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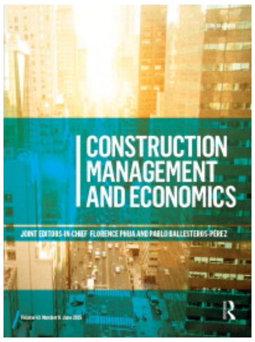

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Organising digital twin in the built environment: a systematic review and research directions on the missing links of use and user perspectives of digital twin in Architecture, Engineering and Construction (AEC) sector

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ABSTRACT
There has been growing interest in the adoption of advanced digital technologies in the Architecture, Engineering and Construction (AEC) sector, as shown by the increasing number of review studies on the adoption of Digital Twin (DT) in the sector. While previous reviews on DT in the AEC sector have emphasised the technical opportunities and challenges, reviews that take a specific organisational and management focus on the use of DT are lacking. In this systematic review, we close this gap by analysing 102 papers from three main scientific databases (Google Scholar, Scopus and Web of Science), which emphasise organisational and management aspects of using DT in the AEC sector across the project and asset lifecycle phases. The findings indicate that, whereas there is still a stronger focus on finding optimisations for various performance concerns (e.g. project efficiency, health and safety and maintenance performance), there is increasing awareness and interest in using DT to encourage collaboration and (end-)user participation. Despite this recognition, our review also identified a number of critical knowledge gaps on the use and user perspectives of DT, which includes how powerful computational tools can be developed into user-friendly interfaces to reduce complexity and increase accessibility to all stakeholders in the decision-making process, and how participatory design frameworks can be combined with structured feedback systems and standardised data access protocols in order to stimulate communication, continuous improvement, and data-driven decision making.

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Introduction

Over the past two decades, the architecture, engineering, and construction (AEC) sector has been undergoing considerable change in becoming more digital. Borrowing from experiences from other sectors such as manufacturing or transportation, digitalisation promises to improve the AEC industry's output and competitiveness (Rafsanjani and Nabizadeh 2021). In embracing the digital turn, and in the context of the fourth industrial revolution where the digital meets the physical through Big Data analytics and the Internet of Things, early studies emphasised potential performance benefits through a technologically deterministic approach (Chan 2020a; Ejohwomu *et al.* 2021; Sherratt *et al.* 2020). Technological advancement is viewed as the key to attaining a better future.

Recent research on digitalization in the AEC sector have revealed that successful project or product deployment needs more than simply implementing technology. It is equally important to consider the social aspects of technology integration within organizational life (Dowsett and Harty 2019). Researchers have explored how digital technologies can become embedded in design practices (Morgan 2019); how such tools can fundamentally alter activity systems, work practices and professional roles in the sector (Akintola *et al.* 2019), and; emphasise the importance of the social framing of technology in realizing performance outcomes (Andersson and Eidenskog 2023; Lundberg *et al.* 2022). As Jacobsson and Linderoth (2021) argued, technological implementation (as opposed to adoption) needs to go hand in hand with organisational adaptation and the changing of mindsets. Similarly, Hall *et al.* (2020) referred to mirror-breaking strategies as they argued that underlying organisational rationalities will need to be reconfigured for digitalisation to meet its full, promised

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potential. Therefore, the implementation of digitalisation goes beyond simplistic accounts of technological adoption and could entail a variety of different organising scenarios (Lavikka *et al.* 2018).

While early studies on organising digitalisation in the AEC industry have centred on building information modelling, a recent emerging technology of interest lies in the concept of digital twins (DT). In characterising DT, researchers have pointed to different facets. Earlier developments of DT, notably from other sectors such as aviation, have emphasised the role of DT in modelling and simulations (Shafto *et al.* 2010). Such modelling and simulations can, as Pan *et al.* (2022) and Korenhof *et al.* (2021) suggest, enable DT to serve as steering approaches that leverage structural and data representations to analyse and manage tangible assets toward specific goals. These perspectives emphasise DTs' technical and functional characteristics. As Graser *et al.* (2021) noted, digital twins is a technical innovation that can expand the use of fabrication for production, replacing traditional-based construction approaches.

More recently, scholars have begun to consider DT from a social perspective. For Vosman *et al.* (2023), digital twins are innovations that go beyond production technologies, as they see how DT will require novel collaborations across different sectors to be realised. Boyd (2021) also used DT to exemplify what he called the hyperreality of digitalisation in construction, where the intensification of abstractions in virtual/digital representations can, he argued, lead to loss of meaning, control and perspective in the physical world.

Scholars that take a social turn tend to emphasise the plurality of multiple perspectives, as they called for more participatory forms of engaging with DT. For instance, Nochta *et al.* (2021) considered the socio-political effects of DTs, as they demonstrated the need for collaborative functions in DT implementation to facilitate participatory knowledge co-production in urban development. Agrawal *et al.* (2023) also developed an integrated framework that anthropomorphises the use of DT, where DT can play four roles of the observer, analyser, decision maker, and action executor.

Positioning the need for this review paper

As digitalisation continues to take hold in the AEC sector, and as advanced technologies such as DT continue to be developed for applications in the sector, it is important to take stock of the growing body of scientific knowledge. In positioning the need for this review, we note that existing review studies (see Table 1) have varied in scope, analysing between 31 and 151 studies,

Table 1. Comparison of review papers on DT related to the research topic.

Author(s)	Number of papers	Source of analysis	Period of analysis	Scope	Findings
Opoku *et al.* (2021)	31	Scopus	2010–2020	Construction	The author presented the origin, technologies and concept of DT. They categorize DT into six areas of application consisting of BIM, structural system integrity, facilities management, monitoring, logistics processes, and energy simulation within the project life cycle (design, construction, and O&M)
Ozturk (2021)	151	Scopus	2013–2021	Built environment	The author argued that DT could be divided into five clusters: ' virtual-physical building integration', 'building lifecycle management', 'information integrated production', 'information-based predictive management', and 'virtual-based information utilization'.
Jiang *et al.* (2021)	134	Scopus	All years	Civil Engineering	The author argued that DT differentiates from BIM and cyber physical system based on factors such as the as-is physical part, virtual model, connections between physical and virtual models, and the twin relationship between the physical and virtual models. The author also provides a research cluster of DT from a service perspective consisting of DT creation, design, construction and O&M.
Deng *et al.* (2021)	123	Scopus, ScienceDirect, GScholar	2010–2020	Buildings	Authors categorize papers based on a representation of BIM to the DT. It is divided into five levels; level 1 (BIM review), level 2 (BIM-supported simulation), level 3 (BIM integrated with sensors), level 4 (BIM combined with AI), and level 5 (ideal DT)
Coupry *et al.* (2021)	68	Scopus, WoS, GScholar, ScienceDirect	All years	Construction	The author proposes DT definition as "A DT is a multi-scale representation of a system, comprising its physical counterpart, virtual reflection, and automated data exchange. It utilizes real-time data, simulation algorithms, and historical or sensor-collected data to predict the system's future state or response". Authors categorize the research domain of DT as usage, creation, and benefits, impact on data management that focuses on the maintenance stage.

with authors utilizing databases such as Scopus, Google Scholar, and Web of Science (WoS). The analysis periods also differed, with most focusing on the past decade, whereas Jiang *et al.* (2021) surveyed all available years.

