frontiers | Frontiers in Built Environment

TYPE Review
PUBLISHED 13 March 2025
DOI 10.3389/fbuil.2025.1523464

OPEN ACCESS

EDITED BY
Vagelis Plevris,
Qatar University, Qatar

REVIEWED BY
Dimitrios Kraniotis,
Oslo Metropolitan University, Norway
Themistoklis Tsalkatidis,
Norwegian University of Life Sciences, Norway

*CORRESPONDENCE
Mahenthiran Sathiyamoorthy,
mahenthiran.s@vit.ac.in

RECEIVED 06 November 2024
ACCEPTED 18 February 2025
PUBLISHED 13 March 2025

CITATION
Venkateswarlu N and Sathiyamoorthy M (2025) Sustainable innovations in digital twin technology: a systematic review about energy efficiency and indoor environment quality in built environment.
Front. Built Environ. 11:1523464.
doi: 10.3389/fbuil.2025.1523464

Sustainable innovations in digital twin technology: a systematic review about energy efficiency and indoor environment quality in built environment

Natakarani Venkateswarlu and Mahenthiran Sathiyamoorthy*

School of Civil Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India

In the contemporary digital age, the built environment undergoes significant changes because of technological innovations that improve building management, optimize building efficiency, and enhance overall productivity. Digital Twin technology has emerged as an indispensable tool for enhancing indoor environmental quality and optimizing energy efficiency in existing buildings. This demonstrates its similarity to several SDGs, where digital twin technology is key to achieving many of them, especially those relevant to our research: 7. Affordable and clean energy; 3. Good health and wellbeing are the primary outcomes of our study; 9. Industry innovation and infrastructure are the focus of our methodology; and 11. Sustainable cities and communication, to which our research contributes. However, some challenges require further consideration. First, to assess the methods and tools used to monitor and represent environmental parameters. Second, to review previous studies on Digital Twin technology in the context of energy efficiency and indoor environmental quality. This study systematically examined 261 academic articles to address these challenges, identifying 17 relevant publications investigating Digital Twin for enhancing energy efficiency and indoor environmental quality in buildings. The research emphasizes Building Information Modeling, Internet of Things, and Big Data, which collectively improve the monitoring and management of physical assets through real-time data replication. Our research illustrates the need for a multidisciplinary framework to rigorously analyze Digital Twin applications, as a comprehensive understanding of the consequences of this technology requires the integration of different fields. The review emphasizes the confined application of sensors for monitoring the environment, the importance of residents subjective impressions, and the need for further comparative studies on energy use estimation methods. For future investigation, enhanced international collaboration is imperative to improve the scholarly exploration of Digital Twin related to this field. Finally, the built environment can benefit significantly from implementing Digital Twin technology. However, the challenges must be addressed before technology can achieve its full potential for creating sustainable and energy-efficient buildings.

KEYWORDS

digital twin, bim, scientometric review, energy efficiency, indoor environmental quality, buildings

1 Introduction

The built environment continues to evolve in the digital age, with novel concepts and technological advances accomplishing cities, homes, and construction more intelligently for the benefit of their occupants. Digital technologies have been exploited as tools to enhance projects and built environment productivity and efficiency (Manzoor et al., 2021). Table 1 represents an overview of a few applications for Digital Twin Technology. A Variety of heterogeneous digital technologies exist, encompassing including Building Information Modeling (BIM), Internet of Things (IoT), Big Data (BD), Artificial Intelligence (AI), Three-dimensional (3D) printing, Blockchain, and Digital Twin (DT) (Asif et al., 2024). The "DT" designation was initially made available to the public in the year 2010 (Conroy, 2010). DT is an emerging technology that can digitally replicate physical objects. Use DT as a foundational framework to combine different technology systems. Use real-time data obtained from sensors attached to an object to reproduce its behavior, facilitate visualization, perform monitoring, and monitor maintenance process (Author Anonymous, 2024; Madni et al., 2019). DT combines several approaches, such as IoT and BIM, to create digital entities and transfer data from a physical to a digital model. The concept of DT, which relates to optimizing energy efficiency and enhancing indoor environmental quality in buildings, is Illustrated in Figure 1. DT is still in its early stages regarding its implementation in the built environment. However, it has already been applied in many industries, including manufacturing, transportation, agriculture, aviation, and the automobile industry (Deng et al., 2021). DT has been utilized in the construction industry's particular design phase and functions as a virtual model with the aid of BIM because it has considered geometric and contextual data (Kaewunruen et al., 2019; Lin and Cheung, 2020; Lu et al., 2020a). It was also implemented during the building phase to instruct workers on on-site logistics, structural integrity, and musculoskeletal injury prevention (Akanmu et al., 2020; Angjeliu et al., 2020; Greif et al., 2020). The applications of DT improve the climate change impact parameters such as building carbon footprint, building asset performance, fault detection in systems, building occupant comfort, energy efficiency, and CO_2 monitoring (Arsiwala et al., 2023; Cespedes-Cubides and Jradi, 2024; Hosamo et al., 2022; Hosamo et al., 2023b; Jafari et al., 2020). However, energy consumption and indoor environmental quality in the built environment are important factors to consider to improve performance and productivity. People's attitudes toward these parameters vary based on activity, mood, and environmental and personal conditions.

DT experiments are created using various methods and algorithms. DT is already used for thermal comfort monitoring, visualization, tracking, energy management prediction, and optimization for existing buildings (Arowoiya et al., 2024). The scientometric study was based on a review article considering energy efficiency and thermal comfort as factors (Arowoiya et al., 2024). This academic review article reassesses the thermal comfort parameter by the basic principles of indoor environmental quality, which includes a comprehensive examination of all dimensions of indoor environmental quality. By implementing air purification systems, proper ventilation techniques, and an effective humidification process, this assessment facilitates the identification of problems and the formulation of remedial strategies.

Incorporating DT into architectural frameworks increases the energy efficiency and quality of the indoor environment and contributes significantly to achieving various Sustainability Development Goals (SDGs), thus promoting a sustainable future for urban ecosystems. SDG 7: Affordable and clean energy is given top priority. Adopting DT can meaningfully increase the energy efficiency of buildings, resulting in lower energy consumption and related costs. Another important goal is SDG 11: Sustainable Cities and Communities. Using DT can significantly enhance building efficiency, thereby facilitating the development of urban communities that prioritize inclusion, safety, resilience, and sustainability. In addition, reflecting the value of SDG 3: Good health and wellbeing, improved air quality, and amenities in buildings can significantly contribute to the overall wellbeing of residents, representing a key dimension of this goal. Finally, SDG 9: Industry, Innovation, and Infrastructure are emphasized through the integration of advanced technologies such as DT systems in the management of buildings.

