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DIGITAL TWIN IN DESIGN ARCHITECTURE: IMPACT OF DT IN ARCHITECTURAL DESIGN FOR IMPROVED BUILDING LIFECYCLE MANAGEMENT

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SUMMARY: *Digital twins (DTs) are increasingly transforming the Architecture, Engineering, and Construction (AEC) industry by enhancing data integration, visualization, collaboration, and decision-making throughout the building lifecycle. Despite these advances, limited research has examined the role of DTs in supporting architectural design for improved Building Lifecycle Management (BLM), particularly during the early design stages. This study investigates the potential of DT technology to enhance BLM by integrating digital twin concepts into the architectural design process. A mixed-methods approach was employed, combining a comprehensive literature review with a questionnaire survey of 60 architecture, engineering, and construction professionals from Saudi Arabia, Nigeria, and the United States to evaluate current awareness, perceived benefits, implementation challenges, and opportunities associated with DT adoption. The findings indicate that while awareness of DT technology is increasing, its application to architectural design for comprehensive BLM remains limited. The study identifies key opportunities for improving decision-making, sustainability, lifecycle performance, and stakeholder collaboration, while highlighting workforce skills, interoperability, and implementation complexity as major barriers to adoption. By integrating literature-based evidence with industry perspectives, the research clarifies how design-stage decisions, digital information, and lifecycle requirements can be connected more effectively through DT-enabled processes. The findings further emphasize the importance of early planning for data integration, sensing requirements, performance evaluation, and interdisciplinary coordination. The study contributes to the growing body of knowledge on digital twin applications in architectural design by providing an evidence-based assessment of current adoption, opportunities, and challenges, offering practical insights for researchers, practitioners, and policymakers seeking to advance Building Lifecycle Management through digital transformation.*

KEYWORDS: *digital twin, building lifecycle management, architectural design, building information modeling (BIM), architecture, engineering, and construction (AEC).*

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1. INTRODUCTION

Buildings are complex, long-term assets whose performance, sustainability, and operational efficiency are largely determined by decisions made throughout their lifecycle, beginning with the architectural design stage and extending through construction, operation, maintenance, renovation, and eventual decommissioning. Managing these interconnected phases effectively is the objective of Building Lifecycle Management (BLM), which seeks to optimize building performance, sustainability, operational efficiency, and lifecycle costs throughout a building's service life. As buildings become increasingly complex and data-intensive, the Architecture, Engineering, and Construction (AEC) industry is progressively adopting digital technologies to improve decision-making and facilitate the efficient management of information across the entire building lifecycle.

Among these technologies, Digital Twins (DTs) have emerged as one of the most promising innovations in the AEC industry. A Digital Twin is a dynamic virtual representation of a physical asset that continuously integrates real-time data to monitor performance, simulate future scenarios, and support informed decision-making, performance optimization, and lifecycle management throughout the asset's service life (Parris et al., 2016). Recent advances in the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), cloud computing, and big data analytics have significantly enhanced the capabilities of Digital Twins by enabling continuous data acquisition, predictive analytics, intelligent automation, and real-time synchronization between physical and virtual assets (Liu et al., 2018; Madubuike et al., 2022).

Digital Twin technology has demonstrated considerable value across numerous industries, including aerospace, manufacturing, automotive, healthcare, energy, telecommunications, and the built environment. Within the AEC industry, Digital Twins have primarily been applied to construction management, infrastructure monitoring, and facilities management, where they have been used to improve operational efficiency, predictive maintenance, asset monitoring, and overall building performance (Madubuike & Anumba, 2023; Rana et al., 2022; Khalid et al., 2024). Collectively, these applications demonstrate the ability of Digital Twins to integrate real-time information, enhance decision-making, and improve building performance throughout the building lifecycle.

Despite the growing adoption of Digital Twins across the AEC industry, existing research has predominantly focused on the later stages of the building lifecycle, particularly construction, operation, and facilities management. Comparatively less attention has been given to the application of Digital Twins during the architectural design stage, despite the fact that many decisions affecting a building's operational efficiency, sustainability, maintainability, adaptability, resilience, and lifecycle costs are established during this phase. Since architectural design decisions have long-term implications for building performance, integrating Digital Twin technologies into the design process represents an important opportunity to support proactive decision-making and improve Building Lifecycle Management across the entire building lifecycle.

1.1 Importance of building lifecycle management (BLM) in the construction industry

Building Lifecycle Management (BLM) is a comprehensive approach to managing a building throughout its entire lifespan, from planning and architectural design to construction, operation, maintenance, renovation, and eventual decommissioning. Unlike traditional lifecycle management approaches that often focus on individual project phases, BLM promotes the continuous integration of people, processes, information, and digital technologies to optimize building performance, sustainability, operational efficiency, and lifecycle costs throughout a building's service life (Kiviniemi & Anttila, 2011). As buildings become increasingly complex, effective lifecycle management has become essential for improving long-term asset value while addressing growing environmental, economic, and social challenges within the built environment.

The principles of BLM are closely aligned with the ISO 15686 series on service life planning, which emphasizes a whole-life approach to building design, construction, operation, maintenance, and replacement. ISO 15686 encourages stakeholders to consider long-term building performance, durability, maintainability, adaptability, and lifecycle costs during the early stages of project development rather than focusing solely on initial construction costs. This lifecycle perspective supports informed decision-making throughout the building's service life and promotes sustainable asset management by balancing economic, environmental, and functional performance over time.

Architectural design plays a fundamental role in achieving effective Building Lifecycle Management because many of the decisions that determine a building's future performance are established during the design phase.

Design choices related to building form, material selection, structural systems, energy efficiency, spatial organization, and building services significantly influence operational performance, maintenance requirements, occupant comfort, adaptability, resilience, and environmental impacts throughout the building lifecycle (Ma et al., 2020). Consequently, improving the quality of decisions made during architectural design has the potential to generate substantial long-term benefits across all subsequent lifecycle stages.

Furthermore, BLM supports sustainability by encouraging lifecycle thinking in the selection of construction materials, resource utilization, energy consumption, and maintenance strategies. This holistic approach enables stakeholders to minimize environmental impacts, improve operational efficiency, reduce lifecycle costs, and extend the useful life of building assets (Nguyen et al., 2018; Shen et al., 2019). In addition, BLM facilitates collaboration among architects, engineers, contractors, facility managers, owners, and other stakeholders by promoting integrated information management throughout the building lifecycle. Such collaboration improves coordination between design intent and operational requirements while supporting proactive maintenance planning, risk management, and informed asset management decisions.

Although Building Lifecycle Management provides a robust framework for optimizing building performance, implementing BLM effectively remains challenging due to fragmented information, limited interoperability between lifecycle phases, and the lack of continuous data integration across the building lifecycle. These challenges have increased interest in digital technologies that can connect physical and virtual building information in real time. Among these technologies, Digital Twins offer significant potential to improve Building Lifecycle Management by providing a continuously updated digital representation of building assets, supporting lifecycle monitoring, predictive analytics, and data-driven decision-making across multiple lifecycle stages.

1.2 Research gap and study motivation

The increasing adoption of Digital Twin (DT) technology across the Architecture, Engineering, and Construction (AEC) industry has highlighted its potential to transform the management of building information throughout the asset lifecycle. Existing studies have demonstrated the successful application of DT technologies in construction management, infrastructure monitoring, facility management, predictive maintenance, and operational optimization (Madubuike & Anumba, 2023; Rana et al., 2022; Khalid et al., 2024). These studies consistently show that Digital Twins improve information integration, operational efficiency, and data-driven decision-making during the later stages of the building lifecycle.

Despite these advances, comparatively limited research has investigated how Digital Twin technologies can be integrated into the architectural design stage, where many of the decisions affecting energy performance, sustainability, maintainability, adaptability, occupant comfort, and lifecycle costs are established. Consequently, the potential of DT to support architects in making lifecycle-oriented decisions during the earliest phases of project development remains insufficiently explored.

Furthermore, although previous studies have proposed technical frameworks for Digital Twin implementation, the literature remains dominated by technological and operational perspectives. Comparatively fewer studies have examined DT as an integrated decision-support framework capable of linking architectural design with subsequent lifecycle stages while addressing practical implementation challenges such as interoperability, organizational readiness, workforce capability, and industry adoption. As a result, a gap remains between the technological capabilities of Digital Twins and their practical application within architectural practice.

Another important limitation in the current literature is the lack of empirical evidence regarding industry perceptions of DT adoption. While previous research has primarily focused on technical development and operational applications, relatively few studies have investigated how architects and other AEC professionals perceive the benefits, challenges, and future opportunities associated with integrating Digital Twins into architectural design. This gap is particularly evident within the context of Saudi Arabia, where digital transformation and sustainable development initiatives under Vision 2030 are creating new opportunities for adopting advanced digital technologies across the built environment.

To address these gaps, this study investigates the role of Digital Twin technology in architectural design for improving Building Lifecycle Management by integrating a comprehensive literature review with a questionnaire survey of Architecture, Engineering, and Construction professionals. By examining current awareness, perceived benefits, implementation challenges, and future opportunities, the study provides empirical evidence that extends

existing knowledge beyond operational applications and contributes practical recommendations for integrating Digital Twin technologies into architectural design to support lifecycle-oriented decision-making and sustainable building performance.

1.3 Research Aim

This study aims to investigate the role of Digital Twin technology in architectural design for improving Building Lifecycle Management by integrating evidence from the existing literature with empirical insights from Architecture, Engineering, and Construction (AEC) professionals. Specifically, the study examines current applications, perceived benefits, implementation challenges, and future opportunities for adopting Digital Twin technologies throughout the building lifecycle.

1.4 Research Questions

1.4.1 RQ1

What is the current state of knowledge regarding the application of Digital Twin technology in architectural design for improving Building Lifecycle Management?

1.4.2 RQ2

How can Digital Twin technology be integrated into architectural design to improve Building Lifecycle Management and overall building performance throughout the building lifecycle?

2. METHODOLOGY

2.1 Overview

To address the research aim and research questions, this study adopted a mixed-methods research design integrating a comprehensive literature review with a quantitative questionnaire survey. A mixed-methods approach was selected because it combines complementary forms of evidence, enabling a more comprehensive understanding of the research problem than either method could provide independently (Fellows & Liu, 2003). The literature review established the current state of knowledge regarding Digital Twin applications in architectural design and Building Lifecycle Management (BLM), while the questionnaire survey captured the perspectives and professional experiences of participants from the Architecture, Engineering, and Construction (AEC) industry. The two components were integrated during the interpretation of the findings, enabling themes identified in the literature to be compared with current industry perspectives. This integration strengthened the credibility, practical relevance, and contextual understanding of the study.

The literature review examined published research relating to Digital Twin technology, Building Information Modeling (BIM), Building Lifecycle Management, architectural design, smart buildings, facility management, and digital transformation within the built environment. Relevant peer-reviewed journal articles, conference proceedings, industry reports, and international standards were reviewed to identify recurring themes related to Digital Twin applications, enabling technologies, lifecycle benefits, implementation challenges, and future research directions. The findings from the literature review also informed the development of the questionnaire by identifying the key concepts and issues requiring empirical investigation.