What is striking is that reviews of DT in the AEC sector have primarily been technically oriented, concentrating on BIM and structural integrity, before evolving to address more complex themes such as linking building lifecycle management with managing the relationship between physical and digital models. For example, Opoku *et al.* (2021), identified six distinct construction industry application areas for DT, highlighting its adaptability and broad applicability. They suggested that DT can significantly influence and improve multiple domains within the construction industry, including BIM, structural system integrity, facilities management, monitoring, coordination processes, and energy simulation. These areas span the entire project lifecycle, covering the design, construction, and operations and maintenance phases.

Previous review papers have illustrated DT's technological capacities and potentials, the transformation of BIM to DT, and the multifaceted integration within the built environment. However, existing body of work primarily focus on identifying and discussing DT's technical challenges, intended technological promises and benefits, with far less attention placed on a human-centric perspective. As already noted, taking a technocentric approach can be limiting in advancing the implementation of any technological innovation, including DT, since it is important to consider how people can use and interact with the technology, the social constructs within which they operate, and the organizations they represent (Dwivedi *et al.* 2018; Jacobsson and Linderoth 2021). Indeed, the role of users and their use perspectives are often lacking in previous reviews, a point that has been noted as a significant factor in the implementation of digitalisation and DT in the AEC industry (Boyd 2021; Erdogan *et al.* 2008; Lavikka *et al.* 2018).

In light of these gaps, this review aims to shed light on these unexplored areas by addressing the following research questions:

1. How are the use and the user of DT characterized in previous studies on DT in the built environment?
2. What knowledge gaps can be identified to provide useful future research directions on the use and user perspectives of DT in the built environment?

The rest of this article is structured as follows. The next section explains the steps taken to undertake the systematic review. Thereafter, the trends, research areas, and key themes found in the analysis of past research will be presented. The paper then concludes with a discussion and identification of possible research directions of DT in the AEC sector.

Method for undertaking systematic literature review

Our research employs a systematic literature review (SLR) to evaluate and synthesize previous studies on the use and user perspectives of DT in the built environment. In contrast to narrative reviews, which frequently experiences sample selection bias and partial data representation, SLR utilizes structured methods to ensure replicability and unbiased analysis, crucial for understanding interdisciplinary domain (Linnenluecke *et al.* 2020; Rahman *et al.* 2019). In conducting the methodology, three stages were adopted: data collection, treatment of documents, and analysis.

Data collection

This review draws on Scopus, Web of Science (WoS), and Google Scholar (GS) as the source databases for retrieving articles on DT in the AEC sector. For the initial retrieval stage, researchers read review articles previously published on DT to identify relevant keywords to inform the search query. It should be highlighted that the search was conducted in June 2022, therefore there were less publications than in 2021. Next, researchers used the saved keywords to evaluate, in an iterative manner, the results from the three source databases, repeating the procedure multiple times to produce a comprehensive sample is generated on DT research done in the AEC industry with particular focus on users from organisational and management perspectives (see Table 2 below). Wildcards of * are also used in a keyword such as building*, organi*, and rail* to extract publications with multiple spelling variations.

A number of inclusion/exclusion criteria was also established, including date (2016 – 2022), language (English language), document type (article, and review), and source (journal).

Filtering process

The filtering process consisted of several stages. In the first stage, the search results for publications in three databases were imported into Microsoft Excel as a CSV file. Studies that did not focus exclusively on DT and instead used it only as a point of reference were removed, as they did not contribute to developing the DT concept. Articles that were not accessible or where the entire text was

Table 2. Keywords used in data collection process.

Main keyword	Application keywords	Life cycle keywords	Management keywords	Exclusion keywords
Digital Twin	Residential Housing Buildings Road Airport Rail Transport Urban City Built environment Infrastructure	Design Planning Construction Operation Maintenance Monitoring Demolition	User Management Decision – making Collaboration Organization	Aerospace Automotive Manufacturing Nuclear

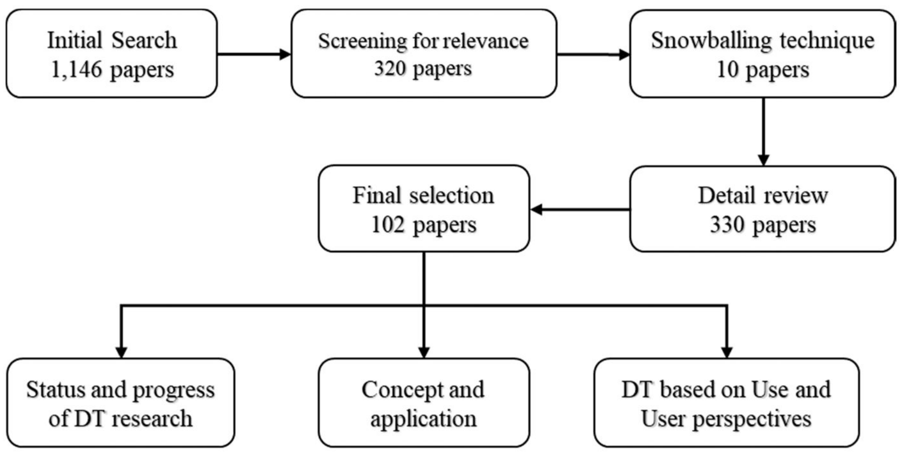

Figure 1. Research flow to address SRQ1 on the current state, trends, and applications of the DT in the built environment. A diagram illustrating the four phases of research flow, including literature search, literature selection, paper selection, and pattern and findings.

unavailable during filtering were also removed. The initial search round resulted in 1146 articles.

In the second stage, errors and duplications were detected by reading the titles and abstracts of the papers identified in the first stage, resulting in 320 papers. Additionally, ten papers were then added to the evaluation by using the snowballing technique. This method involves systematically exploring the literature by examining the reference lists of already identified papers to find additional relevant papers. It ensures that researchers do not miss important papers that may not appear in keyword-based searches.

In the subsequent stage, an in-depth review was conducted by thoroughly reading the 330 papers and considering the status and progress of DT research, concepts, and applications, specifically focusing on the user and usage perspectives of DT as the objective of this research. The final selection of papers for this research consisted of 102 papers. The framework of this review process can be seen in Figure 1.

In-depth analysis

A thematic analysis was done on the final sample to categorize, code, and analyse retrieved articles of DT. This analysis identified themes and patterns and suggested a comprehensive interpretation that can be used to answer research questions on a specific topic. Many researchers have also adopted this analysis within the similar topic of the built environment and other disciplines such as manufacturing, sustainability, business and management for both review and empirical research purposes to produce objective results and better understand the research findings.