The following strategies/methods will be used to achieve these objectives: i) Analyzing the tools and techniques used for parameter monitoring and visualization. ii) Reviewing previous research on DT for energy efficiency and indoor environmental quality, this study provides an iii) comprehensive analysis of the various approaches used for future research.

2 Literature review

2.1 Digital twin

Michael Grieve proposed a DT in 2000 in a course presentation on Product Life Management (PLM). The term DT was coined in 2003 when NASA's technology roadmaps provided the first description of its application, stating that it was used to simulate space conditions and conduct tests in preparation for flight (Tuegel et al., 2011). The concept of DT initially emerged in the aerospace industry and later extended to the manufacturing industry around 2012 (Sharma et al., 2022). Based on (Grieves and Vickers, 2016) DT has three types: DT Instance (DTI), DT Prototype (DTP), and DT Environment (DTE). DTI is a specific physical product that remains linked to it throughout its life; DTP is a prototypical physical artifact that produces a physical model that mirrors the digital model. DT

Abbreviations: DT, Digital Twin; IEQ, Indoor environmental quality; IAQ, Indoor air quality; AR/VR, Augmented virtuality/Virtual Reality; IoT, Internet of Things; BIM, Building information modeling; AI, Artificial Intelligence; ML, Machine learning; PLM, Product life management; GIS, Geographical information system; PRISMA, Preferred reporting items for systematic reviews and meta-analyses; NZEB, Net zero energy buildings; HVAC, Heating, Ventilation, and Air conditioning; ANN, Artificial Neural Networks; LiDAR, Light detection and ranging; IFC, Industry Foundation classes; Lod, Level of development; RIS, Research Information systems; CPS, Cyber-physical systems; BEM, Building energy management; VBM_S, Virtual modeling models; MCTS, Monte Carlo Tree Search; MPC, Model predictive control; BDT, Building Digital Twin; SBS, Sick building syndrome; YOLO, V4 You only look me; O & M, Operation & Maintenance.

TABLE 1 An overview of a few applications for Digital Twin.

Categories	Applications	References
Design and construction phase	Industry 4.0, infrastructure, net zero energy building, Building Digital twinning, visual analytics	Kaewunruen et al. (2019), Desogus et al. (2023), Liu et al. (2023), Moshood et al. (2024), Pregnolato et al. (2022), Tao et al. (2022), Ye et al., 2024; Yoon (2023)
Built environment	Buildings (Simulation, fault detection), carbon emission, predicting monitoring of CO_2 equivalent, cyber-physical systems	Hosamo et al. (2022), Arsiwala et al. (2023), Hadjidemetriou et al. (2023), Koo and Yoon (2024), Lydon et al., 2019; Yoon (2024b)
Operation and Maintenance	Anomaly detection, built asset monitoring Energy consumption and management Footprint, Asset performance	Lu et al. (2020a), Jafari et al. (2020), Agouzoul et al. (2021), 2023; Ni et al. (2023)
Real-time monitoring	Real-time analysis using sensors	Hu and Assaad (2024a), Hadjidemetriou et al. (2023), Es-haghi et al. (2024)

is operated by DTE, which offers a platform for managing and interacting with it.

2.2 Applications of digital twin

DT technology has demonstrated significant importance in various domains, including but not limited to manufacturing, construction, energy, infrastructure, healthcare, and transportation. These represent some main areas where DT technology is applied, as illustrated in Figure 2. Importance of autonomy and DT for future production and it emphasizes the necessity of DT technology for integration, accurate model building, and simulations, which play a crucial role in streamlining manufacturing procedures and preparing for unexpected events (Kritzinger et al., 2018; Rosen et al., 2015). DT in construction involves bidirectional coordination and real-time updates, which improve synchronization between virtual and physical worlds (Madubuike et al., 2022). Building operations and life cycle management may be easily controlled, monitored, and optimized because DT can create virtual models connected to physical assets. Figure 3 shows several topic areas where DT technology is used based on the Scopus database.

DT interactive virtual replicas of structures or infrastructure projects used in the construction trade. Advanced simulation

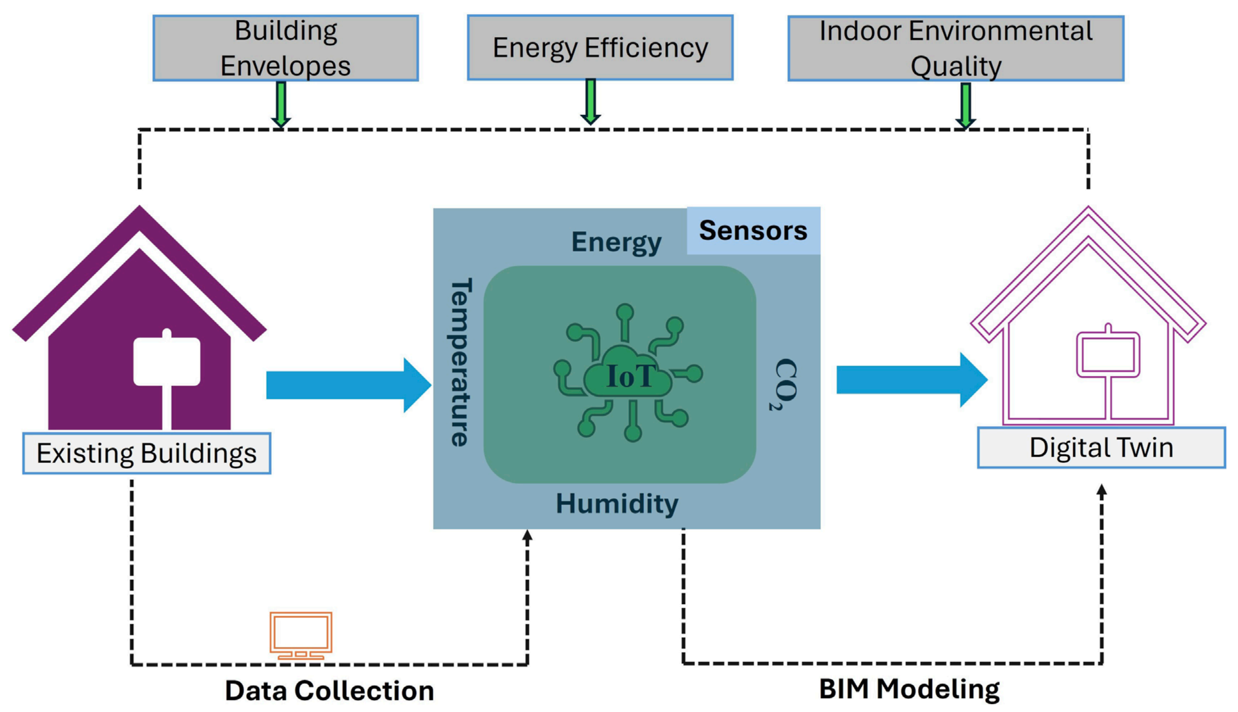

FIGURE 1
The concept of Digital Twin.