A total of 60 completed questionnaire responses were collected from professionals representing key disciplines within the Architecture, Engineering, and Construction (AEC) industry, including architects, engineers, facility managers, project managers, building owners and developers, and researchers/academicians. Participants were selected using a purposive sampling strategy to capture professionally informed perspectives relevant to Digital Twin technologies and Building Lifecycle Management (Liu et al., 2019). This non-probability sampling approach was appropriate because the study sought informed professional perspectives rather than statistical representation of the broader AEC population. Importantly, prior practical implementation of Digital Twin technology was not used as an inclusion criterion; the survey intentionally captured both DT-familiar and less-familiar professionals because awareness and readiness for adoption were themselves variables of interest. The respondents represented diverse professional backgrounds from Saudi Arabia, Nigeria, and the United States, providing a broad range of

perspectives on Digital Twin applications, implementation challenges, and future opportunities across different AEC contexts.

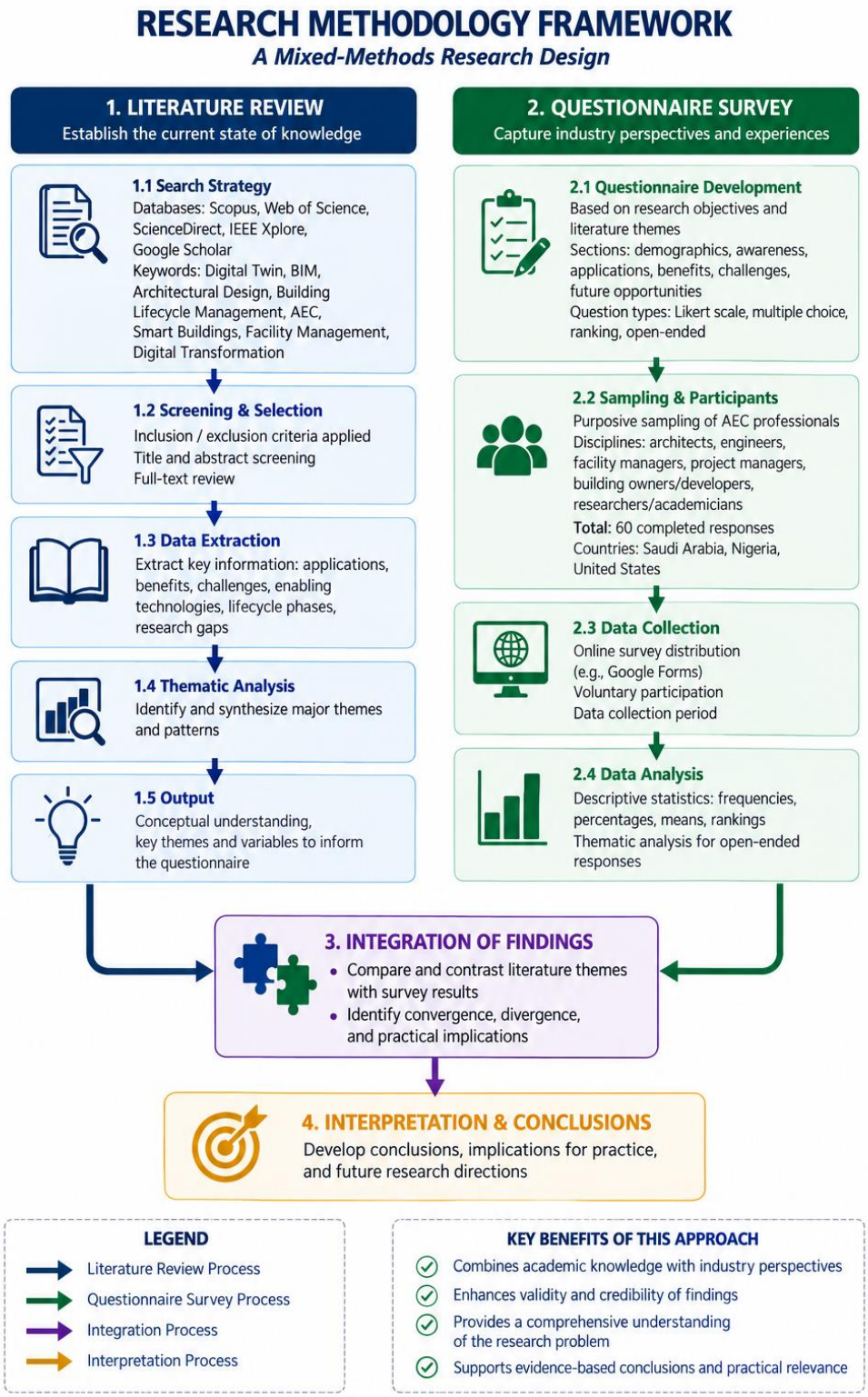

Figure 1: Research methodology framework illustrating the mixed-methods research design adopted in this study and the integration of the literature review and questionnaire survey to investigate Digital Twin applications in architectural design and Building Lifecycle Management.

Figure 1 presents the overall research methodology adopted in this study. The framework illustrates the integration of the literature review and questionnaire survey within the mixed-methods research design. Knowledge synthesized from the literature informed the development of the questionnaire, while the survey findings provided empirical evidence from AEC professionals. Integrating both sources of evidence enabled the findings to be interpreted collectively, providing a comprehensive understanding of Digital Twin applications in architectural design and Building Lifecycle Management.

Figure 1 by Author (Hasanain, 2026).

2.2 Ethics statement

This study received ethical approval from the Institutional Review Board (IRB) of Prince Sultan University, Riyadh, Saudi Arabia (Reference No. PSU IRB-2026-02-0287) under the Expedited Review process. Participation in the questionnaire survey was voluntary, and all participants were informed of the purpose of the study before completing the questionnaire. Completion of the questionnaire was considered to constitute informed consent. No personally identifiable information was collected, and all responses were anonymized and analyzed in aggregate to ensure participant confidentiality and privacy. The study was conducted in accordance with Prince Sultan University's research ethics guidelines and applicable regulations.

3. LITERATURE REVIEW

3.1 Architectural design as the foundation of building lifecycle management

Architectural design is the foundation of Building Lifecycle Management (BLM), as many of the decisions influencing a building's long-term performance are established during the earliest stages of project development. Beyond defining a building's aesthetic qualities, architectural design determines functional performance, spatial organization, structural integration, material selection, environmental responsiveness, and operational efficiency throughout the building's lifespan. Consequently, decisions made during the design phase have lasting implications for energy consumption, maintenance requirements, occupant comfort, adaptability, resilience, sustainability, and overall lifecycle costs (Attia et al., 2013; Hegger et al., 2008).

Building Lifecycle Management adopts a whole-life perspective by considering the planning, design, construction, operation, maintenance, renovation, and eventual decommissioning of buildings as interconnected phases rather than isolated activities. This lifecycle-oriented approach enables stakeholders to optimize building performance while balancing economic, environmental, and social objectives over the asset's service life (Volk et al., 2014). Because design decisions influence all subsequent lifecycle stages, architectural design is increasingly recognized as one of the most influential factors affecting long-term building value and sustainability.

Numerous studies have demonstrated that integrating lifecycle thinking into architectural design improves both environmental and economic performance. Passive design strategies, including optimized building orientation, natural ventilation, daylighting, and thermal mass utilization, significantly reduce operational energy demand while improving occupant comfort (Attia et al., 2013; Cabeza et al., 2014). Likewise, selecting durable, low-impact construction materials reduces maintenance requirements, extends service life, and minimizes lifecycle environmental impacts (Forés, 2010; Cabeza et al., 2014). Design approaches that prioritize flexibility, modularity, and design for disassembly further improve adaptability by enabling buildings to accommodate changing functional requirements while supporting material reuse and circular economy principles (Durmisevic & Brouwer, 2006; Geraedts et al., 2014).

Despite these advances, effective Building Lifecycle Management remains constrained by fragmented information, limited interoperability between lifecycle phases, and insufficient integration of design knowledge with operational data. Traditional design processes often rely on static information that becomes disconnected from the building once construction is completed, limiting opportunities for continuous performance evaluation and informed decision-making throughout the asset lifecycle. Several studies have identified static information models, information loss at handover due to outdated designs, and fragmented lifecycle data as major limitations in traditional design and delivery processes (Opoku et al., 2021; Su et al., 2023; Zhang et al., 2023). Lu et al (2023) and Dong and Moshood (2026) further added that the traditional design process encourages fragmented data as a result of inconsistent information representation arising from manual data handling. Traditional design processes

often produce fragmented and static information at project handover, limiting accurate representation of the completed asset and subsequent lifecycle management. The integration of digital technologies, such as BIM and Digital Twins, within design and Building Lifecycle Management (BLM) enables lifecycle data requirements to be incorporated from the outset, facilitating continuous information continuity and improved decision-making throughout the building lifecycle.

Although BIM has transformed design development by improving visualization, coordination, and information management, it remains primarily a static representation of design intent with limited capability to incorporate operational feedback. Consequently, BIM provides only partial support for lifecycle-oriented decision-making, as design assumptions cannot be continuously validated against actual building performance (Eastman et al., 2018 & Boje et al., 2020). In contrast, Digital Twins extend BIM by integrating real-time and historical operational data, enabling continuous design validation, performance optimization, and informed decision-making throughout the building lifecycle (Boje et al., 2020; Opoku et al., 2021; Su et al., 2023).

These challenges have accelerated interest in digital technologies that maintain dynamic connections between physical assets and their digital representations. Among these emerging technologies, Digital Twin (DT) technology has attracted considerable attention because it provides continuously updated digital representations of physical assets, enabling real-time monitoring, predictive analysis, and lifecycle-oriented decision-making. As a result, Digital Twins are increasingly recognized as a promising technology for strengthening the relationship between architectural design and Building Lifecycle Management across the entire building lifecycle. Specifically, the adoption of Digital Twins has been proposed as a solution to the fragmented data inherent in traditional design processes by enabling continuous information exchange, including the seamless integration of design updates at project handover, thereby supporting effective building lifecycle management (Opoku et al., 2021; Su et al., 2023; Zhang et al., 2023).

Digital Twins have been proposed as an approach to enhance not only building design processes but also facility lifecycle management. Zhao et al. (2022) opined that Digital Twins improve collaboration and information communication from the design phase through operation and maintenance. Su et al. (2023) support this opinion by proposing a Digital Twin-enabled framework that supports the entire construction lifecycle, beginning at the design stage. The effectiveness of Digital Twins in facilitating building lifecycle management depends largely on integrating, maintaining, and continuously updating design information throughout the design and construction phases.

3.2 Digital twin technology in the AEC industry

Digital Twin (DT) technology has emerged as one of the most transformative digital innovations in the Architecture, Engineering, and Construction (AEC) industry by enabling the continuous integration of physical assets with their virtual counterparts. Unlike conventional digital models, Digital Twins continuously synchronize real-time data with dynamic virtual representations, allowing stakeholders to monitor asset performance, simulate future scenarios, predict failures, and support informed decision-making throughout the building lifecycle (Liu et al., 2018; Madni et al., 2019). This capability has transformed Digital Twins from simple visualization tools into comprehensive lifecycle management platforms that facilitate data-driven decision-making across multiple phases of a project.