The study began by examining where research on DT was being conducted globally and identifying the journals where these findings were published. This initial analysis aimed to understand the global landscape of DT research, highlighting the countries at the forefront and the journals that are central to the conversation.

Next, the study delved into the specifics of the research itself. It looked at the questions researchers were asking about DT, the theories they were using to frame their investigations, and the methods they employed to find answers. This step also included an exploration of the areas within the Architecture, Engineering, and Construction (AEC) industry—like housing and commercial buildings—where DT were being applied.

Following this, the research papers were organized based on the various stages of a DT lifecycle. This organization helped in spotting patterns in the research findings, both unique to each stage and common across whole lifecycle. Finally, the focus shifted to the users of DT and the many ways DT were being used at each stage of the lifecycle. This part of the analysis carefully considered what was helping or hindering the use of DT.

Results

Overview from previous studies

In order to provide an overview of the research trends around the topic of DT (see Figure 2), this research found 102 papers that are linked to the case. Most papers (61.76%) were categorized as empirical research papers, while the rest (38.24%) were classified as review papers. Compared to BIM, introduced in the 2000s and has since become the standard for large and medium enterprises in architecture and engineering, DT's popularity has only increased in recent years due to its capacity to support real-time simulation and integrate diverse data across departments.

This attribute contributed to developing an advanced decision-support system for related users. The result indicated that the number of DT-related publications published over the past five years had increased annually. Two publications were published in 2019 on the built environment sector, and more than fifteen papers were published annually after that. In the coming years, interest in DT adoption is expected to rise due to the increased desire for alternative approaches to integrating digital technology throughout the project life cycle phase to improve project performance and delivery.

Some journals that are highly regarded as top journals in the architecture, engineering, and construction sectors (See Figure 3), including *Energy and buildings*, *Building and Environment*, *Engineering, Construction and Architectural Management*, and the *ASCE Journal of Construction Engineering and Management*, have the potential to serve as a platform for publication due to the limited evidence of their coverage of DT-related topics and respective scope. Other journals such as the *Journal of Cleaner Production*, *Cities*, *Smart and Sustainable Built Environment*, *Sustainable Cities and Society*, *Journal of Urban Technology*, and other related journals in the built environment also have the potential as one outlet of publication for the author interested in dealing with digitalization and the built environment in general. Interestingly, *Construction Management and Economics (CME)* does not feature as a journal that has a critical mass of publications on DT in the AEC sector. Given that *CME* has a niche focus on encouraging critical and reflexive accounts of practice, and where the emphasis has shifted from its early roots in engineering perspectives to engagement with the social sciences (Chan 2020c), the absence of papers based on research on DT in *CME* is not surprising and demonstrates how DT research in the AEC industry is still dominated by a techno-centric approach.

Research methods used in the studies analysed

Concept development, case study, interview, experimentation, survey, and mathematical modelling are some methods applied to DT research. Authors can use multiple approaches to address the research objective, such as a combination of mathematical modelling and case study, survey and interview, experiment and case study, or other combinations. Subsequently, "mixed methods" referred to studies employing multiple research techniques. The pilot case study was the most prevalent empirical research

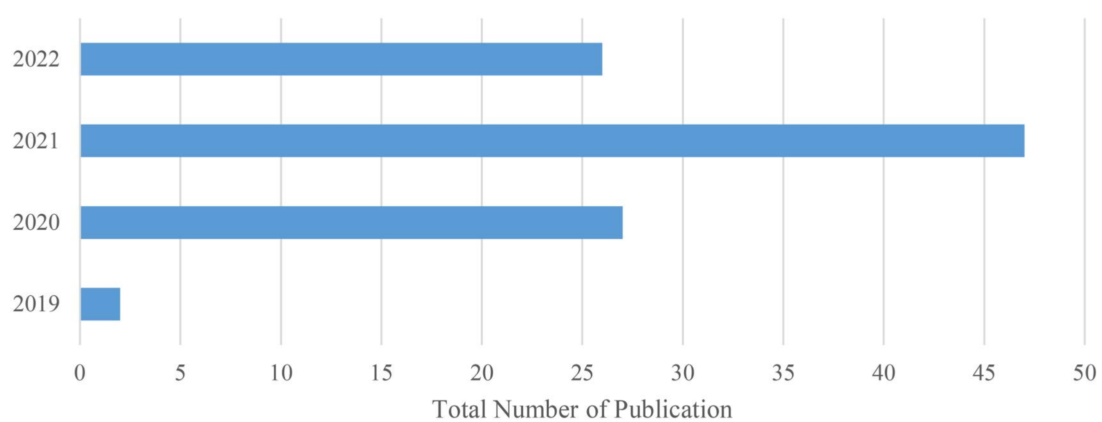

Figure 2. Distribution of Articles on DT by publication date. A bar graph displaying the number of DT publications from 2019 (2 papers), 2020 (27 papers), 2021 (47 papers), and 2022 (26 papers) respectively.

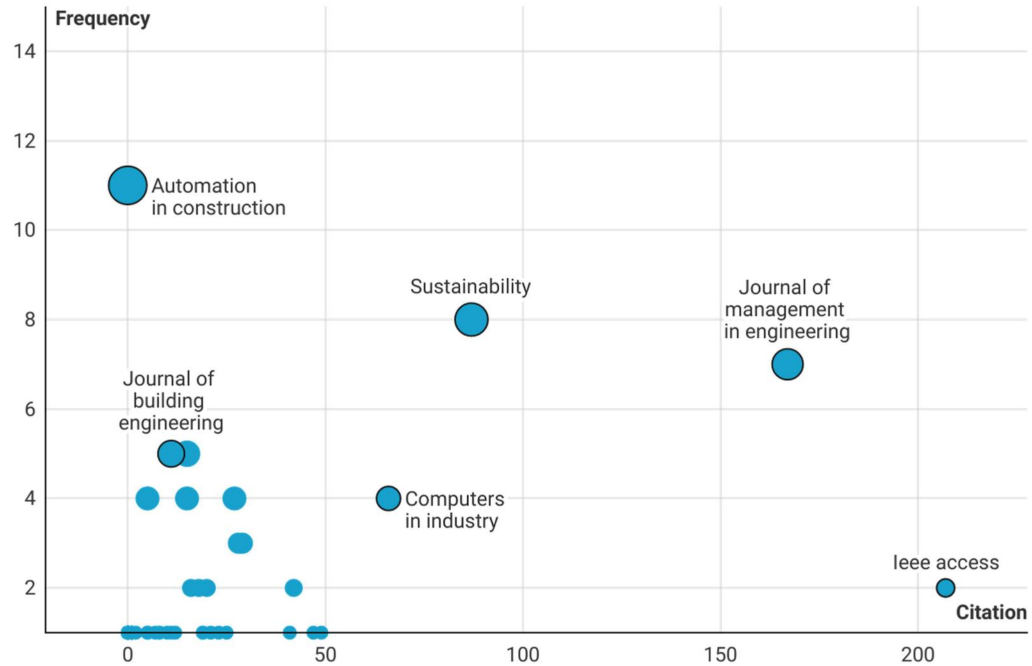

Figure 3. Distribution articles per journal based on frequency and citation. A color-coded map illustrating the distribution of articles across different outlets of publication. Automation in construction generates the most papers on DT, while IEEE Access generates the most citations.