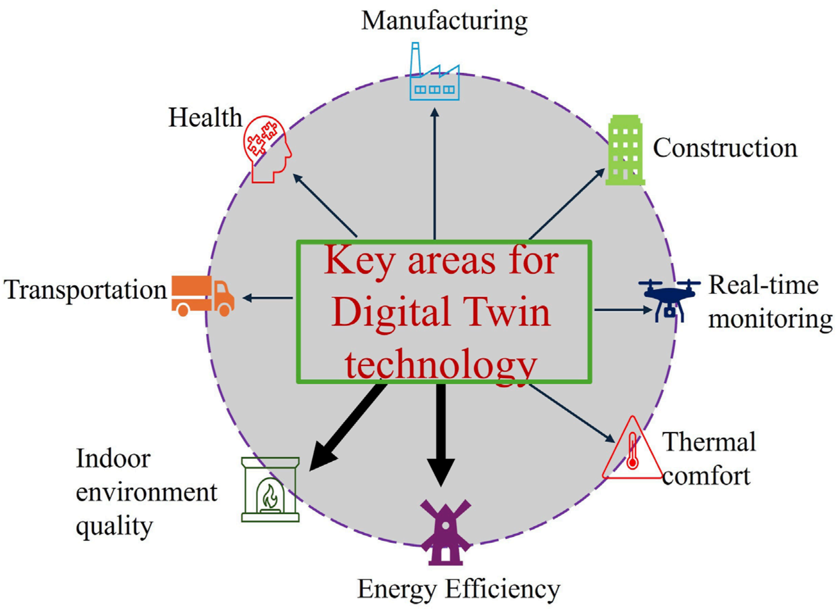

FIGURE 2
A few key areas for Digital Twin technology.

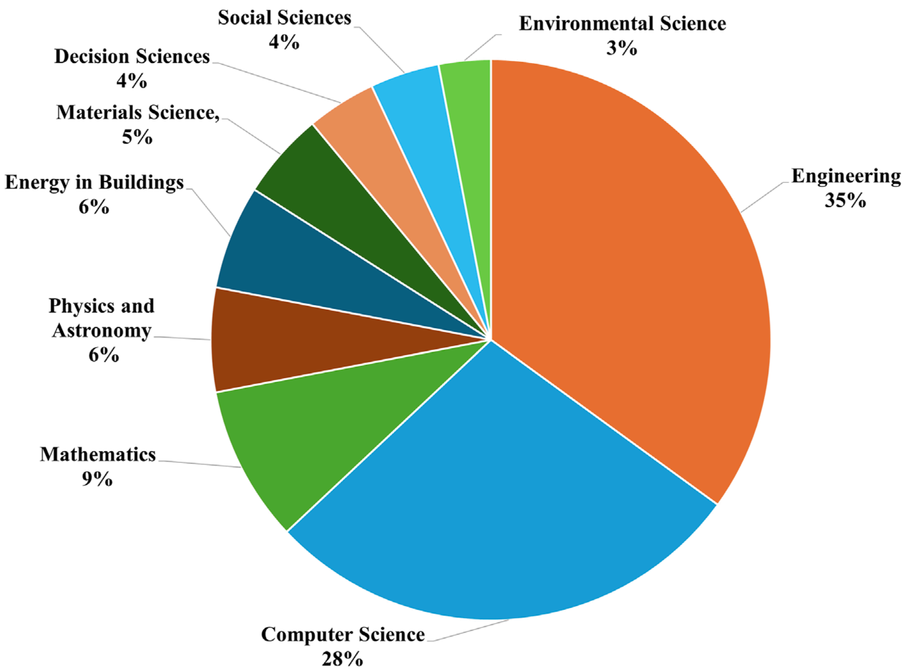

FIGURE 3
Digital Twin applications.

models are also used to construct these virtual replicas, which incorporate real-time data from several sources, including sensors, BIM models, and other IoT devices. Consequently, throughout every project phase, DT enhances decision-making, optimizes performance, and offers insights into the construction process. Development technologies such as BD, Augmented Reality (AR), and Geographic Information Systems (GIS) in the construction industry and discussed various technologies used in the manufacturing industry such as product design, simulation, product forecasting, fault diagnosis, decision-making, predictive maintenance, scheduling, and monitoring (Abanda et al., 2024; Saback et al., 2024) (Table 1).

2.3 Digital twin in the existing buildings

Energy efficiency in existing buildings to improve building energy efficiency to enhance digital technologies such as AI for predictive controls, dynamic BIM for monitoring, and DT for real-time visualization. These technologies can increase energy efficiency by up to 79% while also dramatically lowering expenses and energy usage (Zhou and Liu, 2024). A DT-based framework that evaluates university classrooms energy-saving lighting techniques by integrating occupant behavior, building design, and operating schedules. The DT model allows for quantifying prospective energy savings from methods such as better operation, schedules, and enhanced light source efficiency through the simulation of various scenarios (Seo and Yun, 2022). Simulating actual buildings and utilizing occupant behavior to control lighting and temperature using DT to optimize building energy consumption. This process eventually enables informed decision-making about energy management (Cespedes-Cubides and Jradi, 2024). With the simulation scenario, DT also aids in risk assessment, well-informed decision-making, and accident avoidance. Building system intelligence is further enhanced by integration with IoT technologies (Ghansah and Lu, 2024). DT was used to implement Net Zero Energy Buildings (NZEB) in existing buildings, and a feasibility investigation is ongoing emphasizing renewable technology, energy efficiency, and cost analysis. It accentuates the necessity of precise definitions and rules for NZEBs. It emphasizes the utmost importance of using renewable energy alternatives to achieve sustainability goals while addressing the challenges associated with existing building infrastructure. With an emphasis on improving building envelopes for energy efficiency (Kaewunruen et al., 2019). DT model design using ANN to predict energy consumption in residential buildings in Lebanon. It emphasizes the significance of DT in enhancing the building design processes, overturning a framework for architects and engineers, and improving energy performance in the context of climate change (El-Gohary et al., 2023).

