sustainable building performance [1].

When examining Figure 3, it becomes evident that twin technologies are fundamentally transforming the design, construction, and management of buildings by integrating advanced tools and frameworks across the building lifecycle. These technologies enable the creation of dynamic virtual models that continuously reflect the real-world status and behavior of physical assets. During the conceptual design phase, tools such as Autodesk Revit [24], ArchiCAD [25], and Autodesk Insight [26] facilitate detailed 3D modeling, energy simulations, and feasibility assessments. Additionally, geospatial tools like Esri ArcGIS [27], QGIS [28], and Mapbox [29] integrate environmental and site data into early-stage planning. Real-time data from IoT sensors, processed through platforms such as Siemens MindSphere [30] and IBM Watson IoT [31], further enrich the design process by providing operational insights. In the detailed design phase, immersive visualization tools like Enscape [32], Unity Reflect [33], and Microsoft HoloLens [34] enable stakeholders to collaborate effectively. AI and ML platforms, including TensorFlow [35] and PyTorch [36], optimize resource allocation and predict performance outcomes, enhancing material efficiency and sustainability integration. For construction planning, tools such as Synchro 4D [37], Autodesk Navisworks [38], and Oracle Aconex [39] streamline sequencing, cost estimation, and project controls. During construction execution, real-time data is collected using drones (e.g., DJI) and robots (e.g., Boston Dynamics Spot), with platforms like Procore [40] and Trimble Connect [41] enabling seamless on-site collaboration. Technologies such as Verizon 5G [42] and NVIDIA EGX [43] ensure fast data transmission and localized processing of sensor data, supporting adaptive scheduling and improved resource efficiency. In the operation and maintenance phase, cloud platforms such as Microsoft Azure [44], AWS [45], and Google Cloud [46] provide secure data storage and analytics dashboards like Google Data Studio [47] for real-time monitoring, predictive maintenance, and energy optimization. Advanced simulation tools like Autodesk CFD [48] and EnergyPlus [49] further support system performance analysis. Finally, in the renovation and retrofitting phase, tools like Matterport [50] and Ansys [51] enable precise scanning, modeling, and scenario analysis, facilitating sustainable and cost-effective strategies. Figure 3 demonstrates how these interconnected technologies span the entire building lifecycle, enhancing collaboration, efficiency, and sustainability in the AEC industry.

These interconnected technologies collectively form a robust twin ecosystem, enabling real-time data exchange, predictive analytics, and lifecycle optimization across the AEC industry. While their successful implementation in projects like smart cities and net-zero energy buildings highlights their transformative potential, the ever-evolving nature of these tools presents significant challenges. The value of these significant technologies lies not merely in the adoption of individual tools but in their ability to unify disparate technologies into a cohesive, interconnected framework. However, without standardized protocols, seamless integration, and scalable strategies, these tools risk becoming fragmented solutions, limiting the full potential of twins. Addressing these critical issues is essential to unlocking the transformative capabilities of digital twin technologies. The next section delves into the persistent barriers and gaps in literature, providing a detailed exploration of the challenges that must be overcome to fully realize the promise of DT systems.

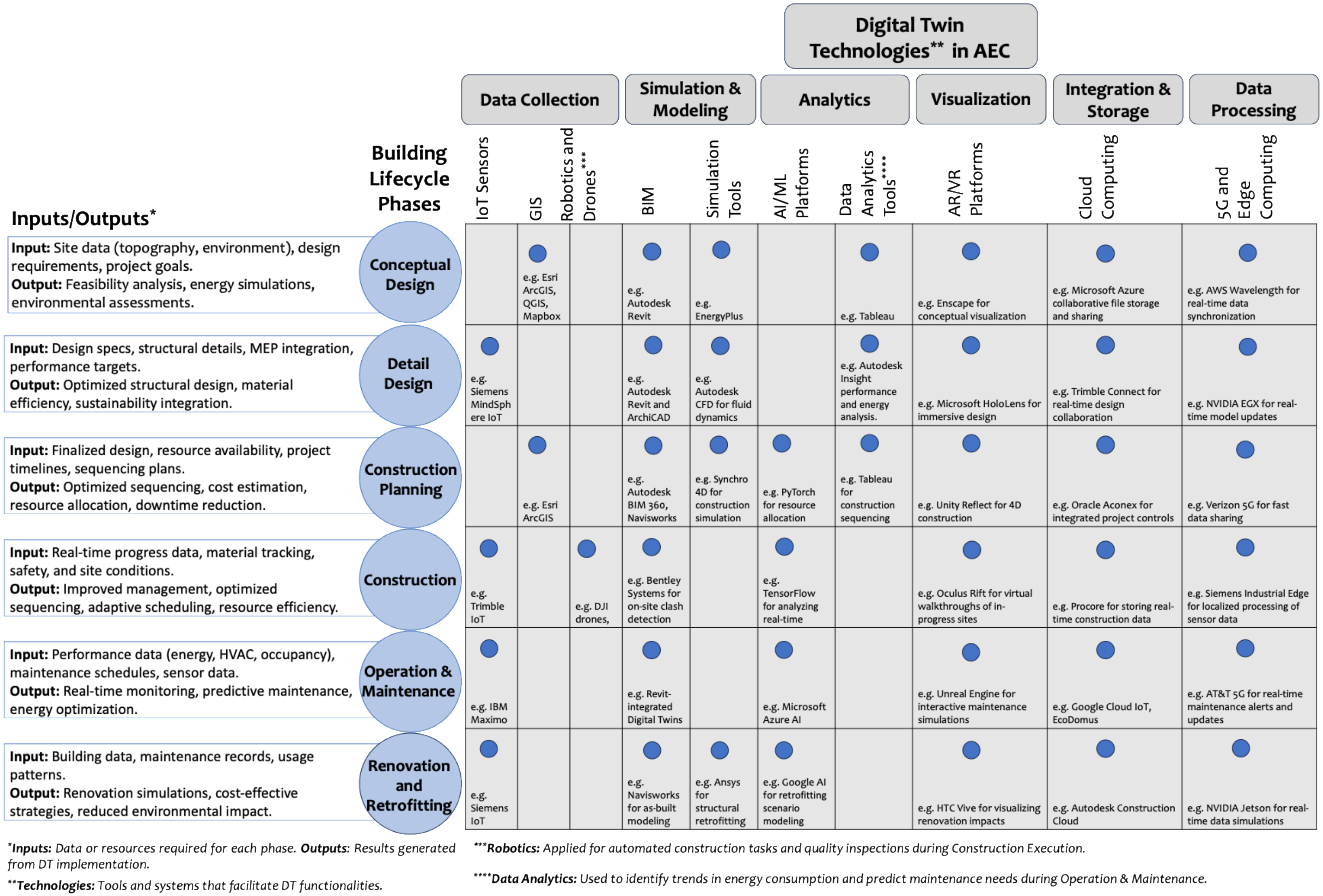


Figure 3. DT technologies categorized by functionality (Data Collection, Simulation and Modeling, Analytics and AI, Visualization and Interaction, and Data Storage). Each technology supports specific building lifecycle phases, facilitating data-driven decision-making and optimization across all stages (developed by the author).

3.3 Barriers and Gaps in Literature

Preliminary findings from the systematic review (detailed in Section 3.4) reveal significant barriers and gaps in the research and application of DT technologies within the building and construction industry. These insights underscore persistent technical, economic, and knowledge-based challenges, alongside notable gaps in lifecycle coverage, emerging technology integration, and scalability. Addressing these barriers is critical for advancing both research and practice.

Among the technical challenges, interoperability issues across various DT platforms are prevalent due to the absence of universal standards for data exchange and system integration, which hinder seamless communication between tools such as BIM, IoT devices, and simulation platforms [16]. Additionally, real-time data synchronization between physical and digital environments is often constrained by bandwidth limitations and latency, particularly in large-scale projects [52]. Economically, the high initial investment required for DT implementation-encompassing hardware, software, and training-poses significant barriers, especially for small and medium-sized enterprises (SMEs). Limited access to funding or incentive structures further exacerbates these economic challenges [53]. Skill and knowledge gaps also impede twin adoption, as expertise in advanced technologies like AI, IoT, and BIM is often lacking among AEC professionals [16]. This issue is compounded by resistance to change from traditional workflows, with many stakeholders hesitant to embrace new technologies. Data security and privacy concerns present another critical obstacle [54]. The reliance on IoT sensors and cloud computing raises the risk of unauthorized access to sensitive building information, which undermines confidence in existing security measures. The literature also highlights substantial gaps in the lifecycle coverage of these technologies. While their applications in design and construction phases are well-explored, there is a notable lack of research addressing their roles in operation and maintenance, renovation, and demolition phases [54]. Similarly, studies focusing on the integration of emerging technologies such as blockchain, robotics, and 5G networks remain limited, despite their potential to enhance data integrity, automation, and real-time communication [53]. Validation and scalability represent additional areas of concern, as few case studies empirically validate DT benefits in large-scale projects like urban infrastructure. The lack of global standards for structuring, exchanging, and securing DT data further complicates scalability [52].

Finally, sustainability and cost analysis are underexplored areas, with insufficient research on the long-term economic and environmental benefits of DT technologies. A comprehensive cost-benefit analysis that incorporates sustainability metrics is necessary to strengthen the business case for their adoption [55].

These barriers and gaps emphasize the need for standardized frameworks, empirical validation, and incentive mechanisms to support broader adoption of twin technologies in building design and construction. Addressing these unresolved issues will enable the development of scalable, sustainable, and innovative solutions, as detailed in the systematic review presented in Section 3.4.

3.4 Systematic Review of Digital Twin Technologies in AEC

This section presents the findings from a systematic review of 95 research papers, comprising both original studies and review articles, to investigate the role of DT technologies across various lifecycle phases in the AEC industry. To ensure a structured and comprehensive analysis, the papers were categorized based on several criteria, including the technologies mentioned (e.g., IoT, BIM, Blockchain), lifecycle phases addressed (e.g., design, operation, and maintenance), scale of application (e.g., building, industry, urban), research objectives, methodologies employed, key contributions to the literature, barriers or challenges identified (e.g., interoperability and data quality issues), and research gaps (e.g., social, legal, and ethical considerations).

The articles for this study were identified through an extensive, systematic literature search using reputable databases, including Web of Science, Scopus, and Google Scholar. Keywords such as “Digital Twin” “AEC” “BIM” and “IoT” were employed to ensure the comprehensive retrieval of relevant studies. Strict inclusion criteria were applied, focusing exclusively on peer-reviewed journal articles addressing DT applications in the AEC industry, along with selected conference papers. To maintain the study’s focus, only sources where these technologies were the main research topic were included. This approach recognizes that many studies discuss related technologies such as AR/VR, IoT, and AI alongside DT. However, to provide a thorough and focused investigation into the current state of DT in AEC and derive robust conclusions, these related technologies were considered secondary and contextual, preventing them from overshadowing the study's main objective. Following these criteria, 95 publications from 2019 to 2024 were selected and analyzed in detail, examining various DT applications where DT served as the central research focus.

The insights from the detailed analysis of 95 publications were synthesized to uncover patterns, trends, and gaps in DT research within the AEC industry. To illustrate the categorization criteria and provide concrete examples, 16 representative studies were selected for in-depth examination, focusing on their relevance, impact, and alignment with the key research themes. These studies were chosen based on their citation impact and their ability to exemplify critical aspects such as lifecycle phases, scales, technologies mentioned, and barriers identified in DT research. This selective approach balances clarity and comprehensiveness while offering a robust framework for the findings. Table 1 below presents a comprehensive breakdown of 16 selected studies, showcasing their contributions, methodologies, and relevance to this study's objectives. A complete list of all 95 reviewed studies, along with detailed insights and analyses, is available in Appendix A (Table 1A).

The selected 16 studies provide valuable insights into the diverse applications and challenges of twin technologies in the buildings. They emphasize key themes, including lifecycle phase integration, scalability, interoperability, and real-world implementation. Methodologies range from systematic literature reviews to innovative frameworks, showcasing the evolving research landscape. Notable contributions include advancements in energy optimization, urban-scale applications, and semantic modeling. However, recurring challenges such as data integration, lack of standardization, and high implementation costs highlight significant barriers to widespread twin adoption. These studies collectively underscore the transformative potential of DTs while identifying critical gaps and pathways for future research.