Table 3. Distribution of research method in previous research.

Interval	2019	2020	2021	2022	No. Paper
Pilot case study	0	8	11	4	23
Experiments	1	2	3	1	7
Interview	0	0	0	1	1
Mixed methods	0	4	5	8	17
Concept development	1	5	4	2	12
Survey	0	0	1	0	1
Mathematical modelling	0	0	1	1	2

method (23 documents), followed by mixed methods (17 documents), concept development (12 documents), experiments (7 documents), and mathematical modelling (2 documents). In DT research development, interviews and surveys are among the least preferred methods (see Table 3).

Preliminary case studies, functioning as pilot experiments, have been conducted to investigate the potential applications of DT in the built environment. These case studies encompass many projects, such as buildings, infrastructure, and organizations, as illustrated in Figure 4. Educational facilities emerged as the most prevalent case study subject in DT research, followed by housing and road projects. By comparing the frequency of various research methods, this study identified an imbalance in the current emphasis of DT research.

The considerable number of case studies in DT research shows a strong focus on both the theory and practice of digital twins. This focus on real-world examples indicates the field's maturity and researchers' efforts to better understand DT concepts and their application. The preference for taking case studies from previous studies highlights how DT is used, which place high value of empirical evidence and real-world application. However, the lack of interviews and surveys suggests that the focus of present study may be more towards technology than on the human aspect of DT. Future research can fill this gap by examining user experiences and the human aspect of DT, which will provide a more comprehensive understanding of its applications and benefits.

Using mixed methods, which combine qualitative and quantitative approaches, has been effective in the built environment studies. These techniques offer a deep understanding of both the technological and human elements. The results, however, indicate that the integrative approaches are less common than anticipated. This suggest that DT research may not be taking full advantage of these approaches. Furthermore, the findings also showed that various approaches can differ in how they address certain DT problems. Though they typically lack the broad applicability required for DT usage, case studies often provide useful insights for those who use it. Similarly, depending too heavily on literature reviews may lead to a reiteration of previous findings without making any progress in the results.

The results showed that educational building and housing as typical case studies in DT. The considerable number of these two is mainly due to the wealth of

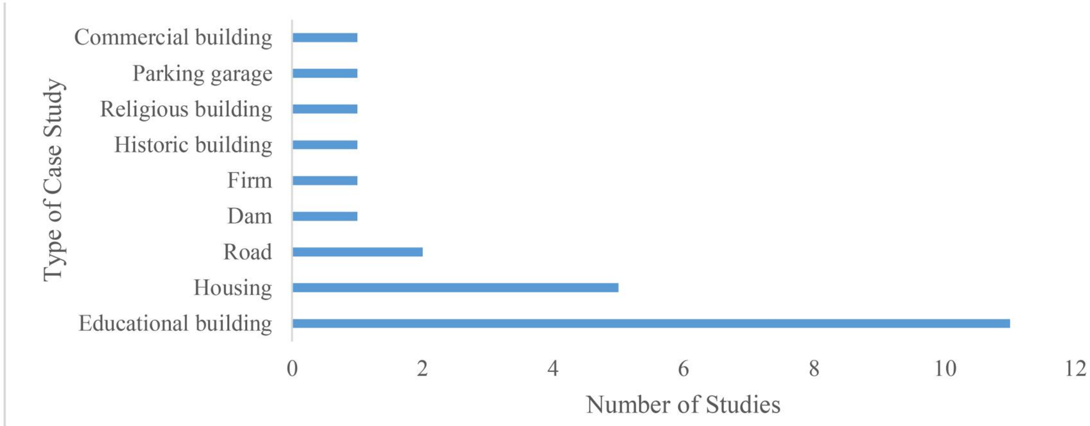

Figure 4. Type of case studies in DT. A bar graph showing different type of case studies. Housing, roads, and other categories (dam, firm, historic building, religious building, parking garage, and commercial building) are utilized as case studies after the educational building.

information they provide. In particular, in developing DT applications, educational buildings offer researchers a useful 'living laboratory' where a variety of spaces in which the researchers are themselves working, including laboratories, classrooms, and administrative areas, can be analysed in terms of multiple layers of operation and usage patterns (Lu *et al.*, 2020a; Seghezzi *et al.* 2021). However, there is a lack of more in-depth analysis of DT in practice within buildings outside of the university context. On the contrary, housing projects may consist of individual homes to complex high-rise apartments, each with distinct characteristics and challenges (Agostinelli *et al.* 2021; Pan and Zhang 2021). This diversity not only improve the research diversity but also contributes to the need of more robust and versatile DT models. Additionally, findings from these sectors are frequently applicable or adaptable to other contexts, which expanding the research's value and scope. As a result, the strategic decision to concentrate on these case studies is not solely motivated by practicality, but rather by the potential for significant, far-reaching, and expandable results.

As shown in Figure 5, most of these case studies are geographically concentrated on European nations, including the United Kingdom, Germany, Austria, Spain, Portugal, the Netherlands, Italy, and Norway. Most types of buildings in Europe, such as educational, housing, apartment, historic, religious, and commercial. Infrastructure projects, particularly on roads are also found as the case study in Europe. On the other hand, case studies from Canada and the United States accounted for 16% of the total in North America. Case studies related to education, housing and apartment were found in this area.

Furthermore, most case studies in Asia (13%) were conducted in eastern Asian region. Countries in this region focus their study on educational buildings, dams, roads, and parking garages. Due to their rapid adoption of technologies, this finding suggests that countries in this region can be used as models for other Asian countries that seek to transform their project towards digitalization. In comparison, only 3% of all case studies in DT research for the built environment came from Australia or South America. This low percentage shows that additional research and implementation in these places may have untapped potential for further development.

Developed countries have adopted DT mostly because of their supporting ecosystems, which foster technological innovation. Due to their enormous financial resources, these nations can make large investments in the study and creation of innovative technologies like DT. Furthermore, the existence of physical infrastructure, including computing, telecommunication, and the internet, is indispensable for the data-intensive characteristics of DT, as it enables effective implementation and operation.