DT technology for indoor environmental quality of existing buildings. This IEQ has four main parameters: thermal comfort, indoor air quality, lighting quality, acoustic comfort, etc. This review focuses on thermal comfort and indoor air quality because many researchers have used DT technology to find thermal comfort and indoor air quality among the remaining parameters. DT framework enabled by BIM that integrates indoor positioning technologies, LiDAR, IoT sensors, and autonomous robotics for real-time indoor environment monitoring (Hu and Assaad, 2024a). Point cloud datasets to address the problem of connectedness identification in building geometry. It presents a surface topology graph to depict interactions between surfaces and suggests a deep geometric neural network architecture for graph reconstruction. Improving DT capabilities for building operation and maintenance (Drobnyi et al., 2024). A methodological way to produce building information models using CAD drawings and photos. It comprises three models: IFC BIM production, building information integration, and structural geometry extraction. It also achieves a Level of Development (LOD) 300 and strongly emphasizes data processing efficiency and cost-effectiveness (Lu et al., 2020b). DT enhances building indoor environmental quality (IEQ) monitoring through three phases: real-time monitoring, visualization, and data integration. Real-time monitoring enables ongoing evaluation of indoor environmental parameters such as thermal comfort and indoor air quality, ensuring a healthy environment for occupants. Visualization makes environmental conditions easily observable, assisting in facility management decisions. For comprehensive environmental assessments, data from IoT sensors and robotics (Hu and Assaad, 2024a). In the context of the COVID-19 pandemic, DT has significant potential for establishing and preserving hygienic indoor settings (Cai et al., 2023).

3 Research method

This review employs scientometric analysis to comprehend the current use of DT in energy efficiency and indoor environment quality in existing buildings. Science mapping analyzes and visualizes scientific areas conceptual frameworks in a substantial body of literature (Cobo et al., 2011; Suleny Bojorquez-Roque et al., 2024). For 10 years (2014–2024), specific keywords such as Digital Twin, energy efficiency, indoor environmental quality, and buildings were used to collect information from the Scopus database. After cleaning duplicates, 261 papers were imported into the Mendeley Reference Manager (MRM) tool and examined with VOS Viewer software. To understand the complex network relationships and to explain existing knowledge gaps in this domain of inquiry, the analysis overlays and visualizes publications in a country and year-wise, document sources, and most cited publications. Figure 4 provides a Prismatic representation of the review paper (Salihu et al., 2022).

3.1 Database and data collection

The primary repository of information for this literature review is the Scopus database, which encompasses many scholarly articles about DT in preexisting structures and their correlation with energy efficiency and indoor environmental quality. Considering the excess of bibliometric data available about alternative databases like the Web of Science and Google Scholar, the field of buildings has been notably underrepresented in academic studies (Meho and Rogers, 2008).

3.2 Strategy for selection of keywords

Using MRM software, the systematic review used the Scopus database to retrieve estimated bibliographic information on selected keywords specific to the research domain. Scopus has established a primary database for keyword selection. It contains many publications compared with the Web of Science and Google Scholar. Keywords coded in that Scopus database TITLE-ABS KEY (((“Digital Twin” OR “Virtual Twin” OR “Virtual twinning” OR “Digital Twinning” AND “Energy efficiency” AND “Buildings” OR “Houses”))) resulted in 254 papers, and similarly coded as TITLE-ABS KEY (((“Digital Twin” OR “Virtual Twins” OR “Virtual twinning” OR “Digital Twinning” AND “Indoor environment quality” AND “Buildings” OR “Houses”))) resulted in 27 papers after applying the exclusion and inclusion

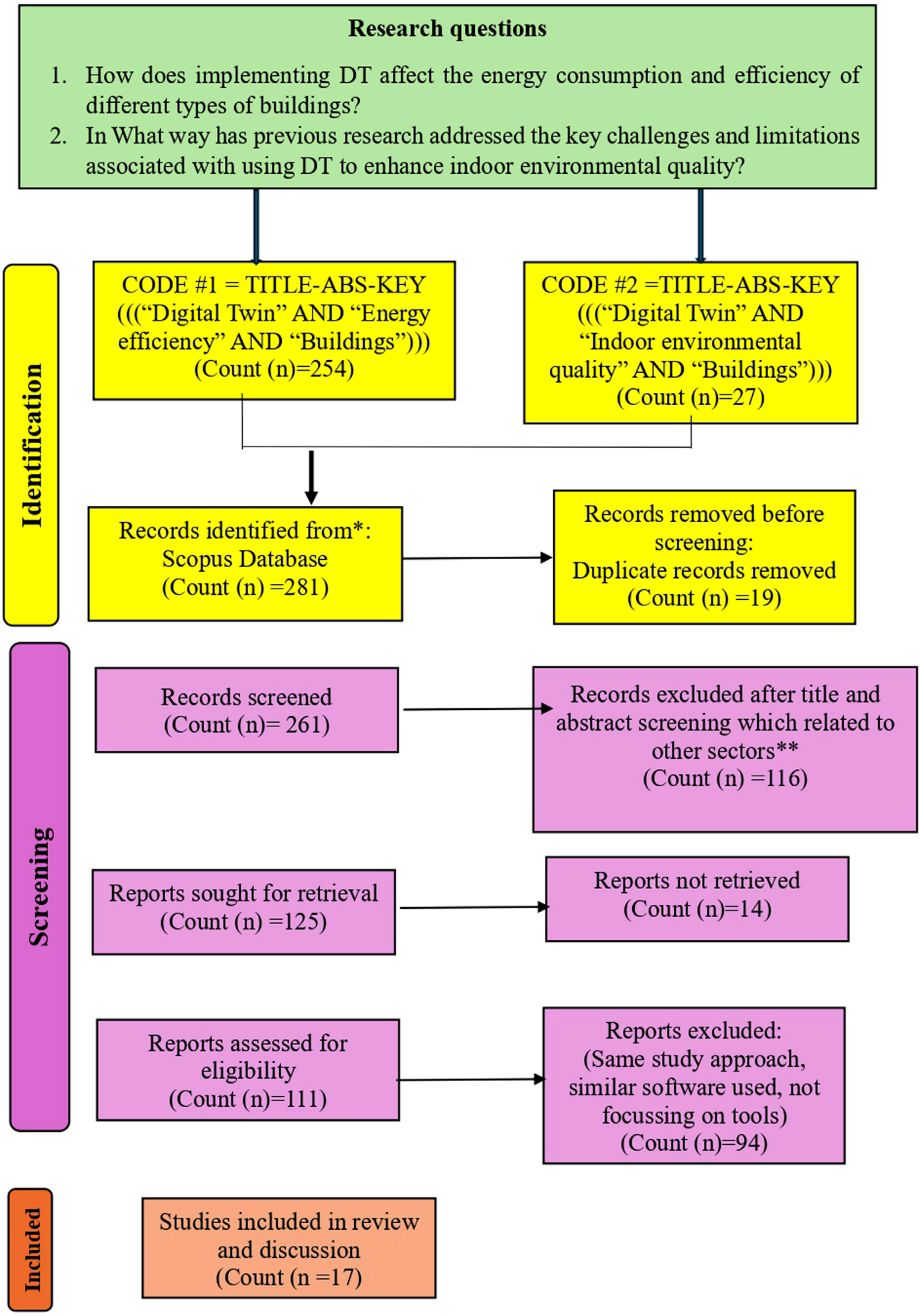

FIGURE 4
Prismatic representation of paper review.