The rapid advancement of enabling technologies has significantly accelerated the adoption of Digital Twins within the built environment. Building Information Modeling (BIM) provides the digital foundation for representing building geometry and asset information, while the Internet of Things (IoT), sensors, cloud computing, Artificial Intelligence (AI), Machine Learning (ML), and advanced data analytics enable continuous data acquisition, real-time monitoring, predictive analytics, and intelligent automation (Haag & Anderl, 2018; Madubuike et al., 2022). The integration of these technologies enables Digital Twins to maintain an up-to-date representation of physical assets, thereby supporting more responsive, efficient, and evidence-based management throughout the building lifecycle.

Building on established Digital Twin architectures and the framework proposed by Madubuike (2022), this study adapts the conventional lifecycle-oriented Digital Twin structure to explicitly position architectural design as the starting point for Digital Twin-enabled Building Lifecycle Management. The adaptation recognizes that effective Digital Twin implementation during operation depends partly on decisions made before construction, including

decisions concerning building geometry, materials, environmental strategies, building systems, sensing requirements, data acquisition, and communication infrastructure. Accordingly, the framework integrates these requirements within the architectural design phase rather than treating sensing and connectivity solely as post-construction additions.

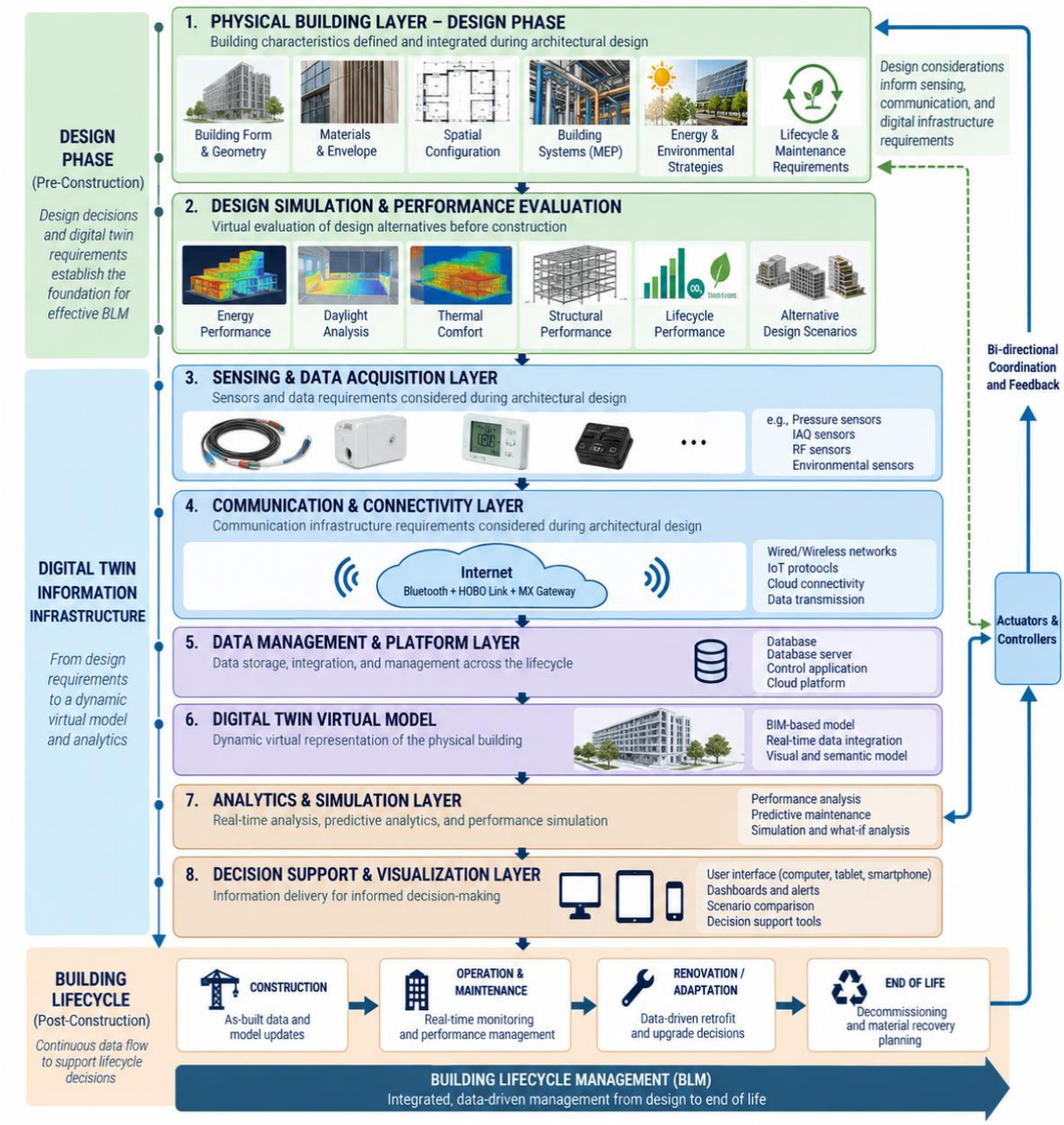

Figure 2: Integrated Digital Twin framework for architectural design and Building Lifecycle Management (BLM), positioning design-stage building characteristics, performance simulation, sensing and communication requirements as the foundation for continuous lifecycle information exchange and feedback (adapted from Madubuike, 2022).

The framework further introduces design-stage simulation and performance evaluation as a link between architectural decision-making and subsequent lifecycle performance. Proposed design alternatives can therefore be evaluated virtually in terms of energy performance, daylight, thermal comfort, structural behavior, environmental performance, constructability, and other lifecycle-related criteria before physical construction. Following construction, operational data acquired from the physical building continuously informs the Digital

Twin through sensing, communication, data-management, analytics, and decision-support layers. This bidirectional information flow enables actual building performance to be compared with design expectations and supports subsequent operation, maintenance, adaptation, renovation, and end-of-life decisions. Figure 2 therefore illustrates how Digital Twin principles can connect architectural design decisions with continuous Building Lifecycle Management rather than limiting Digital Twin implementation primarily to facility operation.

Figure 2 adapted from (Madubuike, 2026).

3.3 Digital twin applications across the building lifecycle

Digital Twin technology has increasingly been recognized as a lifecycle-oriented digital solution capable of supporting decision-making throughout all phases of a building's lifecycle. Unlike conventional digital models, otherwise known as BIM or CAD models, that are typically developed for specific project stages, Digital Twins establish a continuous digital representation of building assets that evolves alongside the physical facility. This continuous flow of information enables stakeholders to monitor performance, evaluate alternative scenarios, and make informed decisions from architectural design through construction, operation, maintenance, renovation, and eventual decommissioning. Consequently, Digital Twins are increasingly viewed as an enabling technology for Building Lifecycle Management by facilitating information continuity across traditionally fragmented lifecycle phases.

3.3.1 Architectural design phase

The architectural design phase offers the greatest opportunity for influencing a building's long-term lifecycle performance because many critical decisions related to energy efficiency, sustainability, constructability, maintainability, and operational performance are established before construction begins. Consequently, recent studies have increasingly advocated integrating Digital Twin technology during the earliest design stages to support lifecycle-oriented decision-making rather than limiting its application to operational management (RICS, 2022; Horvath & Pouliou, 2024). Building on this perspective, the identified literature suggests that Digital Twins significantly improve architectural design by facilitating the simulation and evaluation of alternative design solutions before construction begins. Through integration with BIM and other digital design tools, architects can evaluate energy performance, daylight availability, thermal comfort, structural behavior, buildability, construction sequencing, safety considerations, and environmental performance within a virtual environment (Grieves & Vickers, 2016; Madubuike et al., 2022). These capabilities allow potential design deficiencies to be identified and addressed early, thereby reducing costly design changes, minimizing construction risks, and improving overall building performance.

An additional advantage of implementing Digital Twins during the design phase is the creation of high-quality digital assets that remain valuable throughout subsequent lifecycle stages. Digital building models, associated design information, and project metadata developed during architectural design establish the information foundation upon which construction monitoring, facility management, predictive maintenance, and future building modifications depend. Consequently, early Digital Twin implementation strengthens information continuity throughout the building lifecycle and enhances long-term Building Lifecycle Management.

3.3.2 Construction phase

During construction, Digital Twin technology supports improved project monitoring, coordination, and quality management by continuously comparing planned construction activities with actual site conditions. Unlike traditional progress reporting methods, Digital Twins integrate information from BIM models, sensors, cameras, drones, LiDAR, and other digital data sources to provide near real-time visualization of construction progress (Braun et al., 2018; Madubuike et al., 2024).

Studies demonstrate that these capabilities improve project scheduling, productivity monitoring, quality assurance, and risk management by enabling deviations between planned and actual construction activities to be identified promptly. Furthermore, Digital Twins facilitate collaboration among contractors, consultants, and project owners by maintaining an up-to-date digital representation of project status that supports transparent communication and more informed decision-making. Importantly, the construction phase also establishes much of the sensing infrastructure—including IoT devices and monitoring systems—that enables Digital Twin functionality during building operation and maintenance (RICS, 2022).

3.3.3 Operation and maintenance phase

The operation and maintenance phase represents the most mature application area for Digital Twin technology within the AEC industry. Numerous studies have demonstrated that Digital Twins improve facility management by integrating real-time operational data with digital building models to support continuous monitoring, predictive maintenance, fault detection, and performance optimization (Madubuike & Anumba, 2022; Asare et al., 2024).

By continuously synchronizing information between physical and digital assets, Digital Twins enable facility managers to monitor building systems such as heating, ventilation, air conditioning (HVAC), lighting, indoor environmental quality, energy consumption, and equipment performance. Predictive analytics further allow maintenance activities to be scheduled proactively before equipment failures occur, thereby reducing downtime, extending asset life, lowering maintenance costs, and improving occupant comfort.

Several real-world implementations further demonstrate the practical value of Digital Twins during building operations. Examples such as Singapore's Fraser Tower and Digital Twin-based healthcare facility management systems illustrate how integrating sensor networks, BIM, cloud computing, and data analytics enhances operational efficiency, environmental performance, and lifecycle asset management. Collectively, these studies demonstrate that Digital Twins have become an effective platform for optimizing long-term building performance and supporting evidence-based facility management decisions.

3.3.4 Renovation, adaptation and end-of-life phase

Although comparatively less explored, Digital Twin technology also offers considerable potential during renovation, adaptive reuse, and building decommissioning. Accurate digital records of building geometry, materials, structural systems, and maintenance history provide valuable information for planning refurbishment projects, evaluating structural modifications, and assessing future building performance before physical interventions are undertaken.

During the decommissioning phase, Digital Twins can support circular economy principles by facilitating material inventories, identifying reusable building components, planning demolition activities, and improving material recovery processes. Access to accurate and reliable lifecycle information enables stakeholders to make informed decisions regarding material recycling, component reuse, waste minimization, and environmental impact reduction. Despite the growing recognition of these opportunities, research on the application of Digital Twins during end-of-life building management remains relatively limited, highlighting an important avenue for future research in Building Lifecycle Management (BLM).