Moreover, the existence of advanced educational and research institutions in developed countries plays a critical role. These institutions offer essential education in digital competencies required to investigate and progress technology in domains such as artificial intelligence (AI), machine learning (ML), and Big Data, all of which are fundamental elements of DT. Industry engagement and investment in DT are also significant in developed countries, and they are further boosted by supportive government policies, such as financial support, tax incentives, and regulatory frameworks. Industries are frequently encouraged to adopt and advance DT solutions by the competitive market environment that is frequently promoted by the combination

Figure 5. Location of case studies. This study presents a map representation illustrating the distribution of case studies on DT throughout various regions, namely Asia, Australia, Europe, North America, and South America. The map is constructed based on previously published scholarly articles, with each case study being denoted by dots to indicate its geographical location.

of government and private efforts, resulting in efficiency and innovation.

The use of DT in the built environment

This section addresses the use of DT in the built environment, focusing on the project and asset stages. The project phase consists of planning, design, material manufacture, transportation, and construction (Wu *et al.* 2014). On the other hand, the asset phase includes building or infrastructure operation, maintenance, and management, following construction completion. Although it plays a significant part during the project life, the end-of-life phase will not be included in the study due to insufficient data during data collection process.

DT adoption have significantly evolved over the years, expanding from traditional domains such as urban planning (Schrotter and Hürzeler 2020), and energy management (O'Dwyer *et al.*, 2020) to newer sectors such as wind farm (Solman *et al.* 2022), airport asset management (Keskin *et al.* 2022), and urban road planning (Jiang *et al.* 2022). This evolution indicates that DT impact and relevance has widened in multiple topics within the built environment. The incorporation of different advanced technologies is essential to this growth. Some research tried to combine one technology with the others such as BIM with ML, Geographic Information Systems (GIS), or the Internet of Things (IoT). These combinations have all been crucial in enhancing DT's capabilities and facilitating DT adoption in real world.

The following section explore the use of DT into the project and asset phases, outlining the uses and its (intended) benefits. It synthesises, critically evaluates, and prioritises the trends of DT in shaping its role in the built environment. This approach seeks to provide a better understanding of DT's current application and potential future avenues, considering both technology advances and larger implications for practice, from the use and user perspectives.

Project phase

In examining the project phase particularly the design and planning stages, four thematic areas were identified: "Urban Planning, Simulation, and Decision Making," "Sustainability and Environmental Concerns," "Building Energy Management and Retrofitting" and "Stakeholder Engagement and Governance." Notably, the theme of "Urban Planning, Simulation, and Decision Making" has received the highest attention with eleven papers (see Figure 6). This trend indicates that more people are relying on DT to improve urban planning processes and provide a better decision-making process. They emphasis towards data-driven methods and simulations in early project stages is shows the intention to make the design process more efficient and predictable.

Participatory and user-centred design is now becoming more popular, and recent study shows the importance to include stakeholders and end users in

Figure 6. Distribution of topics in DT on design and planning and construction. A bar graph displaying DT topics during the design, planning, and construction phases. Urban planning, simulation, and decision making (11 papers) is the most key subjects in design and planning, whereas construction efficiency and process optimization (6 papers) are the most key topics in construction.

the planning and design stages. For example, Dembski *et al.* (2020) used DT for urban mobility while incorporating stakeholders' input. The shift toward stakeholder involvement is also evident in sub-sectors such as energy building or airport management, with research focused on stakeholder-centric approach (Banfi *et al.* 2022; Keskin *et al.* 2022). However, most of these studies appear to place more emphasis on behaviour prediction and user expectation using computational approach, and prototype creation, than on actual user interaction in building of DT frameworks or models and the actual benefits or barriers of using the DTs developped.

In the construction stage, "Construction Efficiency and Process Improvement" emerges as the epicenter theme, with six papers (see Figure 6), demonstrating a substantial focus on optimizing the construction processes using DT. Another significant theme is "Safety and Risk Management in Construction," which underscores the industry's commitment to improving safety protocols and mitigating risks on construction sites through advanced technologies such as IoT, BIM, GIS, mixed reality, and cloud platforms. DT in construction also combines various technologies that is similar to design and planning stage to enhance efficiency and improve project performance. The adoption of technologies like ML, IoT, Big data and many more has demonstrated DT's capability to anticipate potential risks and provide accurate risk mitigation strategies for decision makers (Lee *et al.* 2021; Liu *et al.* 2020).

Furthermore, the use of automation and real-time data management is increasingly recognized as indispensable in construction. Although most findings do not specifically mention the use of large datasets, the integration of sensor data, IoT-BIM-GIS combinations, site inspection, and diagnostic functions highlights the necessity of a data-driven approach to address construction challenges. Angjeliu *et al.* (2020) highlighted DT benefit in optimizing processes through the integration of simulation and prediction (Lee and Lee 2021). Notably, a DT diagnosis in a hospital project resulted in significant improvements in management satisfaction, energy savings, and reduced facility defects (Peng *et al.* 2020), demonstrating the tangible benefits of DT in real-world applications.

A key emerging trend in the project phase of DT is its role in promoting collaboration and improving user experience in the built environment. Studies on user experience, interface design, interaction, and information exchange among users or between physical and digital counterparts (Banfi *et al.* 2022; Lee *et al.* 2021; Tran *et al.* 2021), indicate the growing importance of social and collaborative aspect of DT in project construction. This trend is proven in a project where DT is used to improve worker health and safety in construction site (Ogunseiju *et al.* 2021). Although these discussions often focus on technical and engineering aspects, the findings emphasize the potential social and collaborative implications of implementing DT in construction projects, with human involved in the process.

Asset phase

In the asset phase that focuses on the operation and maintenance stage, two themes has emerge as the

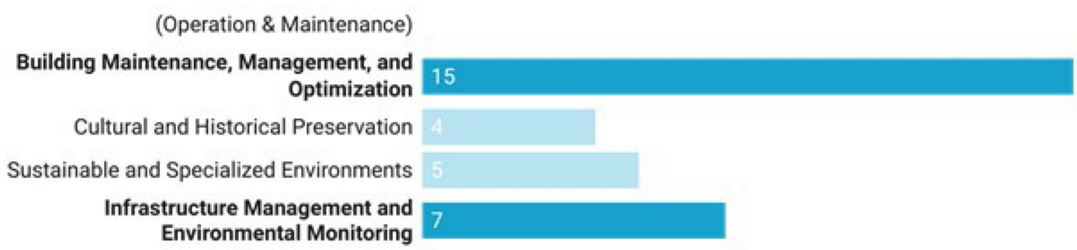

Figure 7. Distribution of topics in DT on operation and maintenance. A bar graph displaying DT topics during operation and maintenance phase. Building maintenance, management, and optimization (15 papers) is the key topic in this phase, followed by infrastructure management, and environmental monitoring (7 papers), sustainable and specialized environments (5 papers), and cultural and historical preservation (4 papers)

dominant theme namely "Building Maintenance, Management, and Optimization" (see Figure 7), both with 15 documents. This number underscores the growing importance of optimizing building performance and operational efficiency. Through DT, strategies for building maintenance and management are being reimagined to enhance building functionality and efficiency. The "Infrastructure Management and Environmental Monitoring" theme has also received notable attention, with seven papers reflecting an increasing interest in applying DT to manage and monitor infrastructure assets, prioritizing their longevity and sustainability. However, themes such as "Cultural and Historical Preservation" and "Sustainable and Specialized Environments" have comparatively fewer papers (4 and 5 documents, respectively). These themes present potential research opportunities, particularly in exploring how DT adoption can preserve building heritage and identity and create sustainable environments in the operation and maintenance context.