While the 16 representative studies provide a focused lens on key applications and challenges of twin technologies in the AEC, the broader dataset of 95 publications offers a comprehensive understanding of research trends, gaps, and advancements. Statistical analyses were conducted on this dataset to uncover patterns across various criteria, including research objectives, methodologies, lifecycle phases, scales, and technologies. Frequency analysis was performed to quantify mentions of specific keywords in the table, such as technologies, lifecycle stages, and scales, while trend analysis was applied to examine publication years. Text analysis techniques were also employed to identify recurring barriers, challenges, and gaps in twin implementation. These findings not only contextualize the

Table 1. Detailed Breakdown of 16 Selected Digital Twin Studies in the AEC Industry: Contributions, Methodologies, and Relevance to Study Objectives with Supplementary Insights from 95 Reviewed Articles (Appendix A, Table 1A)

Author(s) and Year	Article Title	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Kaewunruen et al., 2019 [55]	A Digital-Twin Evaluation of Net Zero Energy Building for Existing Buildings	To evaluate the feasibility of achieving Net Zero Energy Buildings (NZEBs) for existing buildings using digital twins and BIM technologies.	Proposed a hierarchical flowchart methodology combined with BIM, energy simulations, and cost analysis to assess NZEB options.	DT, BIM, Photovoltaics, Wind Turbines, Biomass CHP Systems, Energy Simulation Software.	Focused on the operation and maintenance phases while assessing retrofit applications for existing buildings.	Building-level applications with detailed case studies, including a residential building model.	Proposed a novel evaluation framework for NZEB solutions tailored for existing buildings, highlighting their financial and technical feasibility.	High initial investment, limited integration of renewable technologies, and challenges in adapting existing structures.	Lack of uniform standards for NZEBs and inadequate exploration of lifecycle-wide cost implications.
Enders and Hoßbach, 2019 [9]	Dimensions of Digital Twin Applications - A Literature Review	To provide a cross-industry overview of DT applications and propose a classification scheme.	Systematic literature review following Webster and Watson's approach.	DT, augmented reality, Industry 4.0, IoT	Various phases including design, production, and operations.	Cross-industry applications from small tools to large-scale infrastructure.	Developed a six-dimensional classification scheme for DT applications.	Limited cumulative research, underrepresentation in IS research, and industry-specific limitations.	Few cross-industry studies; insufficient focus on completeness and connection dimensions.
Boje et al., 2020 [16]	Towards a Semantic Construction Digital Twin: Directions for Future Research	To propose a framework for transitioning from traditional BIM approaches to Construction Digital Twins (CDTs), addressing semantic integration and interoperability.	Systematic review of 196 studies and development of a conceptual framework for semantic CDTs.	DT, BIM, IoT, Semantic Web, OWL Ontologies, Linked Data, Machine Learning, AI.	Covers design, construction, and operation stages with an emphasis on real-time data integration and lifecycle optimization.	Focused on building and infrastructure levels, with potential scalability to urban environments.	Proposed a three-tier evolutionary model for CDT implementation, highlighting monitoring platforms, intelligent semantic platforms, and socio-technical integration.	Lack of standards, interoperability issues, data integration challenges, and resistance to technological adoption.	Limited implementation of semantic technologies and real-time decision-making capabilities in current CDT models.
Teisserenc and Sepasgozar, 2021 [56]	Adoption of Blockchain Technology through Digital Twins in the Construction Industry 4.0: A PESTELS Approach	To develop a novel conceptual model for integrating blockchain with DTs to improve trust, security, and efficiency in the BECOM industry.	Literature review using a PESTELS approach and technological framework proposal (DDTC model).	Blockchain, DT, IoT, BIM, Industry 4.0	Lifecycle management including design, construction, and operations.	Applications in construction and mining projects within Industry 4.0.	Proposed the decentralized digital twin cycle (DDTC) framework to enhance blockchain integration with digital twins.	High implementation costs, lack of standards, regulatory uncertainties, scalability and energy challenges in blockchain integration.	Insufficient interoperability, lack of standardization, and the need for decentralized identity and storage solutions.
Coupry et al., 2021[54]	BIM-Based Digital Twin and XR Devices to Improve Maintenance Procedures in Smart Buildings: A Literature Review	To evaluate how BIM-based DTs and XR technologies can improve maintenance operations in smart buildings.	Systematic literature review focusing on the integration of BIM, Digital Twins, and XR technologies in maintenance.	DT, BIM, Augmented Reality , Mixed Reality (MR), Virtual Reality (VR), IoT.	Mainly focuses on the O&M phase of smart buildings.	Smart building-level applications, with implications for facility management.	Explored the integration of BIM and XR technologies with DTs to improve maintenance workflows.	Lack of standardization, high implementation costs, challenges in data management, and privacy issues.	Limited real-world implementations and interoperability challenges in combining BIM, Digital Twins, and XR technologies.
Delgado and Oyedele, 2021 [57]	Digital Twins for the Built Environment: Learning from Conceptual and Process Models in Manufacturing	To enhance the understanding of DTs in the built environment by analyzing conceptual and process models from manufacturing.	Systematic literature review of 54 documents (academic and industry), focusing on structural and functional models.	DT, BIM, Cyber-Physical Systems, IoT, Simulation Models.	Focuses primarily on operations and maintenance, but also discusses applications in design and construction.	Built environment scale, with implications for various sectors such as aerospace and manufacturing.	Identified four categories of DT conceptual models (prototypical, model-based, interface-oriented, and service-based) and six categories of process models.	Lack of standardized definitions, limited integration between physical and digital models, and insufficient focus on lifecycle-wide applications.	Need for detailed frameworks to support DT implementation across AECO lifecycle phases; limited practical case studies in the built environment.
Deng et al., 2021[58]	From BIM to Digital Twins: A Systematic Review of the Evolution of Intelligent Building Representations in the AEC-FM Industry	To review the evolution from BIM to DTs in the built environment, propose a classification taxonomy, and identify research gaps.	Systematic review of 123 papers, categorized into a five-level ladder taxonomy representing the transition from BIM to Digital Twins.	DT, BIM, IoT, AI, Machine Learning, Cloud Computing.	Covers all phases of the building lifecycle with emphasis on real-time monitoring, performance prediction, and control strategies.	Building and community-level applications, with potential for city-scale Digital Twin systems.	Proposed a ladder taxonomy and conceptual framework for the ideal DT, addressing data sensing, simulation integration, and automated feedback.	Data loss in sensing, offline simulation methodologies, limited automated control strategies, and interoperability issues.	Need for real-time data-integrated simulations and autonomous feedback systems for operational efficiency.
M. Mazhar Rathore et al., 2021[59]	The Role of AI, Machine Learning, and Big Data in Digital Twinning: A Systematic Literature Review, Challenges, and	To review the integration of AI, machine learning, and big data in digital twins and highlight challenges and future opportunities.	Systematic literature review of 117 articles, patents, and technical reports on AI-enabled digital twinning across multiple industries.	DTs, AI, Machine Learning, Big Data, IoT, Cloud Computing, Edge Computing.	Covers the entire lifecycle including design, manufacturing, operation, and maintenance.	Focused on industrial, urban, and global-scale applications of digital twins.	Developed a big data-driven and AI-enriched reference architecture for digital twins, emphasizing their deployment and challenges.	Interoperability, high computational demands, data integration, and lack of standardization.	Limited real-time applications; need for scalable architectures and frameworks for diverse industries.
Opoku et al., 2021 [1]	Digital Twin Application in the Construction Industry: A Literature Review	To systematically review the state-of-the-art of DT applications in the construction industry, addressing their lifecycle phases, technologies, and potential benefits.	Systematic literature review of 22 academic publications focusing on digital twin applications in construction.	DTs, BIM, IoT, AI, Wireless Sensor Networks, Cloud Computing, 5G.	Covers design and engineering, construction, and operation and maintenance phases. Notes the lack of research in the demolition and recovery phase.	Building and infrastructure scale applications with potential expansion to smart cities.	Proposed a framework linking DTs with lifecycle phases and identified key technologies and gaps for further exploration.	Slow adoption of digital technologies in construction, data integration challenges, lack of standardization, and high initial costs.	Minimal research on digital twin applications in the demolition and recovery phase; need for detailed frameworks in stakeholder collaboration.
Wang et al., 2022 [60]	BIM Information Integration Based VR Modeling in Digital Twins in Industry 5.0	To integrate BIM, VR, and twins into Industry 5.0 frameworks for improving construction efficiency and lifecycle management.	Proposed a novel DT framework incorporating physical construction site modeling (PCSE), virtual body modeling (DTVB), and virtual-reality interaction (VRI) modeling.	DTs, BIM, Virtual Reality (VR), Machine Learning, IoT, Cloud Computing, Revit, Flink, Spark.	Covers all phases of the building lifecycle, with a focus on real-time data management, predictive maintenance, and quality control.	Focused on construction projects with applications in Industry 5.0.	Developed a BIM-based DT framework for construction with enhanced scalability, predictive capabilities, and real-time interaction.	High computational demands, interoperability issues, and data latency concerns.	Limited exploration of edge computing integration for reducing data latency; lack of large datasets for neural network applications.
Pregnolato et al., 2022 [61]	Towards Civil Engineering 4.0: Concept, workflow and application of Digital Twins for existing infrastructure	To develop and demonstrate a practical workflow for creating DTs tailored to existing infrastructure, with a case study on the Clifton Suspension Bridge.	Developed a five-step workflow integrating Gemini Principles, supported by a case study application on a historical bridge.	DTs, BIM, IoT, Wireless Sensor Networks, Finite Element Models (FEM), Machine Learning.	Primarily focuses on operation and maintenance, but applicable to full lifecycle management.	Infrastructure-scale application for civil engineering, with a focus on existing legacy assets.	Proposed a systematic five-step framework for DT development, highlighting its adaptability to legacy infrastructure.	Lack of standardized procedures, integration difficulties, and high computational requirements.	Need for autonomous decision-making systems and better integration frameworks for existing infrastructure.

Table 1 (Continued). Detailed Breakdown of 16 Selected Digital Twin Studies in the AEC Industry: Contributions, Methodologies, and Relevance to Study Objectives with Supplementary Insights from 95 Reviewed Articles (Appendix A, Table 1A)

Author(s) and Year	Article Title	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Bortolini et al., 2022 [4]	Digital Twins' Applications for Building Energy Efficiency: A Review	To review DT applications for building energy efficiency and identify trends, challenges, and research gaps.	Systematic literature review of 87 publications across four key topics: design optimization, occupant comfort, operation and maintenance, and energy consumption simulation.	DT, BIM, IoT, Artificial Intelligence, Machine Learning, Cloud Computing.	Covers full building lifecycle with emphasis on operation, maintenance, and energy optimization.	Building and urban levels, including individual buildings and city-scale systems.	Classified DT applications into four categories and identified methodologies, benefits, and challenges for each.	Lack of standardization, data integration difficulties, and limited interoperability between systems.	Limited research on integrating original building designs into digital twins; challenges in real-time data use and visualization.
Lv et al., 2022 [62]	Smart City Construction and Management by Digital Twins and BIM Big Data in COVID-19 Scenario	To explore the integration of DTs and BIM with big data for smart city construction and management in the context of the COVID-19 pandemic.	Development of data processing methods based on Bayesian Network Structural Learning (BNSL) and Multi-GPU algorithms for handling complex data in smart cities.	DTs, BIM, IoT, Big Data, Machine Learning, Cloud Computing, Multi-GPU Algorithms.	Covers the design, construction, and operational phases of smart city development.	City-scale applications focused on urban infrastructure, traffic management, and public health services.	Proposed a multi-GPU algorithm for complex data fusion and a Bayesian Network-based approach for data classification in smart city scenarios.	High data complexity, lack of standardization, and computational challenges in real-time processing of large-scale urban data.	Limited exploration of multi-source data heterogeneity and integration frameworks for smart city digital twins.
Lei et al., 2023 [63]	Challenges of Urban Digital Twins: A Systematic Review and a Delphi Expert Survey	To identify and categorize the challenges faced in the design and implementation of urban digital twins, using a systematic literature review and a Delphi survey.	Systematic literature review of 34 papers and a multi-round Delphi survey with 29 expert participants.	Urban DTs, 3D city models, IoT, edge computing, semantic interoperability tools.	Challenges mapped across six lifecycle phases: data collection, processing, generating, managing, simulating, and updating.	Urban-scale applications involving cities and neighborhoods with diverse physical assets.	Comprehensive taxonomy of 16 challenges (8 technical, 8 non-technical) affecting urban digital twins.	Technical: data quality, interoperability, data integration, software, hardware. Non-technical: trust, collaboration, financing, regulatory gaps.	Limited consideration of social and legal dimensions in current studies; lack of consistent definitions and standards.
Weil et al., 2023 [64]	Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities	To provide a systematic review of challenges facing Urban Digital Twins (UDTs) and propose solutions for their implementation in sustainable smart cities.	Systematic literature review of 200 papers, analyzing technical, social, and regulatory challenges of UDTs.	Urban DTs, IoT, AI, BIM, Big Data, Edge Computing, Semantic Models.	Covers planning, implementation, operation, and decision-support phases.	Focuses on urban-scale implementations, including city management, transportation, and environmental systems.	Identified 21 challenges under 8 categories, emphasizing interoperability, semantics, infrastructure, and governance.	Interoperability, semantic integration, data quality, regulatory frameworks, governance, and ethical issues.	Limited social, legal, and ethical considerations; fragmented research on governance and standards.
Tuhaise et al., 2023 [65]	Technologies for Digital Twin Applications in Construction	To identify key technologies used in the development of digital twins in construction, highlight research gaps, and propose potential future research directions.	Systematic literature review focusing on technologies supporting DT development.	IoT, BIM, Machine Learning, Artificial Intelligence, Blockchain, Augmented Reality, Virtual Reality, Cloud Computing.	Covers all phases, with emphasis on real-time monitoring and decision-making in the construction lifecycle.	Focused on construction projects and systems integration at various scales, including individual components and entire buildings.	Proposed a DT system architecture comprising five development layers: data acquisition, transmission, digital modeling, data/model integration, and service.	Data integration issues, lack of standards, high costs, and limited interoperability.	Need for advanced solutions in data processing, transmission, and visualization; limited real-world implementations.

contributions of the selected studies but also provide a robust foundation for evaluating the current state of DT research and its trajectory within the AEC industry.

In Figure 4, Between 2019 and 2024, research on these technologies in the AEC demonstrated remarkable growth, totaling 95 publications. Early contributions from 2019 to 2021 comprised 13.68% of the total output, followed by a sharp increase from 2022 to 2024, which accounted for 86.32%, culminating in 35 papers in 2024. This trend, as depicted in Figure 4, highlights the progression of research activity, with a noticeable rise post-2020. While this increase may partially reflect the dataset's starting point, it also coincides with a global surge in interest in digital and remote solutions, largely spurred by the COVID-19 pandemic. The timing underscores the critical role of DT technologies in addressing pandemic-induced challenges, such as enhancing remote collaboration, improving operational efficiency, and promoting sustainability. These trends not only illustrate the growing prominence of DTs within the built environment but also emphasize their potential to transform building and construction practices in response to evolving global demands.