criteria. Papers published in the last 10 years (from 2014 to 2024 in the English language in Engineering, computer science, Energy, Social sciences, Environmental sciences, etc.) met the inclusion and exclusion criteria. When imported to reference managers, 281 publications were discovered in the database.

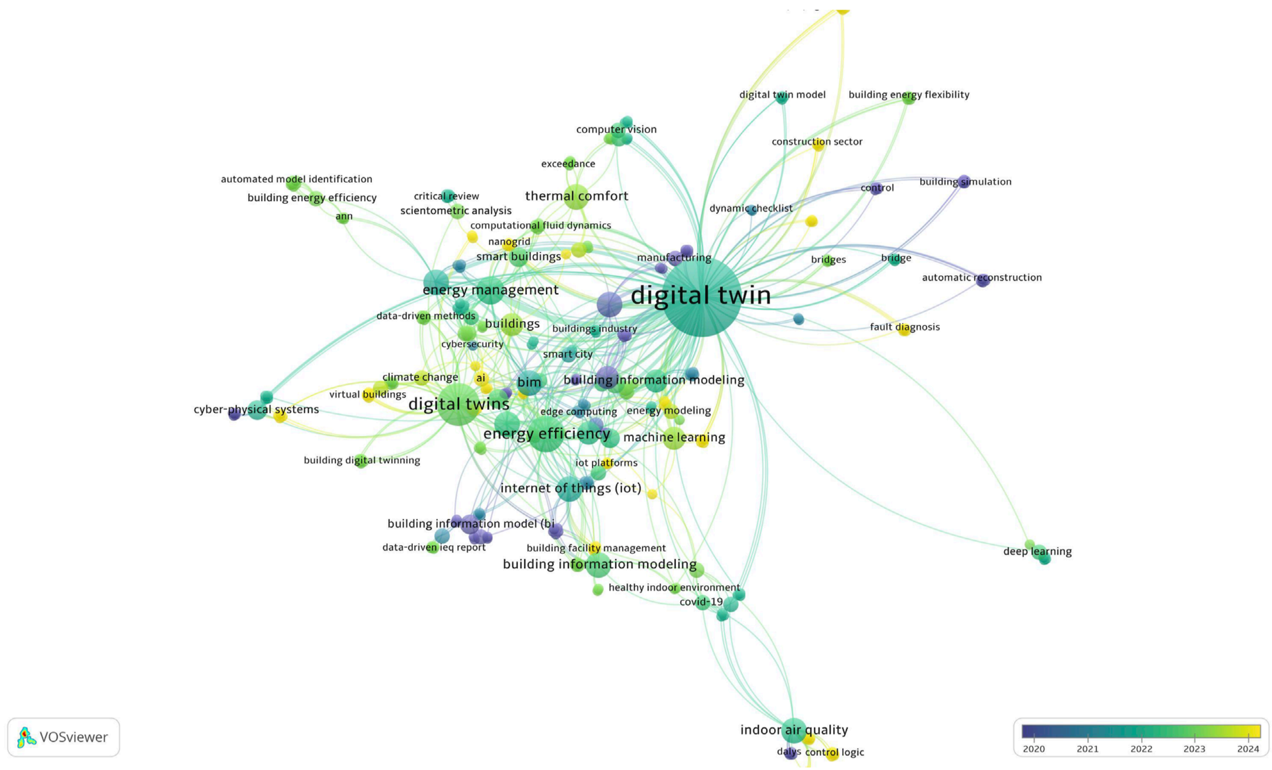

FIGURE 5
Overlay visualization of co-occurrence of keywords.

3.3 Selection of software tools for analysis and review

The scientometric evaluation uses the Scopus database and VOS Viewer software to investigate patterns and trends inherent in research activity. It displays bibliometric maps emphasizing visual aids to evaluate co-authorship and citation networks efficiently (Cobo et al., 2011). The bibliographic information underwent a meticulous review process, resulting in the elimination of duplicate entries. Subsequently, the ensuing articles were utilized to construct a comprehensive map illustrating authorship, countries, sources, and keyword co-occurrence, thereby elucidating the interconnectedness of the network. The keyword co-occurrence analysis facilitates the identification of research gaps within the discipline. It enhances the understanding of the interrelations among the subjects previously investigated by scholars in this domain. Based on the bibliographic information, the data in the Research Information Systems (RIS) file was extracted using MRM software, facilitating the generation of an overlay visualization depicting the co-occurrence analysis of keywords, as illustrated in Figure 5.

3.4 Systematic review steps

This segment elucidates the optimal reporting components for systematic reviews and meta-analyses Preferred reporting items for systematic reviews and meta-analyses (PRISMA) relevant to the article review and the overarching research design. Figure 4 illustrates the methodology employed for extracting files from the database and the procedural steps undertaken to eliminate duplicates and extraneous information from the identified or compiled records. Figure 6 shows an additional overview of the review article.

4 Results

4.1 Year-wise publications

After a comprehensive review of 261 scholarly publications, a total of 116 relevant articles were systematically abstracted and examined. The dominant category was journal articles (n = 67), with a relatively limited number of conference papers (n = 39) and books (n = 10). A yearly breakdown of publications shows that production grew at a slower pace in 2019 (3) and 2020 (6) while experiencing significant growth in 2021 (14), 2022 (23), 2023 (32) and 2024 (38) as indicated in Figure 7.