The integration of diverse technologies with DT, including but not limited to BIM, IoT, AI, ML, and sensor networks has been a significant trend in this phase. These integrations have expanded the capabilities and functionality of DT systems, facilitating the acquisition, processing, and representation of data in real-time. For instance, Angjeliu *et al.* (2020) emphasized specific information-gathering methodologies in their approach to DT application. The field has seen the incorporation of various advanced software and hardware technologies, as well as innovative data collection methods such as scanners, cameras, and sensors. Various forms of built environment projects, such as buildings, railways, and tunnels, have demonstrated substantial advantages resulting from the utilization of DT for inspection and early warning systems (Kaewunruen and Lian 2019; Lu *et al.*, 2020a; Zhu *et al.* 2021).

Case studies in the literature further demonstrate the potential efficiencies of DT applications in practical settings, ranging from buildings to bridges and container terminals. These pilot experiments offer preliminary insights into the practical applicability and benefits of DT technologies in diverse infrastructural contexts. The findings indicate improved energy conservation, maintenance efficiency, safety, and cost reduction. Tagliabue *et al.* (2021) demonstrated an innovative approach to sustainability assessment by incorporating human behaviour and indoor environmental factors into DT models. Another significant contribution by Yu *et al.* (2021) involves developing semantic ontology to streamline data expression and faults detection in tunnel components, offering practical decision support system for O&M management.

User, actor and/or stakeholder? Different user perspectives in DT

Research in DT demonstrates a trend in which researchers play a significant role as primary users of DT systems (Lu *et al.* 2020b). Researchers are likely to interact directly with the DT, using it as a tool for different purposes (Bartos and Kerkez 2021; Yu *et al.* 2021). The researcher and their team members use the DT to simulate various aspects of the project, ranging from living conditions in residential developments to structural integrity in commercial complexes, with their interaction centered on data collection, analysis, and the generation of simulation models (Agostinelli *et al.* 2021; Hunhevicz *et al.* 2022; Ritto and Rochinha 2021).

In construction projects, key actors including design team, IT team, and engineers will serve as stakeholders rather than as active DT users. Their interaction with DTs will often be limited to providing indirect inputs, feedback, or specific requirements to the research team for DT model implementation. For example, in West Cambridge project, the facility and estate management which are in responsible for overall operation and maintenance, do not have direct interaction with the DT model (Lu*et al.* 2020b). Instead, their function frequently entails developing specifications and requirements ensuring, so that the DT provides decision-making support and interaction that aligns with the operational requirements.

In other scenarios, decision-makers are involved to assess DT adoption and its impact on the organisation or decision-making processes (Fialho *et al.* 2022). Various measures such as interviews, surveys, and focus group discussions are often used to gain insight and feedback from them. This measures along with the need to include stakeholders who are directly involved in study context are aims to address the demands of those who manage or use the project/ product.

There is an emerging trend to involve citizens, especially in urban development projects, as active users of DT systems. For example, in scenarios where individuals use virtual reality to interact with DT models of urban settings, they go beyond the usual stakeholder role (Dembski *et al.* 2020; Ham and Kim 2020). They become instrumental in discovering and reporting urban infrastructure issues, thereby actively participating in the urban planning process. This not only facilitates maintenance and improvement in urban project, but it further enhances the accuracy and effectiveness of urban management and what-if scenarios in a variety of situations.

The current research frequently emphasizes the technical components of DT development, with little attention on user-centered approaches. As a result, user-stakeholder roles and interactions are either underreported or secondary to technical aspects. However, there is a growing need for DTs that respond to the specific needs and contexts of a wide range of users or stakeholders, including industry professionals and citizens. Bridging the gap between theoretical applications and practical, hands-on usage represents a significant opportunity for future DT research and development. Advancements in this area would make DTs more useful in practical situations while also ensuring that these systems are user centric.

The insights from Agrawal *et al.* (2023) about separate roles DT can play from Observer to Action Executor are significant to understanding on how DTs can interact with human and how we differentiate levels of automation. For example, DT can perform as human assistance by gathering, digitising, and conveying surroundings data and supply them to DT operator. This task runs from manually collecting the data to fully automated. The later activity is critical for real-time monitoring and preliminary data processing. In the Analyst role, DT can examine and evaluate previously generated data against user requirements. User can use advanced AI to recognise trends, pattern, forecast results, and monitor conditions. Understanding simple evaluations as well as complex environments requiring significant artificial intelligence use depends on this analytical stage.As Decision Makers, DTs use analysed data to facilitate decision-making processes, using rational logic to select actions that maximise utility via modelling, forecasting, and optimisation methodologies. At this point, the degree of automation consists in risk management, operational efficiency enhancement, and information supply to guide the most successful procedures. At last, as Action Executors, DTs physically implement judgements by actuator or robotic interaction with the surroundings. This role's automation ranges from manual human execution based on DT recommendations to completely autonomous actions, showing DTs' potential to directly influence the physical environment. This classification can help determine the allocation of work duties between humans and DTs, facilitating effective collaboration and addressing the individual needs of diverse user groups. Understanding the balance between automation and human control is critical for developing user-friendly DT systems that can adapt to both routine and complicated scenarios. During the process, it is also important to see how DTs and users will further evolve during and after the interactions to keep improving the human-DT interaction.

Discussion: knowledge gaps on use and user perspectives

Previous review have laid the foundation for a better understanding the complex phenomenon of DT capabilities and application across project life cycle in the built environment. For example, Deng *et al.* (2021) and Jiang *et al.* (2021)emphasised the evolution of DT from BIM to cyber-physical systems, whilst Opoku *et al.* (2021) classified its applications across area like structural monitoring and energy simulation. Ozturk (2021) highlighted other research clusters centred on virtual-physical integration and lifecycle management. However, these studies take a mostly technocentric approach, focusing on technological advancements while giving little attention to sociotechnical elements to the organizational, social, and workflow challenges that influence the integration of DT into existing practices.

This review expands on previous attempts by shifting the focus to use and user perspectives, a vital but under-represented area in DT research. It systematically identifies important barriers to adoption, such as technological complexity, a lack of modularity, and low user interaction during development processes, emphasising areas that need to be addressed further. Furthermore, this research provides practical frameworks for user-centric DT integration, including actionable strategies for improving user interfaces, encouraging participatory design, and improving data management procedures. This study extends previous work by bridging the gap between technical potential and practical acceptance, which expected to be useful for future user-centred DT research and practice in the built environment sector.