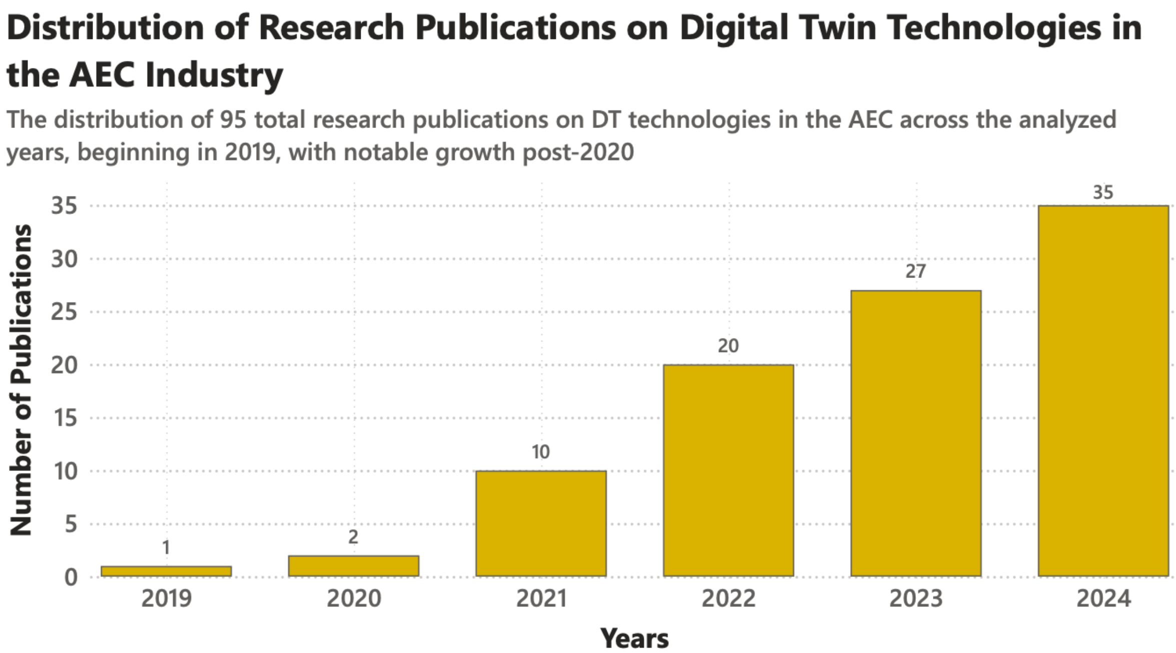


Figure 4. Annual distribution of 95 research publications on DT technologies in the AEC industry, highlighting significant growth in interest and publications post-2020.

In Figure 5, the research objectives of the analyzed publications were categorized into key themes, reflecting the transformative potential of these technologies. The largest share (35.46%) focuses on Technology Integration, highlighting the role of DTs in seamlessly incorporating advanced technologies like AI, IoT, and BIM to enhance processes across the industry [66,67,68]. Lifecycle Applications, encompassing design, construction, and operation, account for 28.37% of the studies, showcasing efforts to improve efficiency and sustainability throughout building lifecycles [16,58,70]. Research on Smart Cities and Infrastructure represents 13.48% of the total, emphasizing urban-scale DT applications aimed at optimizing infrastructure and urban planning [52,70,71]. Studies exploring Energy and Sustainability (12.77%) underscore DTs' contributions to environmental performance, such as energy optimization and predictive management [72,73,74]. Finally, Monitoring and Real-Time Applications constitute 9.93% of the research, reflecting DT-enabled advancements in progress tracking, operational efficiency, and real-time decision-making [75,76,77]. Together, these findings underscore the central role of DT technologies in fostering innovation, operational excellence, and sustainability across diverse AEC domains.

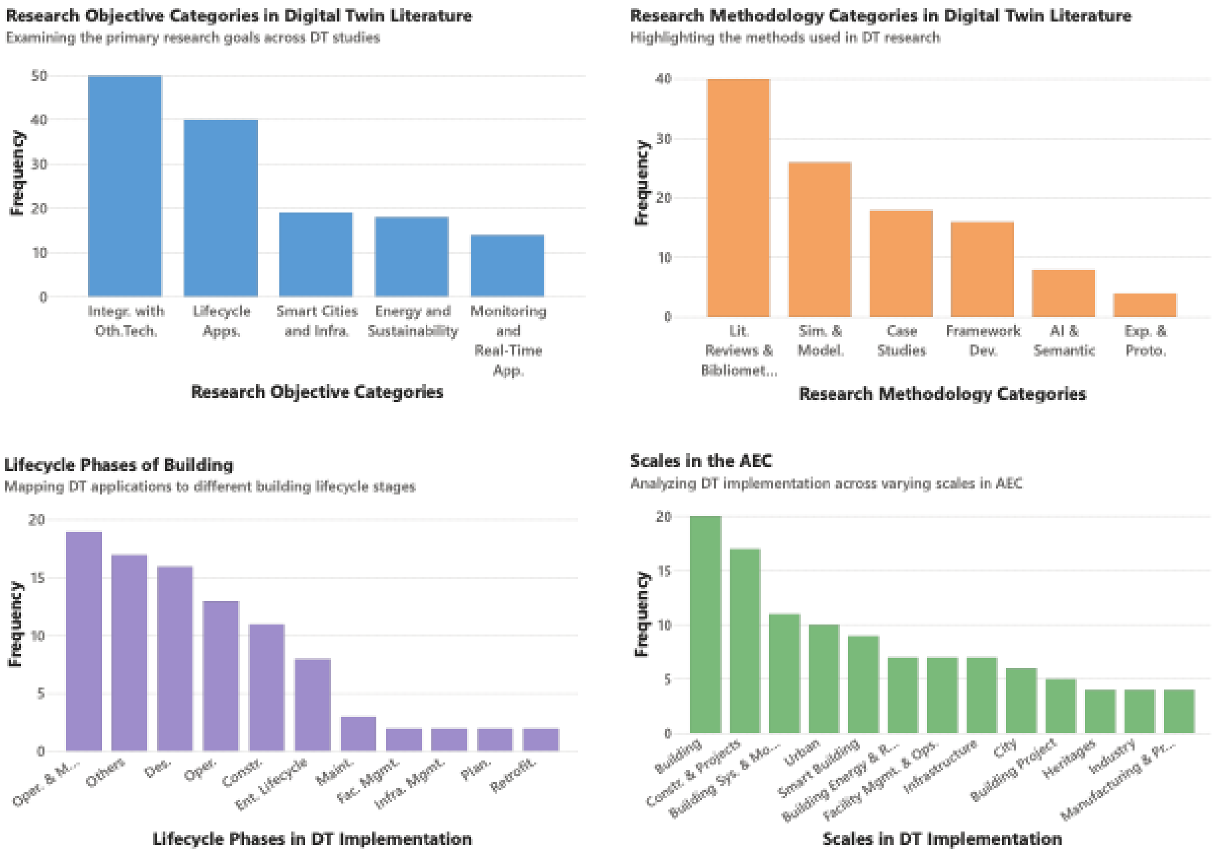


Figure 5. Statistical Analysis of Research Objectives, Methodologies, Lifecycle Phases, and Scales in DT Literature for AEC

The methodologies employed in the analyzed studies significantly shape how twins are explored and applied within the buildings, reflecting a balance between theoretical insights and practical applications. Literature Reviews and Bibliometric Analyses, comprising 35.71% of the studies, synthesize existing research to identify trends, gaps, and opportunities, offering a theoretical foundation but limited empirical insights [78-85]. Simulation and Modeling methods (23.21%) [86-88] explore virtual testing environments, enabling optimization of DT applications; however, these studies often focus on technical aspects, overlooking real-world complexities. Case Studies (16.07%) [89-92] provide valuable insights into real-world twin implementations, uncovering findings related to scalability and stakeholder engagement, though their context-specific nature may limit broader applicability. Research on Framework Development (14.29%) [93-96] contributes structured guidelines for digital twin adoption and integration with technologies like BIM and IoT, offering a theoretical base for future empirical validation. AI and Semantic Technologies (7.14%) [97] emphasize advanced interoperability and decision-making capabilities but remain underexplored in practical scenarios. Finally, Experimental and Prototyping studies (3.57%) [94,98]

demonstrate the feasibility of twin applications in controlled settings, offering tangible evidence of potential outcomes while being constrained by limited scalability. Collectively, these methodologies demonstrate a comprehensive yet evolving exploration of these technologies, underscoring the need for balanced approaches that integrate theoretical rigor with practical validation to address the AEC's complex challenges [99].

The lifecycle phases explored in the analyzed studies reveal the wide-ranging applications of these crucial technologies in the AEC. Operation and Maintenance accounts for 20% of publications [100-105], underscoring DTs' critical role in predictive maintenance, performance optimization, and operational efficiency. Design (16.84%) focuses on enhancing workflows, visualization, and stakeholder integration [106-110], while Operation (13.68%) emphasizes real-time monitoring and optimization [111-113]. Construction (12.64%) highlights DTs' applications in progress tracking and quality control [114-119], and Entire Lifecycle studies (9.20%) demonstrate the potential of DTs to integrate processes across all phases [120-124]. Niche areas, such as Maintenance [125], Infrastructure Management [78], Facility Management [84], Planning, and Retrofitting [126], each at 2.11%, reflect emerging applications. The "Others" category (17.89%) captures innovative uses, indicating an expanding scope. These findings highlight DTs' dominance in operational phases and their potential for comprehensive lifecycle integration

The analyzed studies highlight the diverse scales of these technologies implementation within the AEC industry, showcasing their adaptability across various domains. The "Building" scale accounts for the largest proportion (16.95%) [127], reflecting its widespread use in monitoring [128-130], maintenance, and performance optimization at the structure level. Construction and Projects follow at 14.41%, emphasizing DT applications in planning and execution. Building Systems and Monitoring (9.32%) and Urban applications (8.47%) highlight DTs' role in advancing smart systems and urban-scale analytics. Smart Buildings (7.63%) [131] and studies addressing Infrastructure, Facility Management and Operations, and Building Energy and Retrofitting (each 5.93%) underline DTs' contributions to sustainability, operational efficiency, and resource management. Other scales, including City (5.08%), Building Project (4.24%), and niche areas such as Industry, Heritages [132,133], and Manufacturing and Prefabrication (each 3.39%) [134,135], represent emerging applications, broadening the scope of DT technologies. These findings demonstrate DTs' versatility across scales, from individual buildings to complex urban and infrastructure systems, underscoring their transformative potential in the AEC industry.

In Figure 6, the analysis of 95 studies highlights the critical role of complementary technologies in enhancing the functionality of DTs within the buildings. The analyzed studies demonstrate the broad range of technologies integrated with twins in the AEC, highlighting their interdisciplinary nature. To provide a focused analysis, only technologies with a mention frequency value greater than five were considered, representing the most prominent tools in the dataset. IoT emerged as the most frequently mentioned technology (31.03%), underscoring its critical role in enabling real-time data exchange and connectivity. BIM follows at 26.29%, reflecting its foundational importance in DT applications for creating and managing virtual building representations [136]. AI (15.09%) and ML (4.31%) further demonstrate the integration of predictive analytics and intelligent decision-making. Emerging technologies such as Big Data and Cloud Computing (both 3.88%) support large-scale data processing and scalability, while Simulation and Cyber-Physical Systems (CPS) (both 3.02%) highlight their importance in testing and managing DT applications. Spatial tools like Geographic Information Systems (GIS) (2.59%) and Augmented Reality (AR) (2.59%) facilitate visualization and analytics, while Blockchain [137] and Sensors (both 2.16%)

address security, transparency, and real-world data acquisition. By narrowing the analysis to frequently mentioned technologies, this study emphasizes the key innovations driving digital twin development while acknowledging the broader range of less-represented technologies in the field.

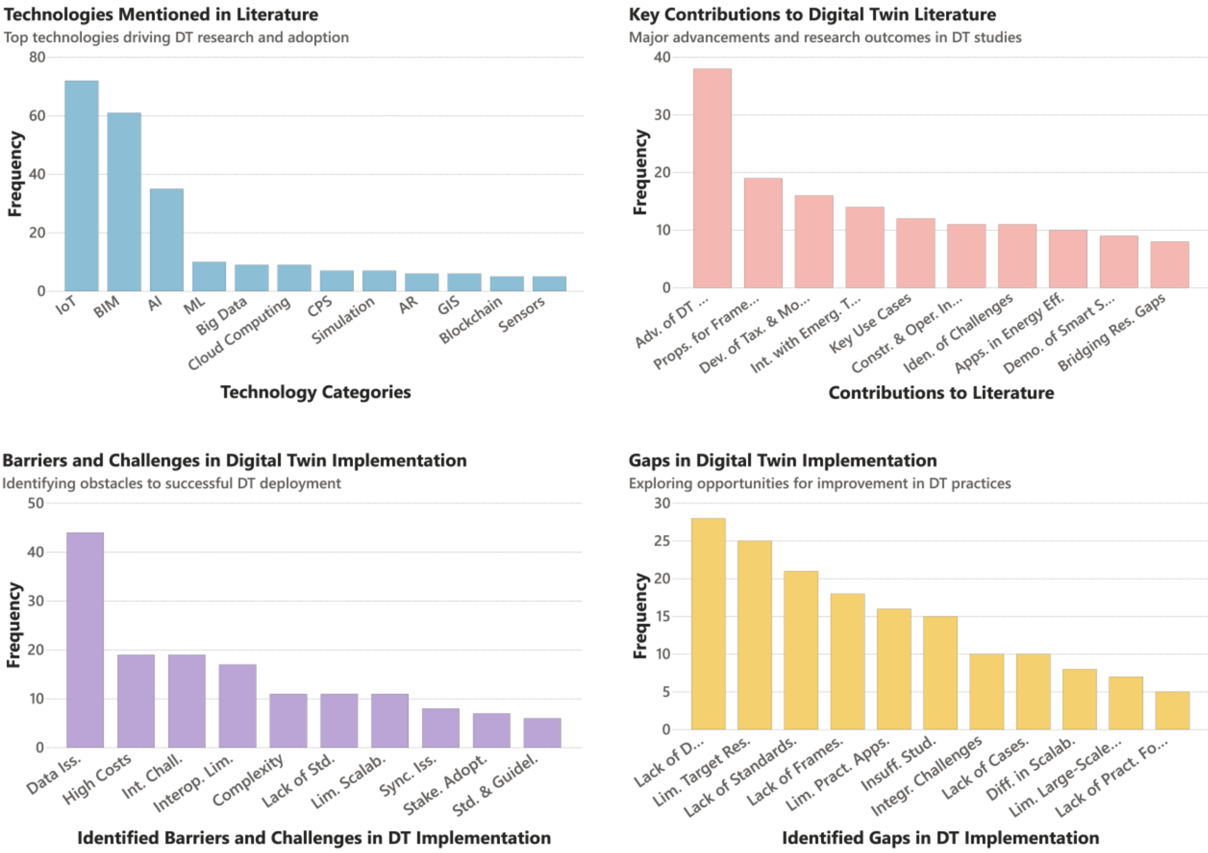


Figure 6. Insights into key technologies, contributions, barriers, and gaps in DT implementation