In 2021, a hybrid approach combining ML and physics-based technologies will be used to create DT in the built environment. Cyber-physical systems (CPS) and BIM highlight cyber security concerns related to DT in the building environment (Alshammari et al., 2021; Lin et al., 2021). Highlighting the uniqueness and expanding interest in this research area in

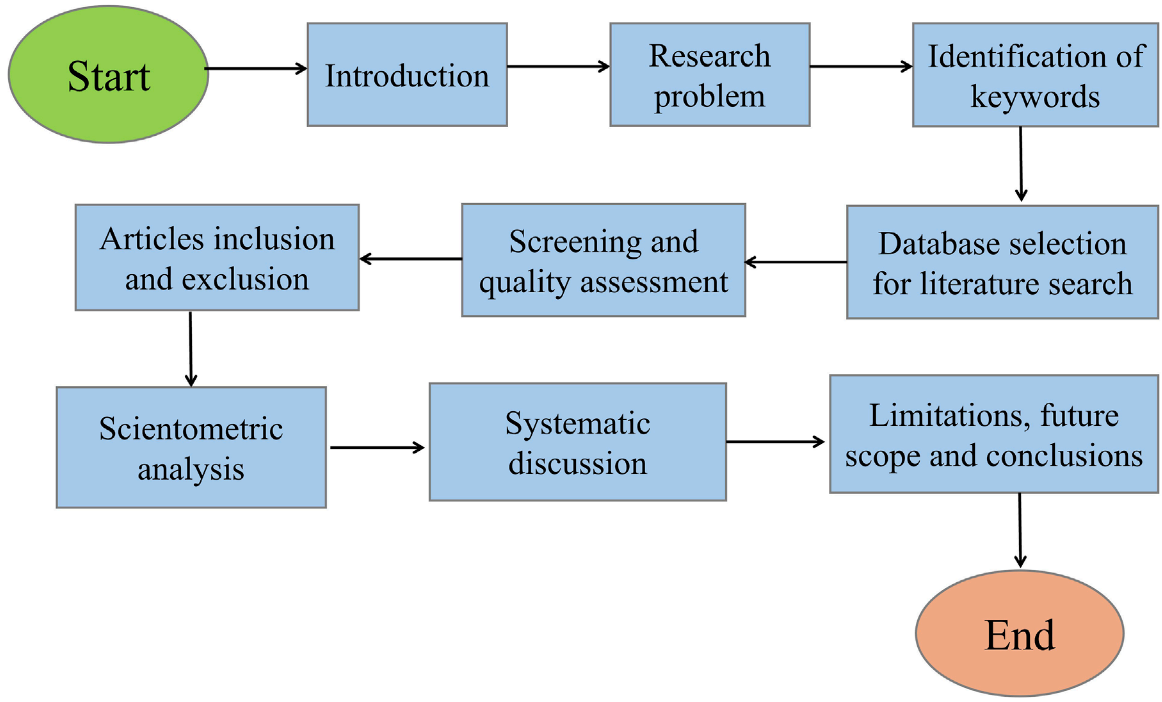

FIGURE 6
Overview of the paper.

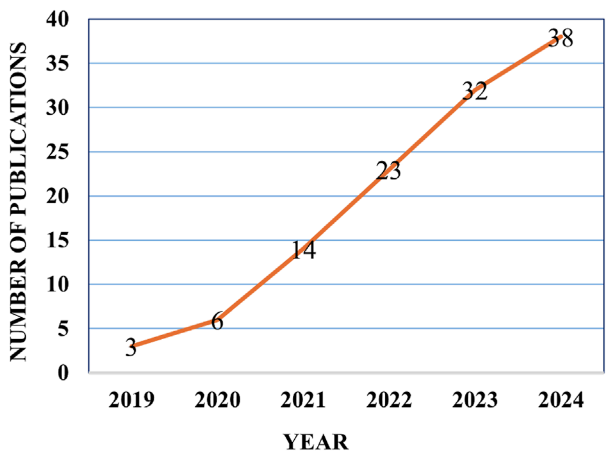

FIGURE 7
Year-wise number of publications.

2022, a Digital Twin Lighting (DTL) system that integrates lighting intelligence with safety features. It analyzes live video feeds, uses YOLOv4 for pedestrian detection, and leverages dynamic BIM to provide a graphical platform for operations and management, integrating DT and green metrics. This concept enhances sustainability planning in smaller buildings and reduces maintenance costs in cities (Corrado et al., 2022; Tan et al., 2022). In 2023, most scholars focused on using DT to enhance building energy efficiency, and they investigated the combination of gray box modeling and building energy management. Using sensor data and thermal energy assessments, it focuses on indoor temperature estimation in a specific zone of an academic facility at Griffith University, improving efficiency and occupant comfort. To develop a framework for energy efficiency assessment of buildings with DT and smart sensors and use dynamic BIM and computer vision to improve energy efficiency can save around 79% (Balali et al., 2023; Jradi and Bjornskov, 2023; Spudys et al., 2023). Virtual Building Models (VBMs) are mathematical representations of actual building behaviors throughout their lifetime, which will be introduced into the built environment in 2024 through VBMs. It has a strong focus on combining *in-situ* modeling with DT technologies to improve decision-making and sustainability in construction activities (Yoon, 2024a).

4.2 Country-wise publications

The total number of publications per country represents two distinct regions using the Scopus database. Figure 8 illustrates a) DT technology for energy efficiency and b) DT technology for indoor environmental quality. China and various European countries are leading research programs on DT aimed at increasing energy efficiency in the construction sector. As illustrated in Figure 8A, India has produced a total of 12 research publications in the last decade. Figure 8B emphasizes the importance of investigating indoor environmental quality, particularly in Europe and Asia, with China, Italy, and the United Kingdom emerging as the most active regions. In the future, India will focus efforts on

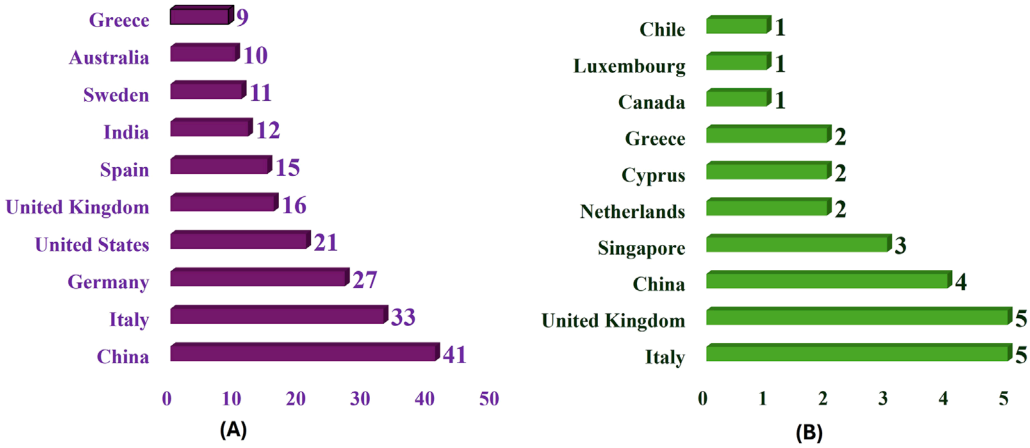

FIGURE 8
Country-wise number of publications of Digital Twin for **(A)** Energy efficiency **(B)** Indoor environmental quality in buildings.

the domain to improve the indoor air quality of its existing buildings.