Perspectives of multiple users

The study's findings indicate that current research on DT in the AEC industry tends to be researcher-led, with a strong emphasis on using DT for data collection, modelling, and theoretical analysis. The review findings further demonstrated that existing DT literature in the AEC industry predominantly emphasizes technical functionalities, with core components for simulation, real-time monitoring, and data integration, with the variety of user perspectives and diverse stakeholder needs in different contexts examined to a much more limited extent. In other words, the actual adoption of DTs in a large scale beyond pilot projects and the actual users and relevant stakeholders besides researchers' reflections and experience are much less studied. This knowledge gap significantly hinders the evaluation and further development of useful DTs for different stakeholders and the direct users and the roles between DTs and humans are not clearly defined. This is also observed by another study that DT in the AEC industry is still exploratory and experimental, highlighting a gap between their conceptual potential and practical application on different scales such as building, community and city scales for various use cases with different stakeholders and users (Deng *et al.* 2021). To bridge this gap, it is critical to consider the different users involved in the DT development, implementation and improvement processes. These users may include researchers and developers, facility managers, engineers, end-users, and non-professional users, each with distinct roles, levels of interaction, and needs. It is also striking that there are multiple scales in which digital twins are mobilised, from urban scale (emphasise participatory design) to the building scale (emphasise building efficiency). How we can find connections between the different scales and study the opportunities and challenges associated with bridging the different scales is also a point for future research (Chan 2020b).

There are unique challenges and opportunities in the design and implementation of DT. As users, researchers and developers are mostly interested in developing new methodologies, investigating theoretical frameworks, and determining the practicality of DT. They work closely with DT systems, interacting with them across multiple phases of computational design, such as coding, modelling, and early deployment. They need collaborative platforms, advanced computational tools, validation data sets, and financing for research and development. Nevertheless, they frequently encounter challenges in converting theoretical research into useful, practical systems. For end-users, DT is utilized through its interfaces that provide information about the condition of residents environment. They need intuitive and user-friendly interfaces, clear benefits like improved comfort and safety, and privacy protection. Ensuring user acceptance, addressing privacy concerns, and providing adequate support are significant challenges.

This way, users who have already expose about DT and are familiar with particular approaches may seek additional features for deeper data analysis and more complex indicators such as life cycle aspect or sustainability in mind. Conversely, users who are new to DT might need more foundational elements such as user-friendly interfaces and basic data visualization tools. In order to make DT systems more inclusive and efficient, it is necessary to take into account the different roles, degrees of involvement, and requirements of these many user groups. With this strategy, innovation, efficiency, and value creation in the built environment can be achieved in a balanced and integrated manner.

Future research is encouraged to explore practical approaches for converting theoretical DT research into real-world implementation. In order to meet responsibilities and needs of many stakeholders in DT environment, advanced computational tools and platforms must be developed accordingly. Research should focus on creating tools that able to break down DT complexity, so that all stakeholders can use and benefit from DT adoption.

User engagement in DT

The engagement of multiple users in the DT in separate phases of project creates a complex environment in which roles and levels of involvement differ dramatically among user groups, as illustrated in the diverse

DT applications reviewed and analysed (for different phases, different purposes, scales and different types of users). The research findings highlight that, while primary users—typically researchers and DT developers—involve directly with DT systems for simulation and analysis, other important stakeholders, such as facility managers, design teams, and engineers, frequently interact with these systems indirectly. These stakeholders may provide input regarding requirements, feedback, or adjustment necessary for the project/product, which then DT developers include into their models. Although this might seems a good idea, this indirect relationship may limit DT adoption due to little involvement to the project/product itself.

The DT literature in AEC highlights the importance of integrating advanced technological capabilities, such as artificial intelligence, sensor networks, and predictive analytics, to enhance asset monitoring and management. However, studies often place limited emphasis on engaging users throughout the development and implementation stages of DT projects. For example, Banfi *et al.* (2022) underscore that while DT systems have significant potential to transform the built environment, most current implementations lack structured frameworks for ongoing user engagement, resulting in systems that are technically advanced but may not fully align with the practical needs and expectations of end-users.

On the other hand, besides the DT application itself, for the broader picture of citizen participation with DT in use, participatory frameworks have been shown to improve system relevance by involving stakeholders in iterative design and feedback processes for new construction projects, leading to more user-centered urban planning applications (Schrotter and Hürzeler 2020). However, DT research in AEC has yet to widely adopt these participatory design principles. This helps further with the future scenarios on how DTs and humans could work together both in an interactive way and also in a reflective way to improve AEC practice.

The review results highlights the needs to better understand the various DT roles including Observer, Analyst, Decision Maker, and Action Executor and the relationship with the humans for different uses, phases and scales (Agrawal *et al.* 2023). There is no clear guidance on in which uses, how, and on what level human and DTs should collaborate and what role each of them should take in which phase. In other words, current DT systems lack flexible interfaces and role-based access to meet the distinct needs of various users involved in the AEC lifecycle. It is important to understand the different needs from user in various tasks and accordingly design the interfaces between human and DT interaction, such as the role and responsibility division etc, to enable wild adoption of the DTs and the full potential intended. To bridge this gap, future DT research should incorporate feedback loops that allow for continuous adjustments based on actual user interactions, enhancing system relevance and usability across various stages of construction and asset management and support various roles with customized interfaces.

To summarize, current DT development is often limiting user involvement to passive data input rather than active participation in shaping system functionalities and requirements, and also limiting in engaging users as decision makers rather than as data interpreters and the roles between DTs and humans ought to be further studied in a context-specific manner. Practically, to improve user engagement in DT projects, future research should create participatory design frameworks that require active participation from relevant stakeholders. This includes incorporating structured feedback systems from the initial stages of DT development to enable continuous improvements based on actual user data, which has also been observed based on the research methods current studies used. Research should also look into how to successfully involve not just main users such as academics and developers, but also facility managers, engineers, and end-users, ensuring that their feedback is incorporated into the design and implementation of DT systems. Such approaches would not only make DT systems more adaptable but would also enhance the accuracy of data inputs and relevance of insights across various stages of the AEC lifecycle, promoting broader user engagement and maximizing the practical impact of DT applications.

Barrier to user/stakeholder participation

The barriers to user/stakeholder participation are complex and multifaceted, including technological complexity, unfamiliarity with technological capabilities, and the lack of a defined structure for incorporating feedback from human to technology or vice versa (Bilal *et al.* 2016; Kassem and Succar 2017). Early research has demonstrated that user/stakeholder participation is inadequately investigated. Technical or systems interoperability is the primary focus of prior literature published by various authors (Kor *et al.* 2023; Papadonikolaki *et al.* 2016). The complexity of integrating DT with existing asset management systems may prevent users who are not familiar with the technology from fully leveraging it. Furthermore, Kor *et al.* (2023) demonstrated a lack of direct communication between DT developers and end-users (both professional such as architects, engineers, facility managers, contractors, and supply chain partners and non-professional such as citizens, residents, and occupants). This condition may prevent exchange of information and prevent necessary insights to improve DT models.