The analyzed studies offer diverse contributions to advancing research on these technologies in building and construction practices. The most significant contribution (25.68%) lies in the Advancement of DT Frameworks, offering comprehensive structures to guide implementation and integration. Proposals for Frameworks (12.84%) and the Development of Taxonomies and Models (10.81%) highlight efforts to formalize DT knowledge and establish conceptual tools for further exploration. Studies on Integration with Emerging Technologies (9.46%) emphasize DTs' adaptability to innovations such as AI, IoT, and blockchain, while Key Use Cases (8.11%) illustrate practical applications across diverse scenarios. Contributions addressing the Identification of Challenges and Construction and Operational Insights (both 7.43%) underline DTs' ability to tackle implementation barriers and enhance lifecycle efficiency. Research on Applications in Energy Efficiency (6.76%) and Demonstrations of Smart Systems (6.08%) showcase DTs' role in sustainability and intelligent systems. Lastly, studies focused on Bridging Research Gaps (5.41%) highlight areas of unmet needs and emerging opportunities. Collectively, these contributions underline DTs' transformative potential while identifying critical pathways for future research and application in the AEC industry.

The analyzed studies identify critical barriers and challenges hindering the implementation of these crucial technologies in the AEC. Data Issues, including quality, integration, and management, emerge as the most frequently cited challenge (28.76%), highlighting the foundational role of accurate and accessible data in DT systems [138]. Integration Challenges and High Costs (both 12.42%) underscore the difficulties of merging DTs with existing systems and the significant financial investments required. Interoperability Limitations (11.11%) reflect the need for seamless data exchange across platforms, while Lack of Standards, Complexity, and Limited Scalability (all 7.19%) emphasize the absence of unified guidelines and the technical sophistication of DT adoption. Other barriers, including Synchronization Issues (5.23%), Stakeholder Adoption (4.58%), and the need for Standards and Guidelines (3.92%), further illustrate the multifaceted challenges facing twin implementation. These findings highlight the critical need for addressing these obstacles to fully realize DT technologies' transformative potential in building and construction practices.

The identified research gaps in DT implementation underscore critical areas requiring further investigation to enhance their adoption and impact within the AEC industry. The most significant gap is the Lack of Advanced DT Applications (17.18%), indicating a need for more sophisticated and innovative uses of DT technologies. Limited Targeted Research (15.34%) and the Lack of Standards (12.88%) highlight the absence of focused studies and unified frameworks to guide DT integration. The Lack of Frameworks (11.04%) and Limited Practical Applications (9.82%) point to the need for actionable methodologies and real-world implementations. Other gaps include Insufficient Studies (9.20%), Integration Challenges, and the Lack of Case Studies (both 6.13%), which reveal the scarcity of empirical evidence and integration strategies. Issues such as Scalability Difficulties (4.91%) and Limited Large-Scale Deployments (4.29%) emphasize technical and operational barriers, while the Lack of Practical Focus (3.07%) calls for aligning research with industry needs. Addressing these gaps is essential for advancing DT technologies and maximizing their potential in the building and construction industry.

IV. DIGITAL TWIN FRAMEWORK FOR AEC

The proposed framework for advancing DT integration in the AEC industry addresses critical gaps, challenges, and trends identified through statistical analysis and a systematic review of DT literature. This comprehensive roadmap enables scalable, sustainable, and innovative DT technologies tailored to the industry's unique demands. It simplifies the growing complexity of these systems, adapts to diverse applications across scales and lifecycle phases, and meets the demand for sustainability and operational efficiency. The framework is visually represented in Figure 7, which illustrates the eight interconnected categories and their relationships. Each category is explained in detail below.

The framework comprises eight interconnected categories, each addressing specific aspects of DT integration: Each category addresses specific findings from the analysis. For instance, "Addressing DT Gaps" focuses on foundational issues such as interoperability and scalability limitations, which were identified as barriers in over 60% of reviewed studies. Similarly, "Overcoming Challenges" deals with high costs and stakeholder resistance, concerns highlighted in 40% of the literature. "Solutions for Scales" ensures DT applicability across diverse contexts, reflecting research trends that emphasize urban infrastructure and smart cities, which accounted for over 50% of applications. "Solutions for Lifecycle Phases" aligns DT applications with design, construction, operation, and maintenance stages, supported by 70% of studies focusing on lifecycle efficiency. Cross-cutting categories like "Improving Methods" address methodological gaps, with 35% of studies calling for more empirical validation and experimental prototypes, while "Leveraging Technologies" highlights IoT, BIM, and AI, cited in over 75% of research as key enablers. Finally, "Incorporating Energy and Sustainability" and "Smart City and Infrastructure Applications" focus on long-term goals, with 45% of studies linking DT to sustainability and urban-scale implementations. Together, these interconnected categories create an iterative framework that addresses current gaps and anticipates future needs. These categories are interdependent, forming a cohesive framework. Foundational elements, such as Addressing DT Gaps and Overcoming Challenges, enable practical applications in Solutions for Scales and Solutions for Lifecycle Phases. Cross-cutting enablers like Improving Methods and Leveraging Technologies refine these solutions, while future-oriented goals in Incorporating Energy and Sustainability and Smart City Applications ensure alignment with industry trends and sustainability objectives. This interconnected structure provides continuous improvement and innovation for DT adoption in the AEC.

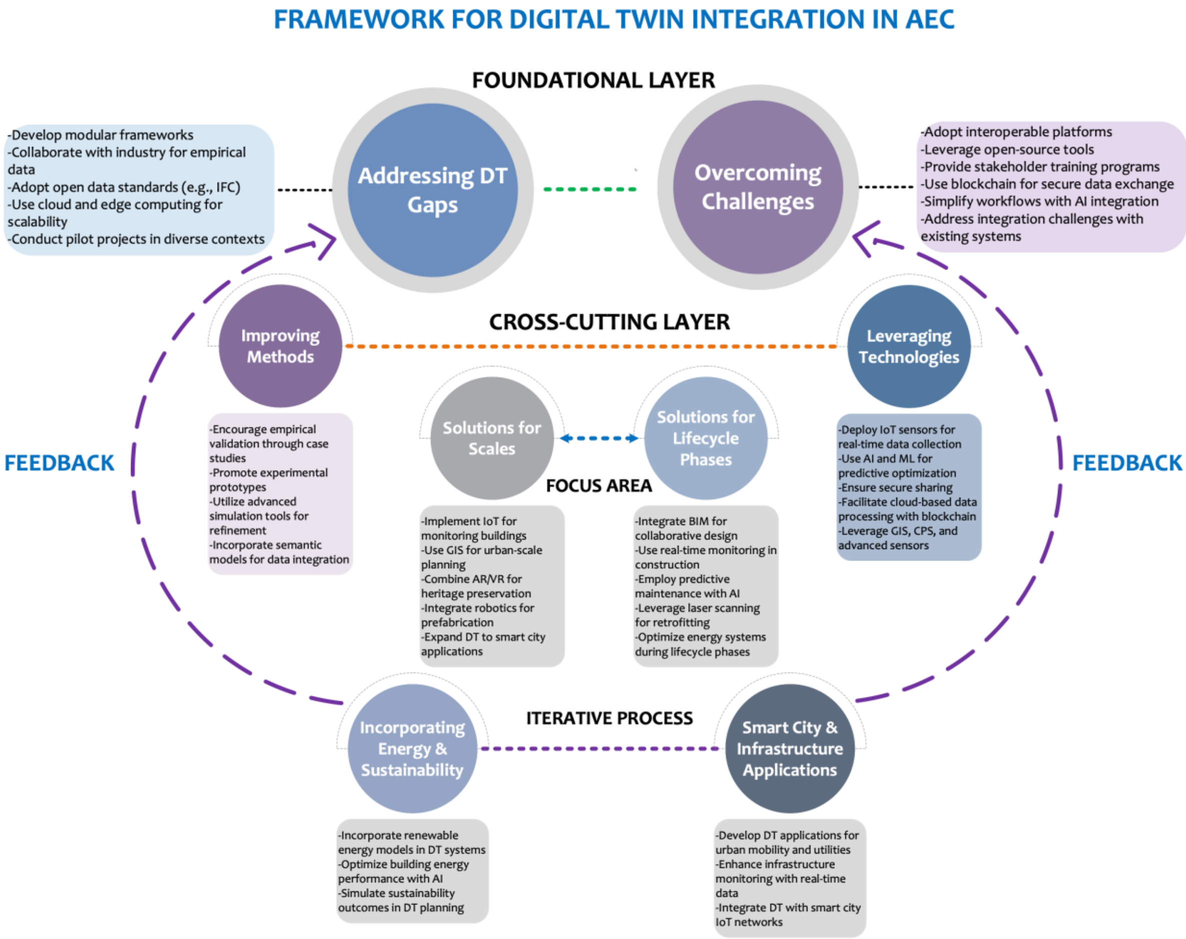


Figure 7. Digital Twin Framework for AEC: The framework illustrates the integration of foundational elements (DT gaps, challenges), application-specific solutions (scales, lifecycle phases), cross-cutting enablers (methods, technologies), and future-oriented goals (sustainability, smart cities), highlighting a dynamic and adaptive approach to advancing the AEC industry (developed by the author)

These categories are interdependent, forming a cohesive framework. Foundational elements, such as Addressing DT Gaps and Overcoming Challenges, enable practical applications in Solutions for Scales and Solutions for

Lifecycle Phases. Cross-cutting enablers like Improving Methods and Leveraging Technologies refine these solutions, while future-oriented goals in Incorporating Energy and Sustainability and Smart City Applications ensure alignment with industry trends and sustainability objectives. This interconnected structure provides continuous improvement and innovation for DT adoption in the AEC industry.

This framework offers a comprehensive guide for implementing these significant technologies in the building and construction practices. By addressing foundational gaps, overcoming challenges, and leveraging advanced technologies, it ensures scalable, sustainable, and innovative solutions. Its adaptability across various scales, lifecycle stages, and industry contexts makes it a valuable tool for advancing digital transformation. Furthermore, its alignment with sustainability and smart city goals positions it as a forward-thinking approach to modernizing the built environment.

V. REAL WORLD APPLICATIONS OF DIGITAL TWIN TECHNOLOGIES IN ARCHITECTURE

DT technologies are revolutionizing AEC industry by integrating real-time data, enabling advanced simulations, and providing predictive analytics. Their transformative impact on architecture is exemplified through diverse buildings that demonstrate extensive applications and significant benefits. These buildings were chosen based on their pioneering design, sustainability initiatives, operational efficiency, and advanced technological integration (Table 2).

The categorization of buildings into domains reflects the effort to comprehensively represent the wide range of DT applications in the AEC. By selecting examples that demonstrate diverse applications from design optimization to urban planning and sustainability, the intention is to provide a systematic overview of how DTs address unique challenges across different areas of AEC. These domains not only highlight DTs' specialized impact but also ensure that the selected buildings collectively represent the breadth of DT technology's transformative potential throughout the lifecycle of architectural and infrastructural projects.