3.4 Benefits of digital twin technology for architectural design and building lifecycle management

The growing adoption of Digital Twin (DT) technology within the Architecture, Engineering, and Construction (AEC) industry is driven by its potential to improve decision-making, collaboration, sustainability, and overall building performance throughout the building lifecycle. Unlike conventional digital models, Digital Twins continuously integrate real-time operational data with virtual building representations, enabling stakeholders to evaluate building performance proactively rather than reactively. The literature consistently identifies several key benefits that position Digital Twins as an important enabler of Building Lifecycle Management.

3.4.1 Improved decision-making and design optimization

One of the most significant advantages of Digital Twin technology is its ability to support evidence-based decision-making throughout architectural design and subsequent lifecycle phases. By integrating Building Information Modeling (BIM), simulation tools, sensor data, and predictive analytics, Digital Twins enable architects and engineers to evaluate multiple design alternatives before construction begins. This capability supports optimization of building orientation, material selection, structural systems, energy performance, daylight availability, thermal comfort, and constructability while reducing uncertainty during project development (Lu et al., 2020; Boje et al., 2020).

Beyond the design stage, Digital Twins continue to support informed decision-making by providing continuously updated information regarding building performance. The ability to simulate future operational scenarios enables

stakeholders to identify potential performance issues, evaluate maintenance strategies, and optimize resource allocation throughout the building lifecycle.

3.4.2 Enhanced building performance and sustainability

The literature consistently demonstrates that Digital Twins contribute to improved environmental and operational performance by enabling continuous monitoring and optimization of building systems. Real-time analysis of energy consumption, indoor environmental quality, lighting, ventilation, and HVAC performance allows facility managers to identify inefficiencies and implement corrective actions before performance deteriorates (Sacks et al., 2020).

Furthermore, Digital Twins facilitate lifecycle-oriented sustainability by supporting energy-efficient building operation, predictive maintenance, resource optimization, and reduced environmental impacts. When integrated during the architectural design stage, Digital Twins also enable simulation of alternative sustainable design strategies, helping designers evaluate environmental performance before construction while supporting long-term carbon reduction objectives and sustainable asset management.

3.4.3 Improved collaboration and information integration

Effective Building Lifecycle Management depends on continuous collaboration among architects, engineers, contractors, facility managers, owners, and other project stakeholders. However, fragmented information and poor communication between lifecycle phases remain persistent challenges within the AEC industry.

Digital Twins address these challenges by providing a centralized digital environment in which lifecycle information can be continuously updated, shared, and accessed by multiple stakeholders. The integration of BIM, IoT technologies, cloud computing, and real-time data improves information transparency, reduces inconsistencies between project phases, and supports more coordinated decision-making throughout the building lifecycle (Opoku et al., 2021). Consequently, Digital Twins enhance interdisciplinary collaboration while reducing information loss that frequently occurs during transitions between design, construction, and operational stages.

3.4.4 Predictive maintenance and lifecycle value

One of the distinguishing characteristics of Digital Twin technology is its ability to support predictive rather than reactive asset management. By continuously monitoring building systems and equipment performance, Digital Twins enable maintenance activities to be scheduled before failures occur, reducing downtime, minimizing maintenance costs, and extending asset service life (Madubuike & Anumba, 2022; Asare et al., 2024).

Predictive maintenance also contributes to improved occupant comfort, operational reliability, and long-term lifecycle value by ensuring that building systems continue to operate efficiently throughout their service life. Consequently, Digital Twins support a transition from corrective maintenance toward proactive lifecycle management that aligns closely with the objectives of Building Lifecycle Management.

3.4.5 Supporting digital transformation in the AEC industry

Beyond individual project benefits, Digital Twin technology is increasingly recognized as a catalyst for the broader digital transformation of the AEC industry. The integration of Digital Twins with BIM, artificial intelligence, cloud computing, IoT, and advanced analytics supports the development of intelligent, connected, and data-driven buildings capable of continuously adapting to changing operational conditions.

As governments and organizations increasingly prioritize sustainability, smart cities, and digital infrastructure, Digital Twins are expected to play an important role in supporting resilient and future-ready built environments. Within Saudi Arabia, the adoption of Digital Twin technology aligns closely with the objectives of Vision 2030, particularly those relating to digital transformation, smart city development, sustainable construction, and improved infrastructure management. Consequently, Digital Twins represent not only a technological innovation but also a strategic framework for advancing Building Lifecycle Management and enhancing the long-term value of building assets.

3.5 Challenges to digital twin implementation in architectural design

Although Digital Twin (DT) technology offers considerable potential for improving architectural design and Building Lifecycle Management (BLM), widespread implementation within the Architecture, Engineering, and

Construction (AEC) industry remains limited. The literature consistently identifies several technological, organizational, and economic challenges that constrain adoption. These challenges extend beyond technical implementation and reflect the complexity of integrating Digital Twins into multidisciplinary project environments where information, people, and processes must operate seamlessly throughout the building lifecycle.

3.5.1 Data integration and interoperability

Effective Digital Twin implementation depends on the continuous exchange of accurate and consistent information between Building Information Modeling (BIM), Internet of Things (IoT) devices, sensors, facility management systems, cloud platforms, and other digital technologies. However, interoperability remains one of the most frequently reported barriers within the literature. Differences in data standards, software platforms, semantic models, and proprietary information formats often prevent seamless communication between systems, resulting in fragmented information and reduced reliability of Digital Twin models (Bousdekis et al., 2021; Balaha et al., 2025).

These interoperability challenges are particularly significant within Building Lifecycle Management because information generated during design, construction, operation, and maintenance is frequently stored using different software platforms and organizational procedures. Consequently, establishing standardized data exchange protocols and integrated information management frameworks has become a major research priority for improving Digital Twin implementation across the building lifecycle.

3.5.2 Cybersecurity, data privacy, and information governance

As Digital Twins increasingly rely on real-time data acquisition and cloud-based information exchange, cybersecurity and data privacy have become critical considerations. Continuous connectivity between physical assets and digital systems expands the potential attack surface, increasing risks associated with unauthorized access, data manipulation, and service disruption (Taherdoost, 2024).

In addition to technical security measures, researchers emphasize the importance of effective information governance, including access control, data ownership, audit trails, regulatory compliance, and privacy-by-design principles. Balancing data accessibility with appropriate security protections remains particularly challenging within collaborative project environments where multiple organizations require access to shared lifecycle information. Consequently, secure information management is increasingly viewed as a prerequisite for reliable Digital Twin implementation rather than a secondary technical consideration.

3.5.3 Economic and organizational barriers

The implementation of Digital Twin technology requires substantial investments in digital infrastructure, software platforms, sensing technologies, cloud services, and workforce development. Although Digital Twins offer significant long-term benefits through improved operational efficiency, predictive maintenance, and lifecycle optimization, the initial costs associated with implementation often discourage organizations, particularly small and medium-sized enterprises (Balaha et al., 2025; Bousdekis et al., 2021).

Beyond financial considerations, organizational readiness also influences successful adoption. Many organizations continue to rely on fragmented workflows, legacy software systems, and traditional project delivery methods that limit digital integration across lifecycle phases. Consequently, successful Digital Twin implementation requires not only technological investment but also organizational change, strategic planning, and long-term commitment to digital transformation.

3.5.4 Workforce skills and change management

Successful Digital Twin implementation depends on professionals possessing both technical expertise and interdisciplinary collaboration skills. The literature highlights increasing demand for competencies related to Building Information Modeling, data analytics, Internet of Things technologies, cloud computing, cybersecurity, systems integration, and lifecycle information management (Qawasmeh et al., 2024).

However, technology alone is insufficient to achieve successful implementation. Organizations must also cultivate a culture that supports innovation, continuous learning, and collaboration across traditionally separate disciplines. Investment in professional training, interdisciplinary education, and continuous skills development has therefore become an essential component of Digital Twin adoption. Without corresponding investment in human capital,

even technically advanced Digital Twin systems may fail to achieve their intended lifecycle management objectives.

3.5.5 Critical reflection

Collectively, the literature indicates that the principal barriers to Digital Twin implementation are not solely technological but also organizational and socio-technical. Interoperability challenges affect information quality; cybersecurity influences stakeholder trust; economic constraints shape implementation decisions; and workforce capabilities determine an organization's ability to effectively utilize digital technologies. These interconnected challenges suggest that successful Digital Twin adoption requires an integrated strategy that combines technological innovation with organizational readiness, standardized information management, and continuous professional development. Addressing these barriers will be essential for realizing the full potential of Digital Twins in supporting architectural design and Building Lifecycle Management.

3.6 Literature synthesis

The reviewed literature demonstrates that Digital Twin (DT) technology has evolved from a visualization and monitoring tool into a comprehensive digital framework capable of supporting Building Lifecycle Management (BLM) throughout the entire lifecycle of built assets. Existing research consistently highlights the potential of Digital Twins to improve information integration, simulation-based decision-making, predictive maintenance, operational efficiency, and sustainability by maintaining a continuous digital representation of physical building assets. Collectively, these studies indicate that Digital Twins can significantly enhance collaboration among stakeholders while supporting data-driven decision-making across architectural design, construction, operation, maintenance, and decommissioning.

Despite these advances, the literature also reveals an imbalance in current Digital Twin research. Most published studies focus on facility management, construction monitoring, infrastructure maintenance, and operational optimization, where continuous sensor data and real-time monitoring are readily available. Comparatively fewer investigations have examined how Digital Twin technology can be strategically integrated into the architectural design phase, even though many decisions affecting building performance, lifecycle costs, adaptability, maintainability, and sustainability are established during the earliest stages of project development. This imbalance suggests that the full lifecycle potential of Digital Twin technology has yet to be fully realized.

The literature further indicates that successful Digital Twin implementation depends not only on technological innovation but also on organizational readiness, standardized information management, interdisciplinary collaboration, workforce capabilities, and effective governance. Persistent challenges related to interoperability, cybersecurity, implementation costs, and professional competencies continue to limit widespread adoption across the AEC industry. Consequently, future research should adopt a more holistic perspective that considers Digital Twin implementation as a socio-technical transformation requiring simultaneous advances in technology, organizational processes, and human expertise.

Although previous studies provide valuable theoretical frameworks and technical developments, relatively limited empirical evidence is available regarding how AEC professionals perceive the role of Digital Twin technology during architectural design and its contribution to Building Lifecycle Management. In particular, there remains a need to better understand current levels of awareness, perceived benefits, implementation barriers, and future opportunities from the perspective of industry practitioners operating in different professional and geographical contexts. Addressing these issues is essential for bridging the gap between technological capability and practical implementation.

Accordingly, this study contributes to the existing body of knowledge by integrating evidence from the literature with empirical findings obtained from a questionnaire survey of Architecture, Engineering, and Construction (AEC) professionals. By examining Digital Twin applications through the perspective of architectural design and Building Lifecycle Management, the study extends existing research beyond operational applications and provides practical insights into how Digital Twin technologies can support lifecycle-oriented decision-making, sustainable building performance, and the digital transformation of the built environment.