4.3 Publications per document source

Key areas of study in energy, buildings, and sustainability are highlighted in Table 2, which includes a wide range of academic resources and counts of their papers. The most comprehensive source, seven papers in "Energy and Buildings," highlight the importance of energy-related matters in construction contexts. Six papers, one each on "Buildings and Environment" and "Buildings," focus on structure and environment interactions. Swiss publications with an emphasis on sustainability are particularly prominent. Additional sources address environmental science, energy technology, urban sustainability, and technological advancements. It covers several subjects, with a few papers, including energy informatics, construction automation, and civil engineering. Drawn from various scholarly areas and magazines, this distribution demonstrates a multidisciplinary approach to the subject. Information on the relationship between energy, buildings, and sustainability represents an important priority in research that pays attention to related technical and environmental issues.

4.4 Most cited publications with applications

The highest reference articles on DT technology were examined for this review to determine energy efficiency and indoor environmental quality in existing buildings. 17 publications out of 125 satisfied the requirements (Kaewunruen et al., 2019). most cited publications (146) use digital technologies such as BIM for energy management; the article highlights the application of net zero energy building concepts to existing buildings. Followed by (Tagliabue et al., 2021) 101 citations highlight the DT and the Internet of Things, and the framework enables real-time sustainability assessments. (Lydon et al., 2019). 85 citations mainly refer to developing thermal systems for lightweight buildings. They highlight using automation in simulation procedures to increase productivity and reduce expert user time. Table 3 represents some of the authors with the most citations with applications.

TABLE 2 Summary of the number of publications according to different sources.

Sources	Number of documents
Energy and Buildings	7
Building and Environment	6
Buildings	6
Sustainability (Switzerland)	5
Energies	4
Sustainable Energy Technologies and Assessments	4
Science of the Total Environment	3
Sustainable Cities and Society	3
Developments in the Built Environment	3
Future Internet	3
Building Services Engineering Research and Technology	2
Frontiers in Built Environment	2
Journal of Building Engineering	2
Lecture Notes in Civil Engineering	2
Automation in Construction	2
Energy Informatics	2

TABLE 3 Summary of most cited publications with applications.

References	Citations	Applications
Kaewunruen et al. (2019)	146	The article highlights the application of net zero energy building concepts to existing buildings using digital technologies such as BIM for energy management
Tagliabue et al. (2021)	101	Using DT and the Internet of Things, the framework enables real-time sustainability assessments
Lydon et al. (2019)	85	Development of thermal systems for lightweight buildings to highlight the use of automation in simulation procedures to increase productivity and reduce expert user time
Zhao et al. (2021b)	52	Using DT and BIM for energy efficiency evaluation, it focuses on converting existing buildings into virtually zero-energy buildings using 3D laser scanning to evaluate retrofitting plans
Ghenai et al. (2022)	49	Using DT technology to reduce fuel consumption in many industries is about 63.75% matter. Studies on industrial fuel consumption, increasing sustainability, and energy savings make up 27.5% of the total. Applications related to power generation accounted for 13.75%
Wang et al. (2022)	48	DT can potentially improve urban governance and spur technological innovation. BIM helps with energy-efficient material and design selection to facilitate simulating industrial processes and monitoring real-world systems
Arsiwala et al. (2023)	47	Using IoT, BIM, and AI technologies, the DT system can automate monitoring of comparable CO2 emissions from existing buildings. It seeks to use data to help data-driven retrofitting techniques in the built environment to meet net-zero goals
Clausen et al. (2021)	38	A DT framework manages building heating and ventilation systems that improve occupant comfort and energy efficiency. This allows switching from rule-based control to model predictive control without compromising energy efficiency or comfort
Hosamo et al. (2023a)	34	The framework increases occupant comfort by enabling real-time problem detection in HVAC systems. Examining Sensor data and occupant input assists in predictive maintenance methods
Hosamo et al. (2023b)	27	The approach estimates comfort levels using building performance characteristics and satisfaction surveys. By integrating real-time sensor data, it can identify HVAC problems and improve system efficiency and reliability. The framework achieves energy savings through performance optimization and HVAC system lifetime extension
Petri et al. (2023)	24	DT provides real-time data and insights for better decision-making, improving energy efficiency and sustainability in industrial and construction applications. Using sensors offers advanced monitoring, improves operational effectiveness, and adapts to environmental fluctuations
Spudys et al. (2023)	20	Using DT, smart sensors, and BIM data, the study suggests a framework for operational energy performance assessment that will improve the accuracy of energy assessments. The objective is to enhance the comprehensive understanding of occupant behavior regarding energy consumption and enable energy evaluations
Manfren et al. (2023)	20	This study uses gas-absorption heat pumps and smart thermostatic radiator valves to improve building energy efficiency
Arowoiya et al. (2024)	16	DT improves construction lifecycle management by emphasizing the design, operation, and maintenance phases. By using real-time monitoring and predictive analytics, they increase buildings' thermal comfort and energy efficiency. Applications in DT include decision-making, asset stability optimization, and performance estimation
Tahmasebinia et al. (2023)	15	DT technology optimizes real-time building energy use, including HVAC and lighting systems. It supports energy efficiency assessment and monitoring of indoor environments, facilitating energy control and cost reduction for sustainable buildings
Zhao et al. (2022)	11	This study improves the ventilation designs of public restrooms by increasing indoor air quality and reducing pollutant concentrations. By using computational fluid dynamics (CFD) and DT technologies, efficient ventilation methods can be designed, resulting in healthy environments and energy savings
Hu and Assaad (2024b)	4	Using this framework, the spatial characteristics of air quality at different indoor locations can be efficiently captured, and indoor air quality can be monitored and visualized in real time

5 Systematic discussion

5.1 Digital twin technology for Building energy efficiency

At the global level, energy consumption represents a significant challenge, as an expanding urban population complicates efforts to satisfy the ever-increasing energy demand. The environment is significantly affected by the depletion of energy resources, including climate change, ozone depletion, and global warming. As a result of changes in building design, energy resource transitions, and technological improvements, building energy use has changed dramatically over time.