Digital Twin technologies have been effectively applied in various domains. In design optimization, The Edge in Amsterdam [145] exemplifies the application of DT technologies to achieve unparalleled design optimization by integrating smart lighting and energy-efficient systems, making it one of the world's most sustainable office buildings. DTs were used to simulate building performance during the design stage, allowing architects to refine energy-saving strategies before construction. Similarly, Apple Park [143] in California employed DTs to model the campus's complex energy systems and landscaping, enabling precise calibration of sustainable design elements. During its design phase, the Bosco Verticale (Milan) [148] utilized DTs through IBM's Watson IoT platform to monitor environmental performance, optimize plant growth, and track microclimatic conditions. These cases highlight DTs' role in early-stage decision-making, ensuring both environmental and functional goals are met effectively (Table 2). In construction management, the Hudson Yards (New York) [141], DTs enabled precise coordination among construction stakeholders, integrating prefabrication tracking and real-time updates. This approach reduced delays and allowed teams to address challenges proactively during construction. Similarly, the YTL Arena Complex (UK) [139] leveraged DTs via Vigilant's platform to simulate crowd dynamics, monitor structural components, and adjust lighting and HVAC systems during events. At Battersea Power Station (London)

[140], Siemens' DT platform helped optimize energy system integration and infrastructure during redevelopment, ensuring predictive maintenance and reduced operational costs. These examples emphasize DTs' role in creating

Table 2. Building examples representing the application and benefit of DT technologies in Architecture

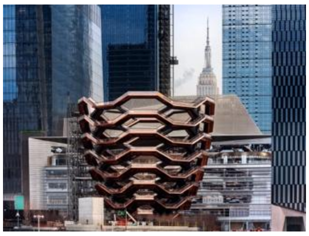
Building	Description	Use of DT	Exemplary application of DT
Bristol's YTL Arena Complex [139] 	YTL Arena, built on Bristol's former Filton Airfield, aims to be one of the UK's most sustainable venues. *Completion Year:* Currently under construction; expected to be completed in 2025. *Design Team:* Feilden Clegg Bradley Studios. Place: Bristol, UK	A DT modeled the building's energy and environmental impacts, ensuring maximum energy efficiency and operational flexibility while simulating crowd flow and safety scenarios.	AI-driven tools like Autodesk BIM 360 optimized the arena's HVAC systems, reducing energy use and improving indoor air quality, while enabling ongoing performance evaluation.
Battersea Power Station, London [140] 	Battersea Power Station's redevelopment into a mixed-use complex required extensive planning and design optimization. *Completion Year:* 2013-2022 *Design Team:* Architect of Power Station: Wilkinson Eyre,; Interior Designers: Gehry Partners and Foster + Partners Place: London, UK	The DT modeled design options early on, facilitating performance simulations, energy efficiency analysis, and smart technology integration, while providing insights into future users' interactions with the space.	DTs planned for energy use and sustainability, optimizing indoor air quality and natural lighting through AI algorithms and BIM tools that analyze real-time data and simulate environmental scenarios. Post-completion, the digital twin enhances facility management and operational efficiency.
Hudson Yards, New York City [141] 	Hudson Yards is the largest private real estate development in the history of the US and includes commercial buildings, residential units, and public spaces. *Completion Year:* 2019 (Various buildings completed in stages) *Design Team:* KPF for the main towers, with additional firms for other structures. Place: New York, USA	DT technology at Hudson Yards helped test design alternatives for energy efficiency, optimize building performance, and simulate pedestrian traffic for better planning.	Hudson Yards' DT improved collaboration, optimized resource allocation, managed timelines, and enabled real-time adjustments during construction.
King Abdullah Financial District (KAFD), Riyadh [142] 	KAFD is a high-profile commercial district in Riyadh that incorporates numerous smart city concepts. *Completion Year:* 2019 (Ongoing development) *Design Team:* HOK and various firms for different components Place: Riyadh, Saudi Arabia	DT technology optimized building performance in extreme climates by simulating environmental and energy systems, enhancing energy use, ventilation, and cooling for desert conditions.	BIM and AI platforms (Autodesk, Siemens' Design CC) optimized design for energy efficiency and sustainability, reducing costs. The digital twin enables real-time monitoring and predictive maintenance.
Apple Park [143] 	Apple Park is a massive campus that emphasizes sustainability and integrates nature with technology. *Completion Year:* 2017 *Design Team:* Foster + Partners Place: Cupertino, California	DT technology was employed to create a comprehensive model of the campus, including landscaping, energy systems, and building performance. It allows for real-time monitoring and management of various systems.	DT enables predictive maintenance, energy optimization, and efficient resource management across the campus. It also facilitates occupant comfort by adjusting environmental conditions based on real-time data and usage patterns.
Singapore's National University Hospital [144] 	The NUH Medical Centre is a healthcare facility known for its innovative design and operational efficiency. *Completion Year:* 2016 (Part of ongoing developments) *Design Team:* CPG Consultants. Place: Singapore	A DT simulated energy use, airflow, patient movement, and equipment operation, optimizing building performance and future planning while modeling emergency scenarios for enhanced safety and efficiency.	DT simulations with AI and machine learning optimized the hospital's energy efficiency, patient comfort, and minimized disruptions, including real-time HVAC monitoring, predictive equipment maintenance, and patient flow simulations.

Table 2 (Continued). Building examples representing the application and benefit of DT technologies in Architecture

Building	Description	Use of DT	Exemplary application of DT
The Edge, Amsterdam [145] 	The Edge is often described as the smartest and most sustainable office building in the world, earning the highest-ever BREEAM rating of 98.36%. *Completion Year:* 2014 *Design Team:* PLP Architecture. Place: Amsterdam, Netherlands	During design, a digital twin used real-time data on occupancy, energy consumption, and environmental factors to optimize energy efficiency, sustainability, and user experience through simulations.	The DT allowed architects and engineers to optimize heating, cooling, lighting, and occupancy systems for energy efficiency, refine flexible workspace design, and integrate renewable energy sources and smart technologies for improved performance.
Nanjing International Youth Cultural Centre [146] 	Zaha Hadid-designed landmark building incorporates twin towers and cultural facilities. *Completion Year:* 2014 *Design Team:* Zaha Hadid Architects Place: Nanjing, China	A digital twin simulated the building's geometry for structural integrity and environmental efficiency, resolving design challenges and ensuring sustainability goals.	Using Autodesk Revit and ANSYS, the twin model simulated energy use, airflow, and structural resilience, while enabling post-completion performance monitoring to optimize operations.
One World Trade Center [147] 	One World Trade Center is a symbol of resilience and innovation in design, serving as an office and commercial space. *Completion Year:* 2014 *Design Team:* David Childs (Skidmore, Owings & Merrill) Place: New York City, US	The digital twin of One World Trade Center was developed to enhance operational efficiency, focusing on security, safety, and energy management.	The digital twin supports predictive analytics for maintenance, optimizing HVAC systems, and improving security protocols by simulating various emergency scenarios. Real-time data helps to maintain operational integrity and efficiency.
The Bosco Verticale (Vertical Forest) [148] 	Bosco Verticale features residential towers adorned with trees and vegetation, enhancing biodiversity and sustainability. *Completion Year:* 2014 *Design Team:* Stefano Boeri Architetti Place: Milan, Italy	A digital twin managed interactions between the building and its natural elements, such as plant growth and energy efficiency.	The digital twin monitors plant health and energy use, optimizes resources, ensures structural integrity, and assesses the environmental impact of green spaces to promote urban biodiversity.

efficient and adaptive construction processes. For facility and asset management, at Singapore's National University Hospital (NUH) [144], Siemens' DT platform tracks real-time energy use and air quality, improving patient comfort and operational efficiency. These applications demonstrate how DTs transform facility operations by integrating real-time insights with proactive management strategies.

In urban planning and smart cities, DTs are instrumental in urban-scale projects such as the Smart Dubai Initiative [149], which uses real-time monitoring to manage energy distribution and infrastructure systems. Similarly, Singapore's Smart Nation [150] integrates DTs to improve urban mobility, optimize traffic flows, and plan infrastructure investments based on predictive models. The King Abdullah Financial District (KAFD) [142] in Riyadh utilizes Autodesk's DT platform to analyze energy consumption and adjust lighting and HVAC based on occupancy patterns, positioning it as a model for sustainable urban development. These projects illustrate how DTs enhance urban planning by fostering smarter, more efficient cities. For heritage preservation, The Notre Dame Cathedral restoration project [151] highlights the use of DTs to create precise digital replicas, enabling structural analysis and guiding restoration efforts after the 2019 fire. Similarly, DT technologies have been employed at Battersea Power Station [140] to preserve its heritage while incorporating modern energy systems. These examples underscore DTs' critical role in protecting and maintaining cultural heritage.

Lastly, DTs have driven sustainability and energy efficiency goals. At Nanjing International Youth Cultural Centre (China) [146], DTs optimize HVAC systems, improving energy efficiency and occupant comfort. One World Trade Center in New York [147] employs IBM's Maximo platform to monitor energy consumption and HVAC systems in real-time, ensuring operational efficiency and reduced energy waste. These projects reflect how DTs enable environmentally conscious solutions in architectural and urban development.

VI. IMPACT OF DIGITAL TWIN TECHNOLOGIES: CASE STUDY INSIGHTS AND SYNTHESIS

As a result of real case building analysis conducted within the scope of this study, it was found that twin technologies play a critical role across various phases of the building life cycle. Significant applications were observed in the design, construction, and operational stages. For instance, the analysis revealed that the YTL Arena Complex in Bristol utilized Vigilant's DT platform during the design phase to simulate crowd dynamics and optimize energy systems. This demonstrated how DTs enable enhanced planning and adaptability. Similarly, Apple Park effectively employed DTs to manage energy efficiency and achieve sustainability targets during operations. The Edge in Amsterdam showcased Microsoft Azure's DT technology for real-time monitoring of environmental conditions via an extensive network of sensors, highlighting the importance of DTs in sustainable building management.

The research further indicated that during the design and construction phases, twins significantly enhance planning and execution processes. For example, the Battersea Power Station redevelopment project utilized Siemens' DT platform to optimize energy system integration, ensuring predictive maintenance capabilities and efficient workflows. Similarly, Hudson Yards in New York City relied on Siemens' Navigator platform to monitor energy consumption, HVAC systems, and occupancy patterns in real time, resulting in reduced energy use and improved project timelines. Additionally, King Abdullah Financial District (KAFD) in Riyadh used Autodesk's DT platform to refine energy consumption and facilitate dynamic adjustments to facility management, underlining DTs' critical role in addressing inefficiencies and adapting to real-time data inputs during these phases. During the operational phase, the study found that DTs offer substantial long-term benefits by enabling performance analysis and predictive maintenance. For instance, Singapore's National University Hospital (NUH) leveraged Siemens' DT platform to optimize energy use, monitor air quality, and ensure patient comfort, demonstrating the effectiveness of DTs in enhancing facility management. Similarly, One World Trade Center used IBM's Maximo platform for real-time operational efficiency, with systems dynamically adjusted based on occupancy patterns. These cases highlight how DTs contribute to sustained cost savings, energy efficiency, and improved user experience. While the current focus remains on the design and construction phases, this study identified significant potential for DT applications in later life-cycle stages, such as renovation and retrofitting. For example, the Bosco Verticale in Milan was found to utilize DTs to monitor and maintain its extensive green infrastructure by optimizing microclimatic conditions and tracking plant health. This approach ensures resource-efficient renovation and maintenance strategies, reflecting the long-term value of DTs in extending building life cycles.

Despite these findings, the research identified several challenges hindering broader adoption of DT technologies. High initial costs of developing and deploying DT systems were noted as a significant barrier, particularly for smaller-scale projects. Additionally, data integration complexity and the lack of standardized approaches to IoT-enabled sensor networks were observed as persistent issues. Data privacy and security concerns further complicate implementation, especially in large-scale urban projects. However, advancements in edge computing and 5G technology offer promising solutions to these challenges. Edge computing enables real-time data processing at the source, reducing latency and minimizing transfer costs, while 5G ensures faster and more secure data transmission. These technological developments are expected to enhance the efficiency and affordability of DT technologies, broadening their accessibility across diverse applications.

In conclusion, the findings of this study confirm that DT technologies are pivotal in transforming practices across all phases of the building life cycle. Early integration during design and construction maximizes their potential for improving planning, execution, and energy efficiency. Operational benefits such as predictive maintenance and real-time monitoring further reinforce their value, while applications in renovation and retrofitting highlight their role in extending the sustainability and functionality of buildings. Although challenges remain, the continuous evolution of supporting technologies will likely address these issues, solidifying DTs' role in shaping smarter, more sustainable built environments.

VII. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This research has demonstrated the transformative potential of DT technologies in addressing key challenges in the AEC industry. By systematically analyzing 95 research publications from 2019 to 2024, this study provided a comprehensive understanding of DT applications, uncovering critical gaps, emerging trends, and significant opportunities for advancement. The findings highlighted underexplored lifecycle stages, such as retrofitting, demolition, and recycling, where DT applications remain limited despite their potential to optimize resource use and enhance sustainability. Furthermore, significant barriers, including interoperability issues, high implementation costs, scalability challenges, and a lack of standardized protocols for data exchange, were identified. These barriers obstruct the seamless integration of DT technologies across different lifecycle stages and limit their potential to fully optimize processes in construction and operational phases. These insights informed the development of a tailored conceptual framework that addresses these barriers while utilizing enabling technologies such as IoT, BIM, AI, and blockchain for seamless integration and enhanced decision-making. The key contributions of this research are listed below:

- Comprehensive Lifecycle Analysis: This research revealed the uneven distribution of DT applications across lifecycle phases, emphasizing the need for targeted innovations in underrepresented stages. These findings provide a roadmap for expanding DT integration to cover the entire building lifecycle.
- Framework Development: A robust framework was proposed to overcome identified barriers, offering targeted strategies for addressing interoperability limitations, high implementation costs, and fragmented data management systems. This framework emphasizes the integration of predictive analytics for proactive maintenance, real-time data synchronization to improve decision-making, and modular approaches for scalable solutions adaptable to varying project sizes. These contributions align not only with sustainability goals and operational demands but also foster enhanced stakeholder collaboration and resource optimization across all lifecycle phases.

- Insights into Emerging Technologies: By examining the dominant and emerging technologies driving DT adoption, this study clarified the synergies required for real-time data processing, predictive analytics, and collaborative workflows.
- Practical Applications: Case studies demonstrated that Digital Twin technologies have significantly contributed to enhancing building performance. By enabling real-time monitoring and predictive analytics, DTs facilitated energy optimization, leading to improved efficiency and reduced waste. Additionally, construction timelines were optimized using dynamic progress tracking and resource allocation systems, minimizing delays and improving workflow. Stakeholder collaboration was enhanced via unified digital platforms that provided transparent communication channels and centralized access to critical data, ensuring more effective decision-making throughout project phases.

While this study has contributed to advancing understanding, further data-driven validation is essential. Key areas for future exploration include:

- Standardization and Interoperability: Developing universal protocols to address interoperability barriers and ensure seamless data integration across platforms.
- Lifecycle Expansion: Exploring DT applications in demolition, recycling, and decommissioning to establish comprehensive lifecycle solutions.
- Economic and Sustainability Evaluations: Conducting detailed studies on long-term environmental and financial benefits to strengthen the business case for DT technologies.
- Scalability for AEC Organizations: Addressing the unique challenges faced by organizations within the AEC industry, this study emphasizes the development of modular and adaptable DT solutions. These include lightweight digital platforms optimized for minimal computational requirements, cost-effective subscription models to lower financial barriers, and targeted training programs to enhance workforce proficiency in DT tools and applications. By prioritizing accessibility and practicality, these strategies aim to democratize the adoption of DT technologies, enabling smaller organizations to achieve improved process efficiency, smarter resource allocation, and informed decision-making while remaining competitive in a technology-driven landscape.