4. RESULT ANALYSIS

4.1 Respondent Profile

A total of 60 completed questionnaire responses were analyzed. The questionnaires were distributed electronically to 120 Architecture, Engineering, and Construction (AEC) professionals, resulting in a response rate of 50%. The respondents represented a diverse range of professional disciplines within the AEC industry. As illustrated in Figure 3, architects constituted the largest respondent group (32%), followed by interior designers (27%), project managers (11%), researchers or academicians (10%), and engineers (8%). Smaller proportions of respondents included facilities or building managers, quantity surveyors, cost managers, interior architects, and building owners or developers.

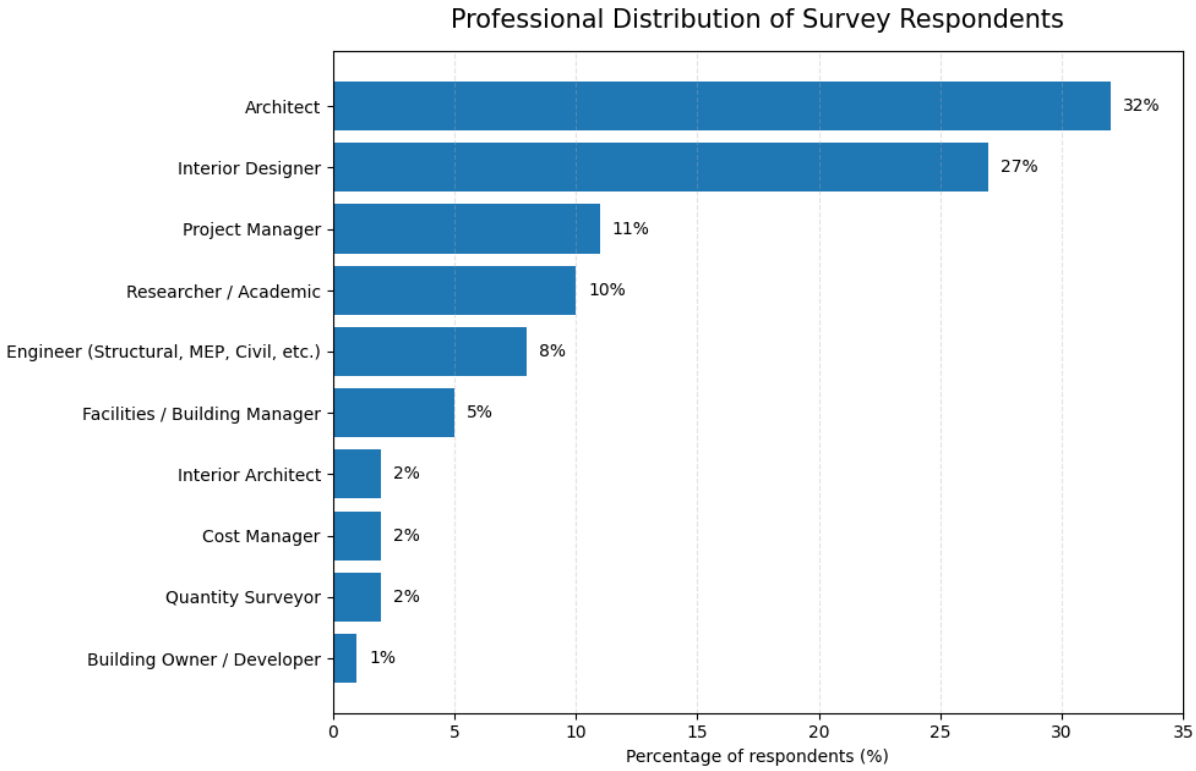

Figure 3: Professional distribution of the 60 AEC professionals who participated in the questionnaire survey.

The professional distribution demonstrates that the survey captured perspectives from multiple stakeholder groups involved in the building lifecycle while maintaining strong representation from architecture and interior design professionals. This distribution is particularly appropriate for the objectives of the study, which focus on the application of Digital Twin technology within architectural design and Building Lifecycle Management. The inclusion of professionals from engineering, project management, facility management, and ownership roles also provides broader multidisciplinary perspectives on current Digital Twin implementation and future adoption within the AEC industry. Furthermore, the respondents represented professional backgrounds from Saudi Arabia, Nigeria, and the United States, broadening the range of perspectives captured while not intending to provide direct statistical comparisons between countries.

4.2 Geographic distribution of respondents

Figure 4 illustrates the geographic distribution of the survey respondents. Participants represented locations across Saudi Arabia, the United States, and Nigeria, providing perspectives from diverse regional and professional contexts within the Architecture, Engineering, and Construction (AEC) industry. The distribution reflects the study's primary focus on the Saudi Arabian AEC sector while incorporating international perspectives from professionals working in different AEC environments.

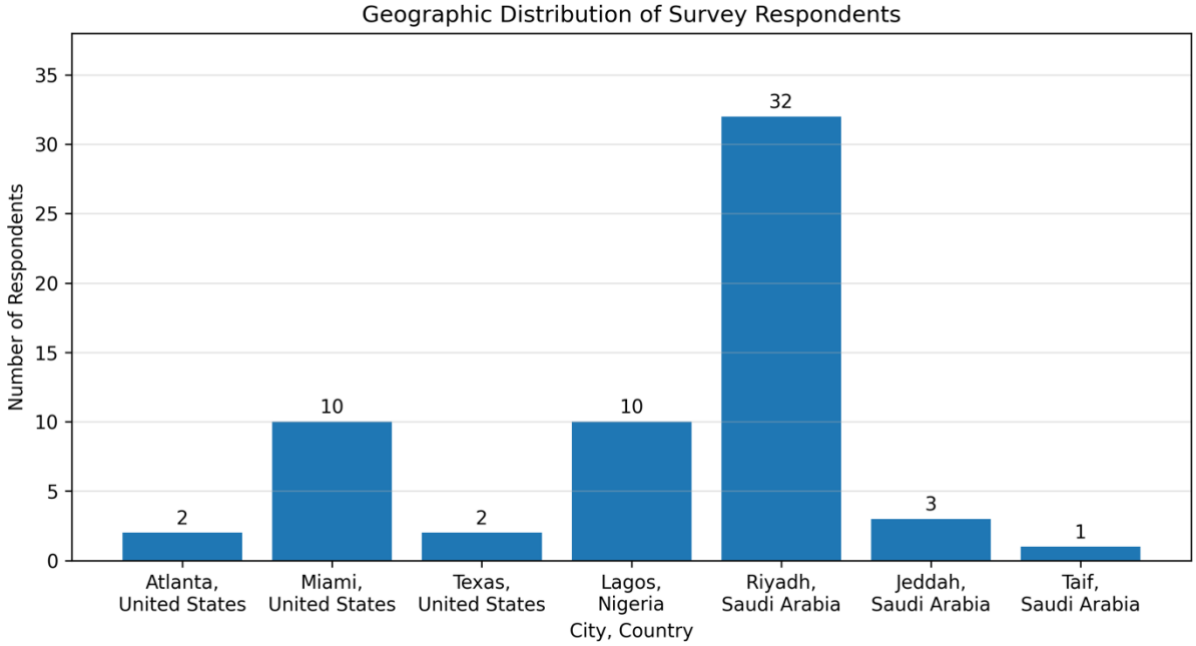

Figure 4: Geographic distribution of survey respondents by city.

The results indicate that more than half of the respondents (53.3%) were based in Riyadh, reflecting the city's position as Saudi Arabia's principal center for architectural, engineering, and construction activities. Respondents from Miami and Lagos each represented 16.7% of the sample, while smaller proportions were drawn from Jeddah, Atlanta, Texas, and Taif. This geographic diversity broadens the range of professional perspectives represented in the survey while maintaining a strong emphasis on the Saudi Arabian context.

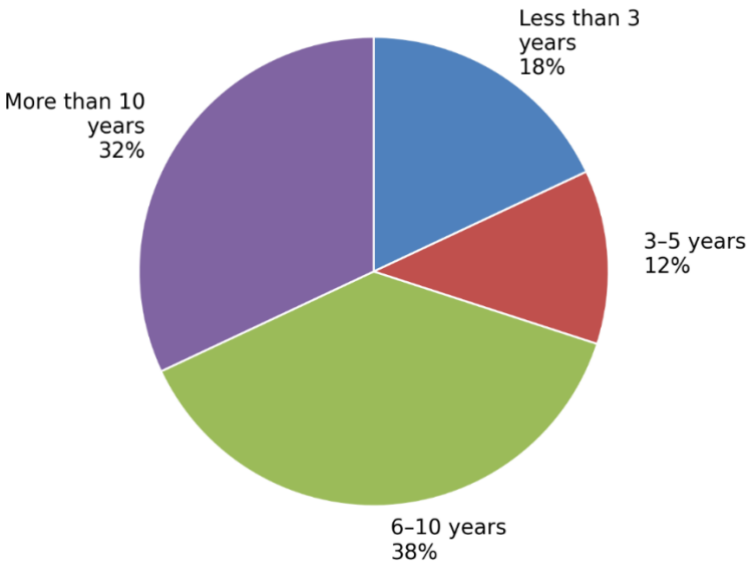

Figure 5: Professional experience of the survey respondents.

The predominance of respondents from Saudi Arabia aligns with the study's objective of investigating the application of Digital Twin technology in architectural design and Building Lifecycle Management within the

Kingdom's digital transformation context. The inclusion of participants from the United States and Nigeria broadens the international perspective of the study while providing complementary insights from different AEC environments. These findings should therefore be interpreted as reflecting a geographically diverse professional sample rather than enabling direct statistical comparisons between countries.

4.3 Professional experience of respondents

Figure 5 presents the professional experience of the survey respondents. The sample comprised professionals with varying levels of experience within the Architecture, Engineering, and Construction (AEC) industry, ensuring representation from both early-career and experienced practitioners.

The survey respondents were predominantly mid- to highly experienced professionals. The largest proportion reported 6–10 years of professional experience (38%), followed by respondents with more than 10 years of experience (32%). In comparison, 18% had less than three years of professional experience, while 12% reported between three and five years of experience.

Overall, approximately 70% of the respondents had more than six years of professional experience, indicating that the survey primarily reflects the perspectives of experienced AEC practitioners. This level of expertise enhances the reliability of the findings, as these respondents are likely to possess substantial knowledge of industry practices, project delivery processes, and the adoption of emerging digital technologies. Nevertheless, the inclusion of early-career professionals broadens the scope of the study by incorporating perspectives from individuals at different stages of professional development.

Having established the respondents' demographic and professional characteristics, the following section examines their awareness and understanding of Digital Twin technology within the AEC industry.

4.4 Awareness and understanding of digital twin technology

The survey examined respondents' awareness and understanding of Digital Twin (DT) technology to assess its current level of adoption within the architectural profession. Although DT has attracted increasing attention in both academia and industry, the findings indicate that awareness among practitioners remains relatively limited.

As illustrated in Figure 6, 43% of respondents answered "Yes" to the combined item asking whether they had previously implemented, been involved with, or understood the concept of Digital Twin technology on construction projects, whereas 57% answered "No".