A possible consequence of such approach is the limited modularity in current DT systems, which results in uniform technical competency across users. Unlike other technology models in AEC, existing DT research has not widely examined modular frameworks that allow different user groups to interact with the system at their level of expertise. For DT research to effectively support multiple perspectives, future studies should focus on developing user-specific interfaces and adaptable data visualizations that can cater to the unique needs of stakeholders across different stages of the project lifecycle (Nochta *et al.* 2021).

For example, in the manufacturing sector, a modular DT system might start with basic monitoring and predictive maintenance modules. As the organisation's DT reach maturity level that has been set, the system can be integrated with more advanced modules such as real-time analytics, process optimisation, and AI-based decision support systems. This adaptability guarantees that the DT system can accommodate different use cases and user requirements, from basic asset tracking to complicated operational processes. Shahzad *et al.* (2022) emphasising this point of view that user interaction and the creation of flexible, modular DT systems is able to accommodate user diversity.

This entails designing user-friendly interfaces to enable users to get overcome technological complexity and misunderstanding of DT capabilities. Studies might also suggest organised feedback systems that would help DT developers and users (both professional and non-professional) to communicate effectively, using modular based approaches. These approaches are supposed to improve seamless integration into current systems and technical acceptance.

Future studies are encouraged to investigate modular, flexible DT systems able to meet changing user requirements at different stages. Modular DT systems provide several important benefits. First, they minimise the initial complexity and cost for new DT technology users by letting them to begin with basic functionality and gradually progress to more advanced features as they become more familiar with the system. Second, modularity promotes scalability, allowing the system to develop alongside the organisation without requiring major overhauls or replacements. Third, this strategy improves participation by offering customised solutions that address the specific demands and maturity levels of different users. Another gap in involving different users for various uses are the gap in data storage, sharing, collection and access for building DTs. The complex nature of data management during the lifecycle of built assets have frequently been disregarded in previous studies. For example, it is encouraged to create accurate metrics and indicators that are applicable from the initial design phase to the end of life cycle such as materials recovery or reprocessing as well as demolition phases but in general this data does not exist. Sun and Liu (2022), Deng *et al.* (2021) and Lavikka *et al.* (2018) discuss the significance of technologies in improving decision-making capabilities, providing data sharing and transparency and offering a better forecasting in building management. Their work supports the discussion on the role of DT in enhancing asset management, emphasizing the importance of robust data management within DT systems but also the needs for transparent data exchange. As demostrated by Kaewunruen *et al.* (2020), DT can improve social and economic advantages through better data management practices. This is consistent with the study's findings that emphasis on the importance of strengthening data exchange protocols to promote better integration between DT systems and existing building management systems, resulting in seamless data flow and improved sustainability indicators.

On the other hand, Broo and Schooling (2023) investigate the critical role of data and DTs in ensuring a sustainable future for smart infrastructure. They advocate for the strategic use of data throughout an asset's lifecycle to enable informed, long-term decision-making. This perspective is consistent with our findings on the creation of safe and scalable data storage technologies, which are critical for the long-term preservation of DT data. Reliability of tracking asset performance over time will highly depends on data preservation, hence DT systems can help to meet sustainability objectives with the help of their efficient contribution. Without the understanding of multiple user perspectives in various phases of using DTs, such data management practice would be very challenging to achieve.

Subsequently, user profiles and their needs can change over time. This feature of transformation presents an interesting area for further study especially in connection with the doubts about identity of users and how DT are applied. The consideration of time as a variable in understanding these shifts in user requirements and perspectives offers a fertile ground for investigation, underscoring the dynamic nature of

DT usage and the interactions with users and its impact on sustainable smart infrastructure development.

Furthermore, using consistent data collection processes across DT applications helps improve the comparability and reliability of indicators. This standardisation can also facilitate data access for users, allowing them to obtain the information they require to make data-driven decisions. By addressing these data gaps, the study contributes to the advancement of DT technology as a tool for promoting sustainability and circularity in the built environment, stressing the innovative and significant contributions to the area.

Conclusions

In this review, research on DT in the AEC industry have often pointed to a number of technical advantages, including but not limited to higher operational efficiency, lower costs, greater decision-making capabilities, increased safety measures, optimal designs and training opportunities. Yet, these studies have tended to be researcher-led, and its widespread use in industry involving professionals and non-professional users (e.g. citizens, residents, and occupants) remains at a nascent stage of development. There is therefore a scarcity of comprehensive studies that explore its practical application and user-centric adoption. This review synthesized the literature concerning the use and user perspectives and discusses its status and application across life cycle stage. Two research questions (the use and the user of DT characterized in previous studies, and knowledge gap and future research direction on the use and user perspectives of DT) that aid in the comprehension of how DT operates were identified and discussed.

The findings highlight a gap between the potential and actual use of DT, particularly in terms of involving different users and stakeholders in the design and implementation process. More research to involve these stakeholders as well as user-centered design approaches are required to fully realize DT potential to improve project/product performance. The growing trend of citizen engagement in DT initiatives, especially in urban development, represents a promising transition away from technological-focused research (BIM, IoT, AI, and many others) and more towards human elements and societal demands into DT models.

Encouragement of multidisciplinary techniques combining data science, user experience design, and interdisciplinary studies to support innovation and efficiency in DT design and implementation is much needed. There is also a need to develop flexible, modular DT platforms to accommodate varying user readiness and expectations, supported by participatory design processes and structured feedback mechanisms. Future studies can also explore scalable, safe data storage options to enable the long-term preservation of DT data, so allowing accurate diversified indicators including project success, sustainability, or circularity and seamless data flow.

Although this study advances our knowledge of the widespread adoption of DT in the built environment, it also reveals multiple barriers that should be addressed in next studies. First of all, language limitations in this study to English-only publications could limit its breadth and hence possibly exclude important insights or results from non-English language research. Thus, including multilingual research would help future studies to provide a more comprehensive review of the matter. Second, the data source for this study was restricted to journal articles from Scopus and Web of Science. As DT technology is in its infancy, there is plenty of undiscovered data in grey literature and conference proceedings which may contain valuable insights that have not yet been documented in the journal type literature. Third, the keywords employed in this study were chosen with the built environment perspective in mind, resulting in the omission of relevant papers that utilized alternative terminology. This constraint may limit the depth of the findings; therefore, future study should explore a broader range of keywords, including those that are not related to the built environment. Last, this study suggests that future research efforts should investigate a variety of methodologies to improve the validity and credibility of their findings. Future studies can cross-validate their findings by incorporating a variety of research methodologies, resulting in more robust and reliable conclusions. This research provides an understanding about DT adoption, but improvement and expansion is necessary to fully comprehend the implications and opportunities of DT adoption in the built environment.

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Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

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