By addressing these areas, this research contributes a solid foundation for guiding future innovations in DT adoption. The insights and framework provided herein are critical for shaping and accelerating the digital transformation of the AEC industry, enabling smarter, more sustainable, and resilient built environments.

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APPENDIX A

Table A1. A complete list of all 95 reviewed studies, along with detailed insights and analyses

Author(s) and Year	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Kaewunruen et al (2019) [55]	Evaluate the feasibility of digital twins for achieving Net Zero Energy Building status in existing buildings.	Evaluation of NZEB solutions using BIM-enabled visualization and simulations.	BIM, renewable energy, simulation	design and operation	Building	Provided feasibility evidence for NZEB solutions in existing buildings.	High costs and implementation barriers for NZEB solutions.	Few studies on NZEB retrofits in existing buildings.
Boje et al (2020) [16]	Define and explore the semantic construction digital twin and its applications.	Review and thematic analysis of BIM and IoT integrations in construction.	BIM, IoT, semantic web, AI	design, construction, and operation	Construction site and lifecycle scale.	Explored transitioning BIM to semantic digital twins for improved processes.	Semantic and data synchronization limitations.	Integration of IoT and AI in real-time construction digital twins.
Lehner et al (2020) [52]	Develop a comprehensive digital twin framework for Vienna as a geodata hub.	Developed a semantic digital twin using geospatial data and 3D models for Vienna.	GIS, 3D modeling, geodata management	urban management	City-scale geodata hub.	Proposed a new strategy for digital twins in urban geodata management.	Data coherence challenges in geospatial datasets.	Limited studies on semantic urban data management.
Camposano et al (2021) [53]	Understand digital twins of built assets using seven metaphors and explore their role in AEC/FM ecosystems.	Qualitative study with semi-structured interviews of AEC/FM practitioners.	BIM, IoT, service-dominant logic	conceptual	Asset scale and broader ecosystem scale.	Identified seven metaphors for understanding digital twins in AEC/FM.	Fragmentation in the AEC/FM industry and lack of standard definitions for DTs.	Lack of consensus on digital twin definitions and frameworks.
Coupry et al (2021) [54]	Explore the combination of BIM and XR technologies to enhance maintenance procedures in smart buildings.	Systematic literature review combining DT, BIM, and XR technologies.	BIM, XR, AR, IoT	operation and maintenance	Building and smart maintenance scales.	Reviewed XR and BIM integrations for smart building maintenance.	Complexity of XR integration in real-world settings.	Few practical XR-BIM use cases in O&M.
Delgado et al (2021) [57]	Analyze DT concepts in manufacturing to derive models suitable for the built environment.	Broad literature review and conceptual analysis of DT models in AECO.	BIM, CPS, conceptual models, process models	design and operation	Industry-wide application with AECO focus.	Mapped DT applications in manufacturing for AECO contexts.	High costs of adapting manufacturing methods to AECO.	Need for AECO-specific DT maturity models.
Deng et al (2021) [58]	Systematically review the evolution of BIM to Digital Twins and assess enabling technologies.	Systematic literature review with a five-level ladder taxonomy.	IoT, BIM, AI, smart buildings.	design, construction, and operation	Building scale within smart city contexts.	Developed a taxonomy for assessing DT maturity in built environments.	Lack of real-time synchronization in many DT implementations.	Insufficient exploitation of IoT-enabled DTs.
Opoku et al (2021) [1]	Analyze DT applications in construction lifecycle stages and provide a roadmap for adoption.	Systematic review and science mapping method.	IoT, AI, data fusion, Industry 4.0	construction project	Project scale in construction.	Presented a comprehensive roadmap for DT adoption in construction.	Limited consensus on DT standards in construction.	Lack of detailed roadmaps for DT lifecycle integration.
Rausch et al (2021) [134]	Analyze geometric DTs for quality control during offsite manufacturing.	Comparative analysis of geometric DT approaches in offsite manufacturing.	3D scanning, laser scanning, BIM, parametric design	fabrication and assembly	Project and component scales in offsite manufacturing.	Proposed quality control mechanisms using geometric DTs in OSM.	High costs and complexity of 3D scanning technologies.	No unified approach for geometric DT in manufacturing.
Teisserenc et al (2021) [56]	To explore the integration of blockchain with digital twins for improving trust, security, and efficiency in Industry 4.0 projects.	Conceptual framework using PESTELS analysis and literature review.	blockchain, IoT, BIM, Industry 4.0	Entire lifecycle: design to operation	Large-scale construction projects.	Proposed Decentralized Digital Twin Cycle (DDTC); addressed scalability, security, and interoperability gaps.	High computational requirements; lack of standardization; regulatory uncertainties.	Insufficient case studies on blockchain-DT integration.
Zhao et al (2021) [93]	To evaluate energy retrofitting schemes for existing buildings using digital twin technology.	Development of a Scan-to-BIM framework; applied to nearly zero-energy buildings (nZEB) retrofitting.	Scan-to-BIM, IoT, Energy Simulation, Photovoltaic Systems	Retrofit and maintenance	Building-level retrofitting projects.	Demonstrated a 14.1% energy cost reduction and 24.13% photovoltaic efficiency increase through DT-enabled retrofitting.	Technical challenges in 3D modeling and data fusion.	Limited exploration of DT retrofitting for large-scale or diverse building types.
Zhou et al (2021) [86]	To explore the use of digital twins in managing prefabricated building construction processes and mitigating risks.	Integrated BIM with digital twins for real-time monitoring and prediction.	BIM, IoT, cloud computing	Construction	Prefabricated building systems.	Demonstrated DT-BIM integration for risk mitigation; real-time monitoring of prefabricated building components.	Complexity in data fusion; high costs in implementing digital twins.	Lack of scalability studies for larger prefabricated projects.
Ammar et al (2022) [89]	Propose a definition of digital twins in construction and explore their applications and challenges.	Semi-structured interviews with nine practitioners and a case study.	IoT, AI, BIM, semantic web	operation and maintenance	Construction projects and building authority integration.	Provided a practical definition of digital twins and identified applications and challenges.	Data preparation challenges, stakeholder alignment, cost issues.	Lack of prototype applications and quantifiable benefits.

Table A1 (Continued). A complete list of all 95 reviewed studies, along with detailed insights and analyses

Author(s) and Year	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Banfi et al (2022) [106]	Develop a 4D multi-user digital twin platform integrating BIM and extended reality (XR) for energy efficiency.	Case study integrating scan-to-BIM processes and cloud-based XR platforms.	BIM, XR, cloud computing, APIs	Design, operation, and retrofit	Building scale with energy and comfort focus.	Showcased a multi-user 4D DT platform integrating BIM and XR.	Interoperability and user adoption challenges.	Scalability of multi-user DT platforms.
Bortolini et al (2022) [4]	Review digital twin applications for building energy efficiency and analyze research trends.	Comprehensive literature review categorized into key topics.	BIM, IoT, cloud computing	Operation and maintenance	Building and operational scale.	Reviewed DT applications in energy efficiency and highlighted future research areas.	Energy data integration and scalability challenges.	Limited comparative analysis of DT tools for energy efficiency.
Eneyew et al (2022) [94]	Propose a BIM-IoT integration framework for semantic interoperability in smart-building digital twins.	Framework development and experimental evaluation for BIM-IoT integration.	BIM, IoT, ontology-based query mediation	Lifecycle-wide integration for smart buildings	Smart building scale with BIM-IoT integration.	Developed a novel semantic interoperability framework for smart buildings.	Lack of real-world validation for BIM-IoT frameworks.	Insufficient research on semantic-level BIM-IoT interoperability.
Gourlis et al (2022) [90]	Develop a holistic DT framework integrating energy modeling for industrial facilities.	Case study comparing semi-automated workflows for building energy modeling in DTs.	BIM, BEM, hybrid simulation, visual programming	design optimization	Industrial facility scale.	Proposed a modular DT framework for integrating energy modeling in industrial facilities.	Data simplification and workflow standardization for energy modeling.	Few practical implementations of holistic industrial DT frameworks.
Hosamo et al (2022a) [100]	Evaluate DT technology's potential for fault detection in building maintenance and operations.	Qualitative assessment of 115 relevant documents on DT for fault detection.	IoT, AI, predictive algorithms, BIM	Operation and maintenance	Building scale with focus on maintenance.	Identified gaps and opportunities to improve DT fault detection.	Hardware/software limitations, financial incentives for stakeholders.	Limited integration of ML with DTs for proactive fault detection.
Hosamo et al (2022b) [120]	Reviewed AEC-FM trends to advance digital twin-driven building management.	Analyzed 77 publications, identifying six research areas: lifecycle management, integration, design, maintenance, semantics, and knowledge.	BIM, IoT, ML, big data	Entire lifecycle: design to maintenance	Building and facility management industry.	Developed a framework for digital twin adoption in AEC-FM, addressing information standardization gaps and identifying six key application areas.	Lack of standardization for data integration; Poor interoperability between BIM, IoT, and FM systems; Data overload and fragmentation.	Highlights gaps in predictive maintenance, occupant-centric twins, and the need for AI-BIM frameworks for adaptive management.
Kosse et al (2022) [114]	Propose a digital twin framework for serial construction using modular precast elements.	Application of Industry 4.0 principles to modular construction with precast elements.	BIM, Industry 4.0, IoT, modular construction	Production and construction	Precast element scale for serial construction.	Advanced modular construction using a digital twin framework.	Limited automation and feedback loops in modular construction.	Few implementations of serial construction DTs.
Lv et al (2022) [62]	Explore BIM and DT integration for smart city construction during the COVID-19 scenario.	Review of BIM and DT integration for big data processing in smart cities.	BIM, cloud computing, big data	construction and operation	City-scale data processing and management.	Demonstrated DT applications in smart city development during COVID-19.	Complexity of big data integration in smart cities.	Lack of scalability studies for smart city DTs.
Megahed et al (2022) [66]	Review the evolution of BIM into DTs and assess their post-pandemic potential in AECO.	Systematic review and bibliometric analysis of 238 publications.	BIM, IoT, AI, cloud computing	All lifecycle phases in AECO	Building and urban scales in AECO.	Proposed a theoretical model for DTs in post-pandemic AECO.	Misconceptions between BIM and DTs.	Limited post-pandemic DT applications in AECO.
Meschini et al (2022) [101]	Develop a cognitive digital twin framework using BIM-GIS for smart campus management.	BIM-GIS integration and AMS app development for university campuses.	BIM, GIS, IoT	Operation and maintenance	Campus-scale asset management.	Showcased BIM-GIS for cognitive campus DTs and emergency management.	Fragmented databases and limited scalability in AMS.	Need for AI-driven applications in cognitive DTs.
Mohseni et al (2022) [87]	Introduce an advanced control method for HVAC systems using DTs and reinforcement learning.	Co-simulation and hardware-in-loop tests with reinforcement learning algorithms.	HVAC systems, PPO, RL, co-simulation	Operation	Building-scale smart systems.	Demonstrated DT-based control for efficient HVAC systems.	Complex system dynamics and high computational demands.	Insufficient adoption of RL in HVAC DT systems.
Naderi et al (2022) [78]	Present a knowledge map of IDT research and identify gaps for future exploration.	Bibliometric analysis of 139 studies with network mapping.	BIM, IoT, network theory, big data	Infrastructure	Infrastructure scale for civil engineering.	Mapped IDT maturity and gaps with a comprehensive knowledge map.	Lack of common understanding and stakeholder collaboration.	Limited research on enabling IDT technologies.
Pregnolato et al (2022) [61]	Develop a workflow for applying DTs to legacy infrastructure and provide a case study.	State-of-the-art review and development of a proof-of-concept framework.	IoT, wireless sensors, SHM, BIM	Management and maintenance	Infrastructure scale (bridges).	Developed a step-by-step DT workflow for existing assets.	Lack of standards and protocols for legacy infrastructure.	Few frameworks for infrastructure DT applications.
Salem et al (2022) [79]	Review DT applications in construction project management and propose a comprehensive framework.	Systematic literature review and structured framework proposal.	AI, CPS, BIM, IoT	construction project	Project-scale construction management.	Provided a structured approach for integrating DTs in construction management.	Resistance to adopting advanced DT technologies.	Limited applications of DTs in project execution stages.
Tan et al (2022) [102]	Developed a digital twin lighting system using computer vision and dynamic BIM for efficient, intelligent lighting control.	14-day experiment using YOLOv4 for pedestrian detection and environment sensing.	BIM, Computer Vision, YOLOv4, IoT	operation and maintenance	Individual buildings.	Introduced DTL system; achieved 79% energy savings; demonstrated improved decision-making accuracy (95.15%).	High initial costs; integration complexities; data privacy concerns.	Limited scalability and real-time adaptability in multi-building scenarios.
Wang et al (2022) [60]	To propose a VR-based digital twin framework for improving construction efficiency and real-time monitoring.	Development of a VR-integrated digital twin framework; performance evaluation via simulations.	BIM, VR, IoT, AI	Construction and operation	Building and infrastructure projects.	Introduced a VR-enhanced DT framework; demonstrated improved scalability and real-time performance.	Technical and financial constraints; scalability issues.	Lack of large-scale implementation studies.