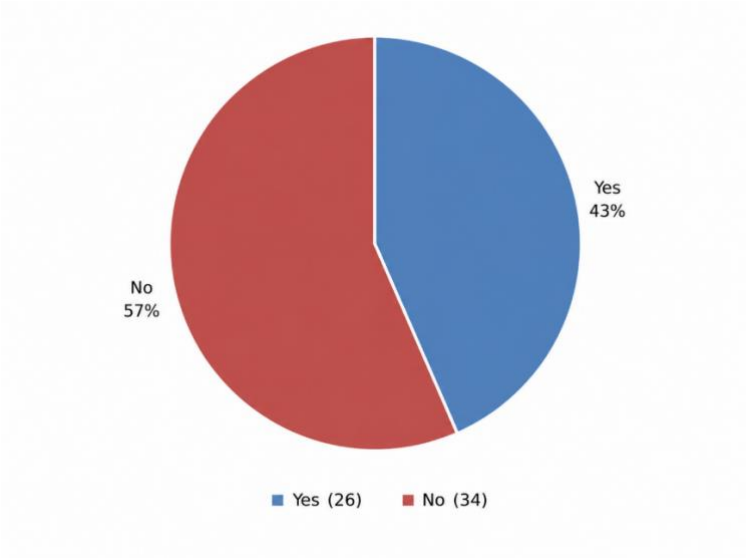

Figure 6: Respondents' prior implementation, involvement, or broad familiarity with Digital Twin technology.

Figure 6 therefore indicates that direct exposure to, involvement with, or broad familiarity with DT was not yet widespread within the sample. This result should not be interpreted as demonstrating that 57% had no conceptual

understanding of DT, because the questionnaire item combined several related but distinct constructs in a single yes/no question.

To examine perceived knowledge more specifically, Question 5 separately asked respondents to rate their understanding of constructing or applying a Digital Twin in architectural design and building management. As shown in Figure 7, 47% reported a good understanding, 37% reported limited understanding, 13% reported very good understanding, and 3% reported no understanding.

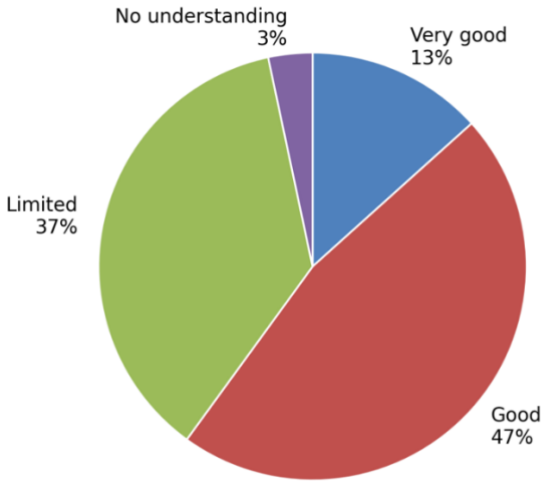

Figure 7: Respondents' self-rated understanding of constructing or applying Digital Twin technology in architectural design and building management.

Taken together, Figures 6 and 7 indicate a distinction between prior exposure or involvement and self-rated conceptual/application knowledge. A respondent could report no previous implementation or involvement under the broad Question 4 item while still reporting some understanding of how DT may be constructed or applied under Question 5. Because Question 4 combined implementation, involvement, and understanding, however, the two figures cannot be used as independent measures of the same construct or as a basis for a formal between-group comparison. The results are therefore interpreted descriptively, and this measurement limitation is explicitly acknowledged in the conclusion.

Although respondents demonstrated limited awareness of Digital Twin technology, those familiar with the concept expressed overwhelmingly positive perceptions regarding its potential applications. The following section therefore examines the perceived benefits and opportunities associated with DT implementation.

4.5 Perceived benefits and opportunities of digital twin in architecture

Despite these positive perceptions, respondents also identified several practical barriers that continue to hinder widespread implementation. The survey examined respondents' perceptions of the benefits and opportunities of implementing Digital Twin (DT) technology across the architectural design process and building lifecycle. Overall, respondents held positive attitudes toward DT, recognizing its potential to improve building performance, support sustainability objectives, and enable data-driven decision-making. These findings align with previous studies, which identify DT as a transformative technology capable of integrating real-time data with digital building models to enhance design, construction, operation, and maintenance (Boje et al., 2020; Sacks et al., 2020; Opoku et al., 2021). As illustrated in Figure 8, respondents identified improved building performance and energy efficiency as the most significant benefit of DT implementation, followed by supporting sustainable and smart building initiatives and enhancing design accuracy and visualization. Other highly ranked benefits included improved facility management, lifecycle optimization, predictive maintenance, and enhanced collaboration among project stakeholders.

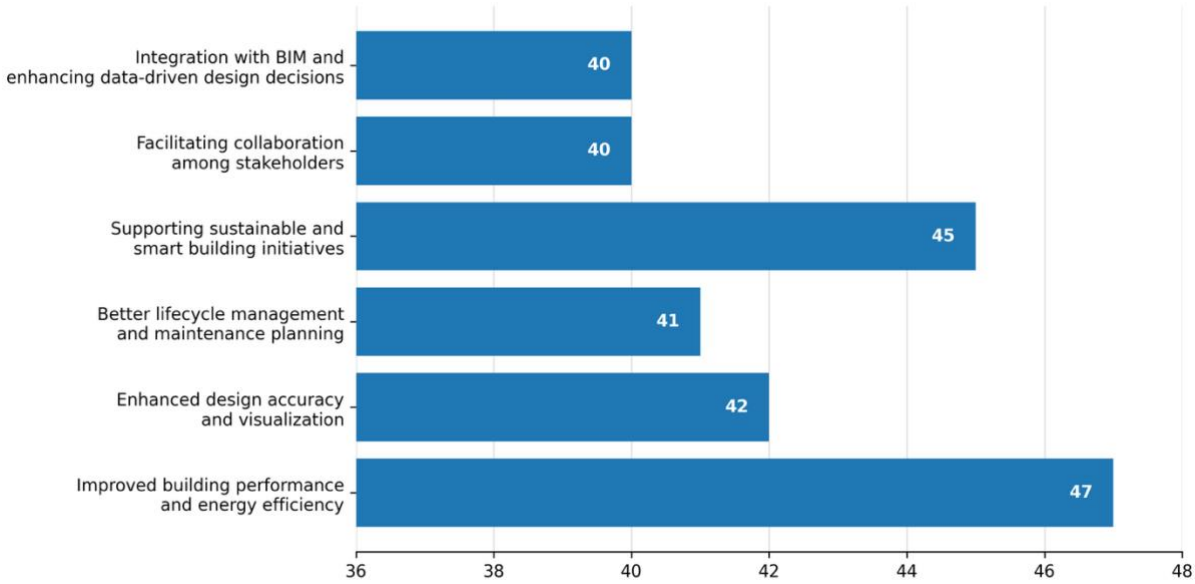

Figure 8: Perceived benefits of applying Digital Twin in architectural design.

The strong emphasis on building performance and sustainability indicates that respondents view DT as more than a visualization technology. Instead, they perceive it as an intelligent platform capable of integrating design information with operational data to support continuous performance optimization throughout a building's lifecycle. This finding reflects the industry's growing shift toward performance-based design and evidence-based decision-making. The survey also investigated the opportunities that DT presents for future architectural practice. As shown in Figure 9, respondents identified real-time data-driven decision-making as the most important opportunity, followed by improving building sustainability, enhancing occupant comfort and safety, and supporting predictive maintenance while reducing operational costs.

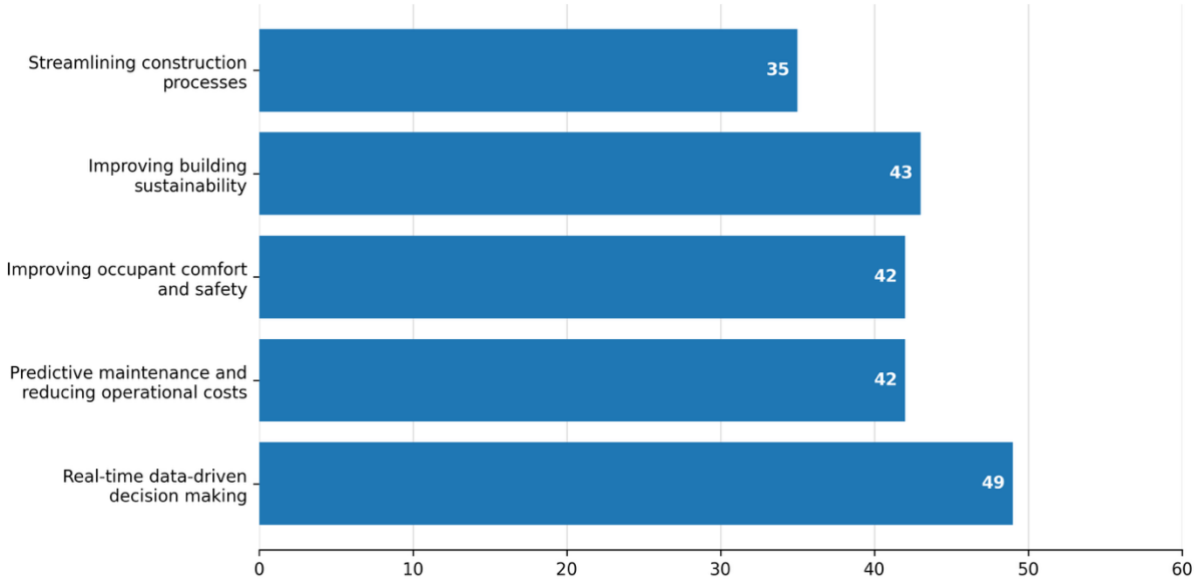

Figure 9: Key opportunities for applying Digital Twin in architectural design.

These findings demonstrate that respondents recognize DT as a strategic technology capable of enabling more intelligent, responsive, and sustainable built environments. Beyond improving operational efficiency, DT is increasingly viewed as a platform for optimizing resource consumption, enhancing user experience, and supporting

informed decision-making throughout the building lifecycle. Such perceptions align with global digital transformation initiatives and Saudi Arabia's Vision 2030, which emphasize the adoption of advanced digital technologies to improve sustainability, resilience, and the performance of the built environment (Opoku et al., 2021; Khallaf et al., 2022).

4.6 Challenges hindering digital twin adoption in architectural practice

Although respondents recognized the considerable benefits of Digital Twin (DT) technology, they also identified several technical, financial, and organizational barriers that continue to hinder its widespread implementation within architectural practice. These findings indicate that successful DT adoption depends not only on technological capabilities but also on workforce readiness, organizational commitment, data management, and the availability of standardized implementation frameworks. Figure 10 summarizes the principal challenges identified by the respondents. The lack of technical expertise and a skilled workforce emerged as the most significant barrier (46 responses), followed by high implementation costs (40 responses). Integration challenges with existing software systems and concerns regarding data security, privacy, and integrity were each identified by 30 respondents. Other frequently reported barriers included uncertainty regarding return on investment (ROI) (29 responses), lack of standards or regulations (28 responses), and resistance from stakeholders or organizational culture (24 responses).