Table A1 (Continued). A complete list of all 95 reviewed studies, along with detailed insights and analyses

Author(s) and Year	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Yang et al (2022) [95]	To analyze the role of digital twins in promoting intelligent green buildings and achieving sustainable urban development.	Comprehensive literature review and conceptual framework.	Green Building, IoT, AI, Sustainable Design	Entire lifecycle: design to operation	Building and urban contexts.	Highlighted integration of DT with green building principles; provided development trends and challenges for intelligent green buildings.	Integration with legacy systems; limited stakeholder engagement.	Need for real-world implementation studies in diverse climates.
Zhao et al (2022) [96]	To propose a fusion of digital twins and machine learning for intelligent building operation and maintenance (O&M).	Developed a digital twin framework and a neural-network-driven O&M prediction mechanism.	ANN, ML, IoT	Operation and maintenance	Building-level applications.	Proposed a digital twin model for predictive O&M; demonstrated the integration of machine learning for risk and life prediction.	High data processing requirements; technical challenges in real-time data synchronization.	Limited studies on full-scale implementation of digital twins in O&M.
Naderi et al (2023) [80]	Analyze infrastructure digital twins (IDTs) with a focus on architectures, interoperability, and future prospects.	Systematic literature review and network analysis of 85 studies on IDTs.	BIM, IoT, network theory, big data	Operation and maintenance	Infrastructure scale.	Mapped the evolution of IDTs and highlighted interoperability solutions.	Complexity and scalability challenges for IDTs.	Insufficient research on IDT architectures and interoperability.
Afzal et al (2023) [67]	Review digital twin developments in construction, identifying key components and advancing DT applications.	PRISMA-based review of DT developments in the AEC sector.	AI, IoT, XR, BIM	Lifecycle management	Building and construction industry scale.	Reviewed DT applications and components critical for AEC practices.	Confusion between BIM and DT, lack of standard frameworks.	Need for advancements in DT maturity and integration technologies.
Desogus et al. (2023) [75]	Develop a scalable, modular framework for monitoring building thermal comfort using digital twins.	Case study and BIM-centered framework development for thermal comfort monitoring.	BIM, IoT, thermal monitoring sensors	Operation	Building scale focused on thermal monitoring.	Proposed a BIM-integrated DT framework for thermal comfort assessment.	Data integration issues and limited user interfaces.	Limited studies on integrating thermal sensors into DTs.
de Wilde et al. (2023) [88]	Critically evaluate how AI and Digital Twins intersect with building performance simulation.	Structured review and thematic analysis of ICT in building simulation and DTs.	AI, ML, IoT, CPS, data mining	Design and operation	Building and data ecosystems scale.	Highlighted synergies between AI, DTs, and building simulations.	Conceptual confusion about overlaps between AI and DTs.	Few practical frameworks bridging AI with DTs.
Drobnyi et al. (2023) [115]	Review methods for constructing and maintaining geometric digital twins for existing buildings.	Systematic review of geometry-based DT methods focusing on as-built conditions.	BIM, scan-to-BIM, deep learning, point clouds	Construction and operation	Building scale with emphasis on geometric accuracy.	Reviewed advancements in geometric DT construction and maintenance.	High costs and manual effort required for geometric DT creation.	Gaps in automated methods for DT geometric updates.
Ghansah et al. (2023) [111]	Identify major opportunities and limitations of digital twins for smart buildings.	Scientometric and content analysis of literature on smart-building digital twins.	IoT, big data, cloud computing, blockchain	Operation	Building scale with a focus on smart buildings.	Identified 24 opportunities and 5 research domains for DTs in smart buildings.	Challenges in data integration, standardization, and security.	Need for standardized methods and tools for smart-building DTs.
Hakimi et al (2023) [103]	Develop a conceptual digital twin framework emphasizing data fusion for efficient civil infrastructure management.	Systematic review of 105 papers on data fusion and DT frameworks in infrastructure management.	OpenBIM, GIS, IFC, multilayer data fusion, AI	Operation and maintenance	Infrastructure scale, focusing on civil infrastructure management.	Proposed a novel DT framework emphasizing multilayer data fusion for lifecycle efficiency.	Data heterogeneity, lack of interoperability standards.	Need for real-world implementations of proposed frameworks.
Jasinski et al (2023) [112]	Develop and validate digital twins of bridges using load tests and FEM models.	Case study of bridge load tests integrated with BIM and FEM simulations.	BIM, FEM, IoT, load testing	Operation	Bridge-scale applications.	Highlighted the critical role of load tests in validating digital twins of bridges.	Data synchronization and model validation issues.	Need for real-world validations of bridge DTs.
Jradi et al (2023) [126]	Provide a scalable digital twin solution for energy retrofitting and decarbonization of Danish buildings.	Energy modeling using ML and AI techniques with IoT sensor integration.	IoT, ML, AI	Operation and retrofit	City-scale and building retrofitting.	Demonstrated energy retrofitting potential using a scalable DT framework.	Limited adoption of advanced IoT and ML models.	Limited focus on non-residential building retrofits.
Lei et al (2023) [63]	Identify and classify challenges in urban digital twins through systematic review and expert survey.	Systematic review combined with a Delphi survey of domain experts.	IoT, AI, edge computing, simulation	Lifecycle management	Urban-scale digital twins.	Mapped technical and non-technical challenges in urban DTs.	Interoperability, business model gaps.	Few holistic frameworks for urban DT challenges.
Lucchi et al (2023) [81]	Analyze digital twin applications in heritage building automation and propose future directions.	Bibliometric and scientometric analysis of DT applications in heritage construction.	BIM, HBIM, VR, AR, IoT	Heritage management	Heritage building scale.	Proposed advanced methods for heritage building automation using DTs.	Lack of tailored standards for heritage automation.	Limited studies on VR/AR applications in heritage DTs.
Marienkov et al (2023) [98]	Develop and validate a digital twin for a 24-story building to model seismic impacts.	Case study with numerical and experimental analysis using FEM and IoT.	IoT, FEM, accelerograms, vibration monitoring	Construction and operation	Building-scale application in seismic zones.	Validated seismic performance using a hybrid DT framework.	Data synchronization and real-time monitoring issues.	Lack of real-world validations in seismic DTs.
Nguyen et al (2023) [107]	Examine the integration of BIM and DT for improved efficiency in building construction.	Systematic literature review focusing on BIM-DT integration.	BIM, IoT, real-time data capture	Design and construction	Building scale for construction efficiency.	Clarified the relationship between BIM and DT in construction.	Fragmented data systems and lack of stakeholder coordination.	Need for practical implementations of BIM-DT integrations.
Oliveira e Sousa et al (2023) [132]	Propose a workflow for using HBIM in developing digital twins for heritage buildings.	Incremental low-code workflow with Grasshopper for Rhino 3D and laser scanning.	HBIM, parametric modeling, laser scanning, Rhino 3D	Heritage management	Heritage building scale.	Proposed a low-code HBIM-DT workflow for historic buildings.	Challenges in accurately modeling complex historic geometries.	Limited studies on parametric HBIM workflows for DTs.

Table A1 (Continued). A complete list of all 95 reviewed studies, along with detailed insights and analyses

Author(s) and Year	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Omrany et al (2023) [82]	Review current DT implementations and enabling technologies in construction.	Systematic review of 145 publications on DT in construction.	BIM, IoT, AI, blockchain, semantic modeling	construction	Building and project scales.	Identified key DT applications and challenges in construction.	Interoperability, scalability, and data privacy issues.	Few frameworks addressing DT scalability and governance.
Osadcha et al (2023) [83]	Provide an overview of DT geometry updating methods for built assets.	Systematic literature review and bibliometric analysis.	UAVs, photogrammetry, laser scanning, data integration	design	Building scale focusing on geometry updates.	Outlined the challenges and methods for DT geometry updates.	High costs and technical complexity of geometry updates.	Need for standardized geometry update processes.
Sepasgozar et al (2023) [116]	Present a roadmap for integrating BIM and DT as converging technologies in construction.	Roadmap creation based on thematic and systematic analysis.	BIM, VR, AR, Industry 4.0, blockchain	construction and facility management	Industry-wide and facility scales.	Highlighted converging technologies for future digital construction.	Expensive technologies and need for advanced workforce training.	Few studies on integrating emerging technologies with DT.
Su et al (2023) [2]	Propose a conceptual framework for DT-enabled construction lifecycle management.	Systematic literature review with conceptual modeling.	IoT, CPS, BIM, predictive analytics	demolition	Building and project lifecycle scales.	Proposed a lifecycle management framework with DT.	Limited adoption and unclear implementation strategies.	Need for holistic frameworks covering entire lifecycles.
Tuhaise et al (2023) [65]	To identify key technologies for digital twin development in construction and highlight future research directions.	Systematic literature review with case studies.	BIM, IoT, big data, AI, ML	Design, construction, and operation	Building and city-scale projects.	Identified 5 development layers for digital twins; emphasized integration and data processing technologies.	Interoperability issues; financial constraints; organizational resistance to change.	Limited focus on real-time data integration and analytics.
Wang et al (2024) [125]	To develop and validate a graphics-based digital twin framework for UAV-aided post-earthquake inspection, ensuring rapid and safe evaluations.	Developed a GBDT framework combining FE and CG models, validated with real data.	UAVs, Finite Element, Computer Graphics (CG), ML	maintenance	High-rise buildings.	Introduced GBDT for rapid inspections; improved damage detection and UAV flight planning under real-world constraints.	Dependency on environmental factors; high computational requirements.	Limited application in diverse seismic regions; scalability issues for larger urban contexts.
Weil et al (2023) [64]	To identify and categorize challenges in the development and implementation of urban digital twins (UDTs) for smart cities.	Systematic literature review using PRISMA approach; analysis of 189 articles.	Urban Digital Twin, AI, IoT, big data, edge computing	City planning and management	Urban environments.	Grouped UDT challenges into eight themes (e.g., interoperability, data quality) and highlighted environmental sustainability in smart cities	Interoperability issues; governance constraints; insufficient standardization.	Lack of real-world case studies; limited frameworks addressing multi-domain integration.
Xie et al (2023) [97]	To develop a digital twin-enabled framework for real-time fault detection and diagnosis in HVAC systems.	Symbolic AI techniques for semantic tagging; real-time data integration using a digital twin data platform.	Semantic Web, AI, IoT, HVAC	Operation and maintenance	Building systems.	Developed a semantic fault tagging system, improving HVAC fault diagnosis and reducing overfitting.	Complexity in semantic integration; high data processing requirements.	Lack of large-scale implementation and validation.
Xu et al (2023) [128]	To propose a digital twin model for structural health monitoring by integrating BIM and 3D scene models.	Fusion of BIM with real-scene 3D modeling; validated using the Nanjing Museum case study.	\BIM, 3D Modeling, Oblique Photogrammetry	monitoring (structural health)	Individual historical buildings.	Demonstrated integration of SHM data with BIM for dynamic health representation.	Complexity in integrating heterogeneous data sources.	Limited application to non-historical or large-scale structures.
Yevu et al (2023) [135]	To explore real-time carbon emissions monitoring in prefabrication supply chains (PSC) and enhance smart construction processes.	Mixed-method review involving scientometric and qualitative analysis.	RFID, GPS, IoT, Laser Scanning	Manufacturing and supply chain management	Prefabrication supply chains and building projects.	Proposed systematic DT-enabled carbon monitoring solutions; identified essential smart technologies for PSC.	Data inconsistency; limited adoption of real-time monitoring technologies.	Lack of frameworks for integrating DT in large-scale PSC applications.
Zhang et al (2023) [12]	To identify enabling technologies for DT applications in the operation and maintenance phase of the AEC industry	Review of 825 publications; analysis of technologies and strategies.	IoT, AI, Cloud Computing, big data	Operation and maintenance	AEC industry O&M applications.	Proposed DT strategies for O&M with key enabling technologies highlighted.	High dependency on data synchronization; interoperability challenges.	Insufficient strategies for large-scale O&M DT implementations.
Zhou et al (2023) [104]	Explore computer vision enabled BIM for real-time updates in building digital twins (BDTs)	Developed a CV enabled BDT scheme integrating 2D object detection and 3D estimation networks	BIM, Computer Vision, IoT	Operation and maintenance	Building automation systems.	Achieved real-time updates with low error rates; advanced integration of CV and BIM	Addressing inconsistencies in dimensions and coordinate systems.	Lack of applications beyond operational phases.
Arsecularatne et al (2024) [72]	Investigate the use of digital twin (DT) technology to improve building energy management and analyze occupant behavior.	Systematic literature review and scientometric analysis of 466 articles from the Scopus database.	real-time monitoring, predictive maintenance, AI	Operation	Building and urban scales.	Identifies challenges and proposes future research directions for DTs in energy efficiency.	Interoperability issues, privacy concerns, data quality challenges, and high implementation costs.	Lack of standard frameworks and insufficient integration of occupant behavior in DT models.
Bäcklund et al (2024) [127]	Develop a human-centric digital twin to improve navigation and operational excellence in educational buildings.	Case study on digital twin applications in university campus buildings in Sweden.	3D scanning, geospatial data, real-time monitoring, AI, fault detection	Operation	Building scale (educational buildings).	Introduced a novel human-centric approach for digital twins in educational facilities.	Interoperability issues, replicability challenges for other building types.	Limited validation of digital twin innovations in real-world contexts.
Almatared et al (2024) [131]	Develop a digital-twin-based framework for improving fire safety management in smart buildings.	Questionnaire-based survey with FM professionals and literature review.	BIM, IoT, AI, AR	Fire safety and evacuation	Building scale (smart buildings).	Proposed a comprehensive DT framework for FSM and highlighted industry readiness.	Integration issues, high costs, data security, and user acceptance.	Gap in adoption of DTs for fire safety and lack of comprehensive frameworks.

Table A1 (Continued). A complete list of all 95 reviewed studies, along with detailed insights and analyses

Author(s) and Year	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Aranda et al (2024) [70]	Develop and evaluate a digital twin for a university campus integrating urban sustainability.	Case study-based development and pilot testing of a digital twin model.	GIS, IoT, BIM, 3D modeling	urban and infrastructure management	Campus-scale case study.	Demonstrated a digital twin's role in sustainability and urban management.	Integration challenges, data standardization issues.	Need for integrating real-time urban and sustainability data.
Arowoiya et al (2024) [73]	Review digital twin technologies for thermal comfort and energy efficiency in buildings.	Scientometric review and systematic analysis of methods and technologies.	AI, IoT, ANN, sensors	Operation	Building scale focusing on energy and thermal comfort.	Summarized state-of-the-art applications and highlighted gaps in energy efficiency.	Limited adoption of sensors, subjective occupant perceptions.	Insufficient focus on human-centric energy optimization.
Bakhshi et al (2024) [117]	Investigate how digital twins can address challenges in the construction supply chain (CSC).	Mixed-method systematic literature review (SLR) and discussions.	IoT, cloud computing, AI, big data	construction supply chain	Supply chain scale.	Explored CSC-specific digital twin challenges and potential solutions.	Fragmentation of processes, lack of real-time information.	Limited exploration of DT applications across CSC phases.
Chacón et al (2024) [91]	Develop pipelines for synchronizing data flow between physical construction sites and digital twins.	Case study of office building construction using real-time data and sensor networks.	IoT, sensor networks, real-time dashboards, knowledge graphs	construction	Building construction scale.	Showcased the implementation of real-time DT in construction processes.	Stakeholder alignment, data heterogeneity, cost issues.	Limited case studies on DT in active construction sites.
Chen et al (2024) [92]	Integrate multifunctional models in digital twins for lifecycle management of assets and systems in smart cities.	Case study-based framework development with hierarchical tiers for DTs.	IoT, BIM, remote sensing, spatiotemporal analysis	Entire lifecycle on urban systems	Campus-scale for integrated management.	Proposed a DODT concept for multifunctional DT integration.	Lack of standards for multifunctional DTs.	Insufficient research on hierarchical DT models.
Cheng et al (2024) [133]	Improve thermal performance in heritage buildings by using digital twins to optimize heater placement.	CFD and HBIM simulations for thermal performance improvement in heritage buildings.	IoT, CFD, HBIM, structural simulation	Operation and heritage buildings	Building scale focused on heritage preservation.	Demonstrated the use of DTs for improving heritage building performance.	Challenges in coupling CFD and HBIM simulations.	Lack of scalable applications for heritage buildings.
Ellul et al (2024) [129]	Develop data-centric digital twins for health and safety and progress monitoring using gaming engines.	Two case studies leveraging Unreal Engine for construction digital twins.	Gaming engines (Unreal Engine), GIS, 4D modeling	Construction and monitoring (health and safety)	Project scale for highway construction.	Demonstrated the feasibility of low-code approaches for construction digital twins.	Interoperability issues and data fragmentation.	Limited exploration of gaming engines in DT applications.
Ghorbani et al (2024) [105]	Define digital twins for the AECO industry and propose a classification system.	Systematic literature review and expert validation of proposed definitions and classifications.	BIM, CPS, ontology-based classifications	Operation and maintenance in AECO	Industry-wide AECO focus.	Provided a common definition and classification structure for AECO digital twins.	Confusion over DT definitions and classifications in AECO.	Lack of consensus on DT classification systems in AECO.
Hakimi et al (2024) [84]	Conduct a bibliometric review to identify trends and gaps in digital twin applications for facility management.	Bibliometric analysis of 248 articles using VOSviewer to identify trends and research gaps.	BIM, AI, CPS, IoT	Facility management	Building and facility management scale.	Identified state-of-the-art trends and gaps in DT applications for smart FM.	Data interoperability, standardization challenges in FM.	Insufficient focus on semantic interoperability in FM DTs.
Hauer et al (2024) [136]	Systematically review BIM and DT integrations for advanced building control strategies, focusing on lighting systems.	Systematic literature review using keyword searches across databases.	BIM, advanced lighting controls, AI, IoT	Design and operation	Building scale with focus on control systems.	Highlighted the integration potential of BIM and DT for lighting system optimization.	Interoperability issues, proprietary system limitations.	Lack of advanced BIM-DT integrations in lighting systems.
Hu et al. (2024) [130]	Develop an intelligent BIM-enabled DT framework for structural health monitoring with IoT and digital signal processing.	Experimental demonstration using a prototyped structural frame for SHM under varying load conditions.	IoT, DSP, structural analysis, BIM	real-time monitoring (structural health)	Structure/component scale for SHM.	Demonstrated a scalable framework for integrating SHM data into BIM with real-time visualization.	Sensor data quality issues, lack of interoperability in SHM frameworks.	Need for frameworks addressing sensor data preprocessing in SHM.
Jeong et al (2024) [138]	Propose a method for constructing building-related digital twin data models using public data.	Data modeling and mapping using CityGML and UML diagrams.	CityGML, UML, public data integration	Data modeling	Building-scale applications.	Proposed an interoperable digital twin data model for buildings.	Lack of interoperability in public data standards.	Insufficient research on public data-based DTs.
Yang et al (2024) [108]	Advocate for site-scale DTs to enhance urban planning and landscape design.	Case studies of urban interventions using site-scale digital twins.	IoT, urban sensing, participatory design	Design and operation	Site-scale for urban elements.	Promoted site-scale DTs for more effective urban interventions.	Complexities in urban-scale data integration.	Lack of scalability studies for site-scale DTs.
Kang et al (2024) [76]	Define connectivity and predictability as core requirements for real-time DT frameworks in building monitoring.	Case study of environmental performance monitoring in buildings using real-time data.	IoT, BIM, real-time monitoring, predictive analytics	Operation for building monitoring	Building-scale environmental monitoring.	Presented a detailed framework for DT connectivity and predictability.	Challenges in ensuring data quality and system integration.	Limited frameworks addressing connectivity in DTs.
Mitera-Kiełbasa et al (2024) [118]	Enhance information management in construction using AI-based automation of Exchange Information Requirements.	Use of Word2Vec and SVM for AI-driven text classification in Exchange Information Requirements.	AI, BIM, Word2Vec, SVM	construction projects	Project-scale EIR management.	Improved EIR management in construction with AI-driven classification.	Insufficient standardization in EIR practices.	Gaps in AI integration for BIM and DT projects.
Lam et al (2024) [71]	Propose methods to integrate IFC, CityGML, and semantic graphs for 3D city model visualization.	Case study using IFC, CityGML, and semantic graph data visualization with Neo4j.	CityGML, IFC, semantic graphs, Neo4j	Urban management and planning	City-scale visualization and analysis.	Enhanced interoperability and visualization in 3D city modeling.	Data synchronization, interoperability issues.	Lack of real-world validation for proposed models.

Table A1 (Continued). A complete list of all 95 reviewed studies, along with detailed insights and analyses

Author(s) and Year	Research Objective	Methodology	Technologies Mentioned	Lifecycle Phase	Scale	Key Contributions to Literature	Barriers/Challenges Identified	Gaps Identified
Lauria et al (2024) [68]	Critically review future challenges of applying digital twins in building lifecycle management.	Systematic literature review from Scopus and other databases focusing on lifecycle phases.	BIM, IoT, AI, lifecycle analytics	Operation and maintenance	Building-scale lifecycle analysis.	Identified key challenges and future research directions in building DTs.	Limited integration across building lifecycle phases.	Insufficient research on decarbonization impacts of DTs.
Li et al (2024) [74]	Create an intelligent monitoring platform for building energy consumption using digital twin technology.	Case study with simulation using Designbuilder software for energy monitoring.	BIM, IoT, predictive control, smart sensors	Operation and maintenance	Building-scale energy monitoring.	Developed a DT platform to optimize building energy use.	Low adoption of intelligent control systems.	Need for frameworks integrating occupant behavior data.
Li et al (2024) [119]	Define a conceptual framework for intelligent tunnel construction using digital twins.	Critical review and conceptual modeling of DTs in tunnel construction.	BIM, IoT, ML, point cloud	construction	Infrastructure and tunnel-scale construction.	Outlined a DT framework for addressing tunnel construction challenges.	Uncertainty in geological data and slow decision-making.	Scarcity of DT applications in real-time tunnel operations.
Mohandes et al (2024) [109]	Identify and prioritize barriers to DT adoption in sustainable construction.	Iterative method with literature review and stakeholder survey in Hong Kong.	IoT, BIM, AI, simulation	Sustainability-focused lifecycle stages	Building and project-scale sustainability efforts.	Identified actionable barriers and solutions for DT adoption.	Low data reliability and stakeholder coordination issues.	Few frameworks integrating sustainability with DTs.
Naeem et al (2024) [137]	Analyze Industry 4.0 technologies' applications in renewable energy with a focus on DT.	Systematic literature review combined with industrial insights.	AI, IoT, blockchain, cybersecurity	Energy lifecycle in renewable systems	Energy systems scale with a renewable focus.	Explored digital technologies' impact on renewable energy sectors.	High costs and cybersecurity risks.	Lack of comprehensive studies on Industry 4.0 in RES.
Opoku et al (2024) [77]	Develop a BIM-IoT integrated DT for monitoring indoor conditions in living labs.	Development of a BIM-IoT DT for Indoor Environment Monitoring	IoT, BIM, live data platforms, semiotic representation	real-time monitoring	Building scale for indoor condition optimization.	Demonstrated a practical DT for library indoor condition monitoring.	Challenges in integrating live data into DTs.	Insufficient real-world DT applications in living labs.
Osama et al (2024) [124]	Develop a framework for user-centered DT applications in the built environment.	Applied research on city-scale user-centered DT development.	user-centric design, city-scale DT	Built environment lifecycle with user focus	City-scale applications for urban environments.	Developed a user-centric DT framework for built environments.	Insufficient frameworks for user-centric DTs.	Limited research on human-centric DT applications.
Oulefki et al (2024) [113]	Survey AI strategies for enhancing smart building operations using DTs.	Review of AI in DT applications for smart buildings.	AI, ML, deep learning, IoT, federated learning, reinforcement learning	Operation	Smart building scale with AI integration.	Reviewed advanced AI strategies for smart building DTs.	Data processing challenges and scalability in AI-powered DTs.	Few studies on integrating advanced AI with DTs.
Piras et al. (2024) [3]	Present a comprehensive framework for integrating digital twin technologies in the AECO sector.	Thematic review based on extensive literature analysis.	BIM, GIS, IoT, AI, remote sensing	All lifecycle phases in AECO	Building and urban scales.	Outlined enablers for DT implementation in AECO with a comprehensive framework.	Data standardization and stakeholder coordination issues.	Limited real-world implementations in AECO.
Radzi et al. (2024) [85]	Explore the relationship between BIM and DT in construction projects and synthesize existing research.	Systematic literature review of 54 studies.	BIM, CPS, IoT, geo-referencing	Entire construction lifecycle: design to decommissioning	Building and project scales.	Clarified the relationship between BIM and DT, addressing misconceptions.	Misunderstandings of BIM-DT integration among practitioners.	Lack of knowledge sharing on BIM-DT relationships.
Revolti et al. (2024) [70]	Investigate the transition from BIM to DT technologies in building construction and facility management.	Systematic review and development of a conceptual framework.	BIM, IoT, cloud computing, data analytics	Design, construction, and operations phases.	Building scale in facility management.	Identified gaps and opportunities for BIM-DT integration.	Limited protocols for dynamic BIM-DT transitions.	Insufficient focus on dynamic capabilities of DTs.
Wang et al. (2024) [99]	To analyze the integration of Building-Integrated Photovoltaics (BIPV) with digital twin technologies across building lifecycles.	Literature review and lifecycle analysis of BIPV-DT applications.	BIM, IoT, BIPV, ML	Entire lifecycle: design to demolition	Building-level BIPV systems.	Showcased DT's role in enhancing BIPV efficiency and lifecycle integration strategies.	Integration complexities; lack of standardization; high costs.	Scarcity of lifecycle-oriented BIPV-DT studies.
Walczyk et al. (2024) [110]	To evaluate the role of BIM and DT in enhancing smart building design and energy efficiency.	Review of existing frameworks and case studies.	BIM, IoT, Smart Readiness Indicator (SRI)	Design and operation	Smart buildings.	Provided guidelines for integrating DT and IoT in smart buildings; highlighted SRI applications.	Complexity in IoT integration; lack of expertise in advanced DT applications.	Need for advanced methods for evaluating smart readiness.
Yang et al. (2024) [121]	Analyzed digital twins in construction, focusing on lifecycle applications and challenges like data quality and integration.	Systematic review using PRISMA approach; analyzed architectures and enabling technologies of digital twins in construction.	BIM, IoT, AI, Cyber-Physical Systems, VR, AR	Entire lifecycle: design to demolition	Construction industry and project level.	Analyzed DT lifecycle integration, highlighting emerging trends and challenges.	Data quality issues; integration difficulties; lack of standardization.	Insufficient studies on DT's role in demolition and restoration phases.
Yeom et al. (2024) [122]	Explored DT and XR integration for improved energy management and sustainability.	Comprehensive review with proposed DT-XR integrated solutions for energy management and occupant comfort.	XR, IoT, Metaverse, AI	Design, operation, and maintenance	Building energy management systems.	Highlighted DT-XR integration's potential for energy optimization, bridging gaps in comfort and system fidelity.	Lack of fidelity and interoperability; high data security concerns.	Need for practical applications demonstrating real-world DT-XR integration.
Zahedi et al. (2024) [123]	To review the role of digital twins in promoting sustainability throughout the construction lifecycle.	Systematic review of 235 papers; thematic analysis of DT integration in sustainability.	AI, IoT, AR, BIM	Entire lifecycle: design to demolition	Sustainable construction projects and urban environments.	Identified sustainability-driven DT advancements; emphasized AI-IoT integration for sustainability.	Lack of IT infrastructure; data privacy and security issues.	Need for standardized frameworks for DT implementation in sustainability contexts.