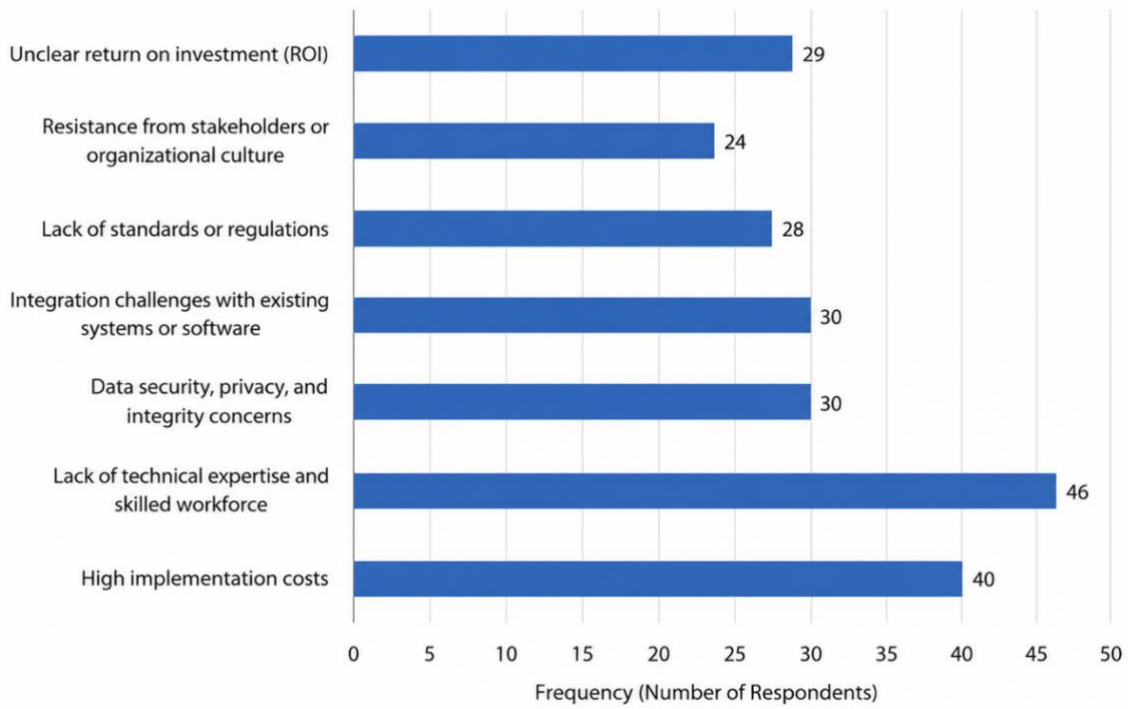

Figure 10: Major barriers affecting the implementation of Digital Twin technology in architectural design.

The findings indicate that workforce capability remains the primary challenge limiting DT adoption within the AEC industry. Respondents consistently identified the shortage of professionals with expertise in digital technologies as a greater obstacle than the technology itself. Financial investment requirements, software integration challenges, and concerns related to data security also emerged as important barriers, highlighting that DT implementation extends beyond software adoption to encompass organizational and technical readiness. Overall, the results demonstrate that the successful implementation of Digital Twin technology requires addressing multiple interconnected challenges rather than focusing solely on technological advancement. These findings provide a foundation for understanding the technological innovations and implementation strategies that respondents believe will facilitate the future adoption of DT within architectural practice, which are examined in the following section.

4.7 Emerging technologies and future innovations

The qualitative responses provided valuable insights into the emerging technologies that respondents believe will shape the future development of Digital Twin (DT) applications within the architecture, engineering, and construction (AEC) industry. Participants consistently emphasized that the future evolution of DT extends beyond digital modeling toward intelligent, connected, and autonomous systems capable of supporting data-driven decision-making throughout the building lifecycle.

Artificial Intelligence (AI) and generative design were identified as the most influential technologies for advancing DT capabilities. Respondents highlighted the potential of AI to automate design optimization, enhance predictive analytics, and enable self-learning DT systems capable of continuously adapting to changing building conditions. Similarly, real-time integration with Internet of Things (IoT) technologies was viewed as essential for enabling continuous monitoring of building performance through sensor-generated data, thereby improving operational efficiency and supporting proactive facility management.

Several respondents also emphasized the growing importance of predictive maintenance, augmented reality (AR), and virtual reality (VR) technologies. These innovations were perceived as valuable tools for improving design visualization, facilitating stakeholder collaboration, and supporting maintenance planning through immersive and data-rich digital environments. In addition, respondents recognized the increasing significance of kinetic and adaptive building systems, carbon tracking technologies, and sustainability-oriented DT models for enhancing environmental performance and supporting net-zero building objectives.

Another emerging trend identified through the qualitative analysis is the expansion of DT beyond individual buildings toward urban-scale Digital Twins and smart city applications. Respondents viewed city-scale DT platforms as promising tools for integrating building performance, infrastructure management, transportation systems, and environmental monitoring within unified digital ecosystems. Collectively, these findings indicate that DT is evolving toward an intelligent, interconnected technology capable of supporting adaptive, resilient, and sustainable built environments.

4.8 Future adoption potential of digital twin technology

Despite the challenges identified in the previous section, respondents expressed strong confidence in the future adoption potential of Digital Twin technology within architectural practice. The survey findings indicate that professionals increasingly recognize DT as a valuable technology for improving building performance, enhancing sustainability, and supporting lifecycle-oriented building management. Nevertheless, current implementation remains limited, suggesting that industry perceptions are more advanced than actual adoption.

The findings further indicate that several factors are expected to accelerate DT adoption in the coming years. Respondents emphasized the importance of expanding professional education and technical training to improve awareness and implementation capabilities. They also highlighted the need for documented real-world case studies that demonstrate the practical benefits and economic value of DT across different project types.

Cost-effectiveness emerged as another important consideration. Participants suggested that reducing implementation costs and demonstrating measurable returns on investment would significantly increase industry willingness to adopt DT technologies. Furthermore, respondents emphasized that seamless integration with existing BIM workflows is essential for minimizing implementation complexity and encouraging broader acceptance among architectural professionals.

Overall, these findings suggest that the future adoption of DT will depend not only on continued technological advancement but also on investments in workforce development, organizational readiness, interoperability, and evidence-based implementation strategies.

4.9 Thematic analysis of open-ended responses

The qualitative responses were analyzed using thematic analysis, resulting in five recurring themes that reflect respondents' perspectives on the future implementation of Digital Twin technology within architectural practice. These themes complement the quantitative findings by providing a deeper understanding of the factors influencing DT adoption and implementation.

The first theme, education and professional training, was the most frequently discussed. Respondents emphasized that increasing awareness through university curricula, professional development programs, and industry training initiatives is essential for developing the technical expertise required to implement DT effectively.

A second recurring theme concerned integration with existing digital platforms. Participants highlighted the importance of establishing seamless interoperability between DT, Building Information Modeling (BIM), Computer-Aided Design (CAD), Geographic Information Systems (GIS), and facility management platforms. Improved integration was viewed as fundamental for maximizing the practical value of DT throughout the building lifecycle.

The third theme focused on standardization and governance. Respondents emphasized the need for clear implementation frameworks, technical standards, and industry guidelines to ensure consistency, improve interoperability, and facilitate broader adoption across the AEC sector.

Another important theme related to usability and accessibility. Participants noted that simplifying DT interfaces and reducing implementation complexity would make the technology more accessible to architects and other stakeholders who may not possess advanced technical expertise. Improving usability was therefore viewed as a key factor in encouraging wider industry acceptance.

Finally, respondents advocated for a gradual and strategic implementation approach. Rather than introducing DT technologies on a large scale immediately, participants recommended phased adoption supported by pilot projects, demonstration case studies, and continuous organizational learning. Such an approach would allow organizations to evaluate the benefits of DT, build internal expertise, and reduce implementation risks before wider deployment.

Taken together, these themes reinforce the quantitative findings by demonstrating that successful DT adoption depends on a balanced combination of technological innovation, workforce development, organizational preparedness, and supportive industry frameworks. They also highlight that the transition toward Digital Twin-enabled architectural practice requires coordinated efforts from academia, industry, technology providers, and policymakers. Table 1 summarizes the five themes identified through the thematic analysis, together with their key findings and implications for the adoption of Digital Twin technology within the AEC industry.

Table 1: Summary of Themes Identified from the Thematic Analysis of Open-Ended Responses

Theme	Key Findings	Implications for DT Adoption
Education and Training	Need for professional and academic training	Enhances technical competency and industry awareness
System Integration	BIM, CAD, GIS, and FM interoperability	Facilitates seamless data exchange and implementation
Standardization	Need for industry frameworks and policies	Promotes consistency, interoperability, and scalability
Usability	Simpler interfaces and workflows	Improves accessibility and encourages wider adoption
Strategic Implementation	Pilot projects and phased deployment	Reduces implementation risk and supports organizational readiness

The thematic analysis complements the quantitative findings by highlighting the organizational, technical, and educational factors that respondents consider essential for successful Digital Twin adoption. Collectively, these themes reinforce the importance of integrating technological innovation with workforce development, interoperability, and strategic implementation to support the broader adoption of DT within architectural practice.

Together, the quantitative and qualitative findings provide a comprehensive understanding of the current state of Digital Twin adoption within the AEC industry. The following section summarizes the principal findings of the study before presenting the broader discussion.

4.10 Summary of key findings

The survey findings indicate that although Digital Twin technology remains at an early stage of adoption within architectural practice, professionals recognize its considerable potential to improve building performance, sustainability, and lifecycle management. Limited technical expertise, implementation costs, interoperability challenges, and the absence of standardized frameworks remain the primary barriers to wider adoption. Nevertheless, respondents expressed strong optimism regarding the future of DT, particularly when supported by advances in artificial intelligence, IoT integration, and enhanced BIM interoperability. Collectively, the quantitative and qualitative findings provide a comprehensive understanding of the opportunities, challenges, and

future directions of Digital Twin implementation within the AEC industry and establish the foundation for the discussion presented in the following section.

5. SYNTHESIS AND DISCUSSION

The findings of this study demonstrate that Digital Twin (DT) technology is increasingly recognized as a transformative approach for enhancing architectural design and Building Lifecycle Management (BLM). Although respondents expressed strong confidence in the potential of DT to improve building performance, sustainability, lifecycle decision-making, and operational efficiency, the results also reveal a substantial gap between perceived value and practical implementation. This disparity suggests that the current challenge facing the Architecture, Engineering, and Construction (AEC) industry is not the recognition of DT's benefits but the industry's readiness to implement the technology effectively.

The survey findings reinforce previous studies that describe DT as an intelligent platform capable of integrating Building Information Modeling (BIM), Internet of Things (IoT) technologies, Artificial Intelligence (AI), and real-time operational data to support evidence-based decision-making throughout the building lifecycle (Boje et al., 2020; Opoku et al., 2021). However, while existing research has primarily emphasized the technological capabilities of DT, the present study highlights that organizational readiness, workforce capacity, and interoperability are equally critical determinants of successful implementation. This finding extends the current literature by demonstrating that technological advancement alone is insufficient to accelerate DT adoption within architectural practice.

One of the most significant findings of this research is the contrast between respondents' limited awareness of DT and their highly positive perceptions of its potential once the technology is understood. This suggests that education and professional exposure may be among the most effective mechanisms for accelerating adoption. The qualitative findings further reinforce this interpretation, with respondents consistently identifying education, professional training, and practical case studies as essential prerequisites for wider implementation. These findings support the view that successful DT adoption should be considered a socio-technical transformation requiring simultaneous investment in technology, human capital, and organizational change.

The study also demonstrates that respondents perceive the future of DT as closely linked to advances in Artificial Intelligence, IoT, predictive analytics, and immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR). Rather than viewing DT as a standalone digital model, participants recognized it as an intelligent decision-support platform capable of continuously learning from operational data and optimizing building performance throughout the lifecycle. This evolution reflects the broader digital transformation occurring within the AEC industry and supports the growing convergence of DT, smart buildings, and Industry 4.0 technologies.

Although respondents acknowledged the considerable benefits of DT, several barriers continue to hinder widespread implementation. Technical expertise emerged as the most significant challenge, followed by implementation costs, interoperability limitations, cybersecurity concerns, and the absence of standardized implementation frameworks. These findings are consistent with previous research that identifies fragmented information management and organizational readiness as major constraints to DT adoption (Lu et al., 2020; Sacks et al., 2020). However, the present study suggests that these barriers should not be viewed independently. Instead, they represent interconnected technological, organizational, and governance challenges that require coordinated solutions involving educational institutions, software developers, industry practitioners, and policymakers.

The findings have particular relevance within the Saudi Arabian context. As the Kingdom continues to pursue the objectives of Vision 2030, including digital transformation, sustainable development, and smart city initiatives, DT offers considerable opportunities to improve lifecycle-oriented decision-making across the built environment. Nevertheless, realizing this potential will require strategic investment in workforce development, standardized implementation frameworks, interoperable digital infrastructures, and collaborative partnerships between academia, government agencies, and the construction industry. Such efforts will be essential for bridging the gap between technological capability and practical implementation.

Overall, this study demonstrates that the future of DT in architectural design depends not only on continued technological innovation but also on the development of an ecosystem that supports knowledge sharing, interdisciplinary collaboration, and lifecycle-oriented thinking. By integrating empirical evidence from industry professionals with existing scholarly research, the study contributes a practical perspective on the factors

influencing DT adoption and identifies key priorities for advancing Building Lifecycle Management through digital transformation.

6. CONCLUSION

This study investigated the role of Digital Twin (DT) technology in architectural design and its contribution to improving Building Lifecycle Management (BLM) within the Architecture, Engineering, and Construction (AEC) industry. By integrating a comprehensive literature review with empirical evidence collected from AEC professionals, the study provides an up-to-date assessment of industry awareness, perceived benefits, implementation barriers, and future opportunities associated with DT adoption.

The findings indicate that DT is increasingly recognized as a transformative technology capable of enhancing building performance, sustainability, lifecycle management, and data-driven decision-making. However, its practical implementation remains at an early stage due to technical, organizational, and financial barriers, including limited technical expertise, interoperability challenges, implementation costs, cybersecurity concerns, and the absence of standardized implementation frameworks. These findings demonstrate that successful DT adoption depends not only on technological advancement but also on organizational readiness, workforce development, effective governance, and interdisciplinary collaboration.

A key contribution of this study is its emphasis on the architectural design stage as a critical point for integrating Digital Twin technologies to support lifecycle-oriented decision-making. While much of the existing literature has focused on construction, operation, and facility management, this study demonstrates the importance of incorporating DT during the early design phase to improve long-term building performance, sustainability, and lifecycle value. By combining evidence from the literature with the perspectives of AEC professionals, the study contributes empirical insights into current industry perceptions and extends the understanding of Digital Twin applications within architectural design and Building Lifecycle Management.

The study also highlights the strategic importance of DT within Saudi Arabia's Vision 2030 agenda. Respondents emphasized that broader adoption will require greater investment in professional education and training, improved interoperability between digital platforms, stronger collaboration among industry stakeholders, and the development of standardized implementation frameworks supported by real-world case studies.

Several limitations should be acknowledged. First, the study was based on a relatively modest sample of AEC professionals, which may limit the generalizability of the findings to the wider industry. Second, the findings rely on self-reported perceptions rather than observations of actual Digital Twin implementation and may therefore not fully reflect organizational practices. Third, the study adopted a cross-sectional survey design that captures perceptions at a single point in time, whereas attitudes and implementation practices may evolve as Digital Twin technologies mature. Finally, one questionnaire item combined respondents' familiarity with Digital Twin technology and their practical implementation experience within a single question. As these represent related but distinct constructs, this wording may have introduced some ambiguity in respondents' interpretations.

Future research should expand upon these findings by examining Digital Twin implementation across different building types, project scales, and geographical contexts using larger and more diverse samples. Longitudinal studies are recommended to evaluate the long-term effects of Digital Twin adoption on Building Lifecycle Management, sustainability, operational performance, and lifecycle costs. Future studies should also develop and validate standardized implementation frameworks, investigate organizational readiness and workforce capabilities, and explore the integration of Digital Twin technology with emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Building Information Modeling (BIM), and predictive analytics. In addition, future survey instruments should assess respondents' conceptual familiarity with Digital Twin technology separately from their practical implementation experience to improve measurement precision and construct validity.

In conclusion, Digital Twin technology represents more than a digital innovation; it provides a strategic framework for transforming architectural design into a lifecycle-oriented process that supports intelligent, resilient, and sustainable built environments. As digital transformation continues to reshape the Architecture, Engineering, and Construction industry, the successful integration of Digital Twin technologies into architectural practice will play an increasingly important role in advancing Building Lifecycle Management, improving decision-making throughout the building lifecycle, and supporting the development of future-ready, sustainable built environments.

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AUTHOR *C*ONTRIBUTIONS

Dr. Fatma A. Hasanain contributed to the conceptualization and research design, literature review, development of the survey instrument, preparation of figures and tables, interpretation of the findings, manuscript drafting, adaptation of the Digital Twin framework, critical review and revision of the manuscript, and final approval of the manuscript. Dr. Obinna C. Madubuike contributed to the conceptual development and adaptation of the Digital Twin framework, technical knowledge transfer, development of the survey instrument, critical review and revision of the manuscript, and final approval of the manuscript. Dr. Obinna C. Madubuike contributed to the conceptual development and adaptation of the Digital Twin framework, technical knowledge transfer, assisted in the survey instrument development, critical review, and final approval of the manuscript.

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APPENDIX

Digital Twin in Design Architecture: Impact of DT in Architectural Design for Improved Building Lifecycle Management

Dear Participants,

Request to participate in this study through a Questionnaire Survey.

Digital technologies (DTs) have proven helpful in the Architecture, Engineering, and Construction (AEC) industry due to their varied benefits to project stakeholders, such as enhanced visualization, better data sharing, reduced building waste, increased productivity, sustainable performance, and safety improvement. Therefore, researchers have conducted various studies on DTs in the AEC industry over the years. Even with these studies, there is still a huge gap between the level of DT implementation in the AEC industry and other DT-leading industries, such as the manufacturing, aerospace, and automotive industries. This study proposes a digital twin (DT) platform in Architectural Design for improved Building lifecycle management (BLM). To address this concept, the study developed two major research questions as follows:

I. What literature exists addressing the impact of DT in architectural design for improved building lifecycle management?

II. How can DT be applied in architectural design to help improve building lifecycle management and performance?

Please be sure that all questions in this questionnaire are within the purview of the research objectives and will be used strictly for the study. Hence, your valuable time and inputs in contributing to this study by answering the questions are highly appreciated.

Yours faithfully,

Research Co-ordinators

Part 1: Demographics and Background

1. What is your role in the architecture, engineering, or building industry?

- ○ Architect
- ○ Engineer (Structural, MEP, Civil, etc.)
- ○ Facilities/Building Manager
- ○ Project Manager
- ○ Building Owner/Developer
- ○ Researcher or Academic
- ○ Other (please specify): _____

2. How many years of professional experience do you have?

- ○ Less than 3 years
- ○ 3-5 years
- ○ 6-10 years

- More than 10 years

3. Are you open to improving the AEC industry with new technological ideas?

- Yes
- No

Part 2: Awareness and Perception of Digital Twin

4. Have you previously implemented or been involved with, or understand the concept of Digital Twin technology on construction projects?

- Yes
- No

5. How would you rate your understanding of constructing or applying a Digital Twin in architectural design and building management?

- Very good
- Good
- Limited
- No understanding

Part 3: Professionals' Perspectives on Applying DT in Architecture

6. In your view, what are the main benefits of applying Digital Twin in architectural design? (Select all that apply)

- Improved building performance and energy efficiency
- Enhanced design accuracy and visualization
- Better lifecycle management and maintenance planning
- Supporting sustainable and smart building initiatives
- Facilitating collaboration among stakeholders
- Other (please specify): _____

7. What do professionals in the industry see as the key opportunities for applying DT in architectural design? (Open-ended or select options)

- Real-time data-driven decision making
- Predictive maintenance and reducing operational costs
- Improving occupant comfort and safety
- Streamlining construction processes
- Improving building sustainability

Part 4: Challenges Hindering DT Adoption in Architectural Design

8. What are the main problems and barriers affecting the implementation of Digital Twin in architectural design? (Select all that apply)

- High implementation costs
- Lack of technical expertise and skilled workforce

- ○ Data security, privacy, and integrity concerns
- ○ Integration challenges with existing systems or software
- ○ Lack of standards or regulations
- ○ Resistance from stakeholders or organizational culture
- ○ Unclear return on investment (ROI)
- ○ Limited awareness or understanding of DT's potential
- ○ Other (please specify): _____

9. How do these challenges impact the feasibility and effectiveness of DT in architectural projects? (Open-ended)

Part 5: Ideas and Technologies for Enhancing DT in Architecture

10. What digital twin technologies or ideas do you believe could be implemented to improve architectural design and building lifecycle management? (Select all that apply)

- ○ IoT sensors for real-time building data
- ○ AI and machine learning for data analytics and predictive maintenance
- ○ 3D modeling and BIM integration
- ○ Augmented Reality (AR) / Virtual Reality (VR) for visualization and simulation
- ○ Cloud-based data management platforms
- ○ Automated reporting and performance dashboards
- ○ Modular or scalable DT frameworks
- ○ Other (please specify): _____

11. Are there any emerging DT ideas or innovations that you believe could revolutionize architectural design and lifecycle management? [Open-ended]

Part 6: Impact and Future Perspectives

12. In your opinion, how impactful is DT in improving building performance and sustainability?

- ○ Highly impactful
- ○ Moderately impactful
- ○ Slightly impactful
- ○ Not impactful

13. How motivated are you or your organization to adopt Digital Twin technology for future projects?

- ○ Very motivated
- ○ Motivated
- ○ Neutral
- ○ Unmotivated
- ○ Very unmotivated

14. Please provide any additional comments, insights, or suggestions regarding the application and development of Digital Twin in architecture and building management.