Energy efficiency in existing buildings has developed significantly because of the need to reduce energy consumption and combat climate change. Many strategies have been used to improve the energy efficiency of ancient and modern buildings, including modern modeling techniques and retrofitting. BIM is becoming a crucial tool for designing energy-efficient buildings, enabling better energy simulations and building thermal system optimization. Research from China has demonstrated how BIM can improve design efficiency and energy standard compliance (Zhao L. et al., 2021). Simulation-based decision support systems have been developed to help investors make educated decisions on energy-efficient solutions, estimating energy consumption after retrofitting (Neves-Silva and Camarinha-Matos, 2022). Using a combination of passive strategies and advanced technology to reduce energy consumption in existing buildings is possible. According to (Pavirani et al., 2023), using demand response algorithms such as Monte Carlo Tree Search (MCTS) can achieve a 4% reduction in energy costs by optimizing heating systems while maintaining thermal comfort. Smart thermostats that detect human activity can save up to 15% in energy by dynamically adjusting set points based on occupancy and facility needs (Mata et al., 2023). Building designs that use thermal mass and passive solar energy can dramatically reduce energy consumption savings by up to 34.71%, which is seen in Mediterranean habitats (Bekele and Atakara, 2023).

Building energy efficiency is being revolutionized by DT, which allows real-time monitoring and optimization of energy use. Ultimately, this technology promotes sustainable behaviors by improving building design, operation, and retrofitting through integration with BIM. Investigates how BIM and DT technologies will be used to improve functional energy assessments of buildings. To bridge the performance gap between asset and operational energy ratings, it proposes a collection of 26 indicators for real-time monitoring and analysis. It highlights the role of digital tools and smart sensors in increasing energy efficiency (Spudys et al., 2023). According to (Kaewunruen et al., 2019), DT facilitates the assessment of NZEB solutions for existing buildings. This enables efficient integration of renewable technologies and accurate cost estimation. Energy consumption analysis can be performed automatically by tools developed using BIM plugins, which significantly helps designers optimize energy consumption during the design phase (Kurniawan et al., 2023). AI-powered simulations coupled with DT can improve building performance through consumption pattern analysis and layout optimization, increasing user comfort and energy efficiency (Almusaed and Yitmen, 2023). The fragmented structure of the construction sector and the demand for specialized personnel in BIM and DT technologies present opportunities but also constraints. To maximize the benefits of energy efficiency, it is imperative to address these gaps through focused training (Alhamami et al., 2020).To improve building occupant comfort and energy efficiency (Clausen et al., 2021), describe a DT framework that utilizes Model Predictive Control (MPC). By integrating occupancy prediction with a multi-objective optimization approach, the methodology demonstrates possible energy savings and improved comfort levels compared to existing management systems (Zhou and Liu, 2024).

A Digital Twin framework for evaluating energy savings strategies for lighting in university classrooms. By controlling occupancy and adjusting lighting, it finds potential savings of more than 60% without the need to replace the system (Seo and Yun, 2022). A computer vision and DT-based method (Tan et al., 2022) for improving interior lighting energy efficiency. The proposed approach significantly reduces energy consumption, savings up to 79.86% by combining real-time data with intelligent control mechanisms. A DT-driven architecture for IoT-based energy trading between intelligent nano grids, improving stability and efficiency. Integrating blockchain for secure transactions and the use of advanced predictive algorithms has revolutionized energy management practices, resulting in a 24% increase in renewable energy use and a 52% reduction in peak demand (Jamil et al., 2024). A cloud-based digitalization framework that utilizes DT, IoT, and AI for energy efficiency and intelligent management of historic structures. The framework uses information collected from environmental sensors to provide analytics and real-time monitoring (Ni et al., 2021).

AI methods and DT will increase energy conservation in the Roman residential area (Agostinelli et al., 2021). It strongly emphasizes improving energy efficiency by combining IoT and providing affordable IT infrastructure for reliable data collection and analysis (Agostinelli et al., 2021). An approach to building energy efficiency using DT to manage issues with thermal parameters and privacy issues raised by residents. Integrating data-driven and mechanism models to provide optimum dispatch speed guarantees fault tolerance and privacy protection. It makes building energy flexibility more effective, which helps achieve carbon neutrality goals (Song et al., 2023)Although much of the research has focused on tracking, monitoring, and optimizing energy efficiency, it has not included applications of DT in this domain recent DT applications for building energy efficiency, as shown in Table 4.

5.2 Digital twin technology for indoor environment quality

As urban growth moves away from adding new buildings towards maximizing existing ones, the environmental quality of such structures has become a significant issue. While they often lack contemporary infrastructure, historic buildings present difficulties in indoor quality management due to antiquated materials and systems that lead to unfavorable environmental conditions (Qian et al., 2024a). Research shows that various pollutants affect residents' wellbeing and health and require proper IEQ management (Qian et al., 2024a). In addition, it has been suggested that integrating cutting-edge technologies such as DT technology and adaptive HVAC systems can improve energy efficiency and indoor environmental quality in heritage buildings, thus addressing the historical context of environmental quality (Zhang et al., 2023). The potential for enhancing the environmental quality of existing buildings by adopting innovative energy management approaches is highlighted, resulting in considerable savings in energy consumption (Borja-Conde et al., 2023). As urban development moves from growth to optimization of built environments, the history of indoor environmental quality in existing buildings has garnered more attention. Studies emphasize how important it is to monitor and regulate indoor environment quality conditions, such as sick building syndrome (SBS), which is brought on by occupants emissions of carbon dioxide (CO_2) and

TABLE 4 Recent applications of DT for energy efficiency.

References	Research method	Tools used	Applications
Cespedes-Cubides and Jradi (2024)	Case study	Arup's Neuron Building twin Autodesk Tandem	Scenario modeling, predictive maintenance, operational optimization, anomaly detection, and component monitoring
Han et al. (2024)	Experimental	Mat lab Unity 3D engine	DT is used in industry, transport, healthcare, and smart cities. Using machine learning, they are developing predictive models for energy efficiency
Aguilera et al. (2024)	Case study	SciPy module for python	Monitoring and optimizing large-scale, fouling-prone heat pumps in real-time. Using a model-based approach for set point optimization improves energy performance
Koltsios et al. (2022)	Experimental	BIM AI	Energy efficiency measurement platform for building DT (BDTs). AI integration for building performance analysis, assessment, and energy efficiency applications for energy consumption correlation in the building design process
Bonomolo et al. (2024)	Case study	DIALux LabView	Thermal comfort study and visualization of buildings, HVAC system optimization, and visual comfort monitoring
Renganayagalu et al. (2024)	Case study	3DF Zephyr Leica BLK 360 Leica Cyclone Unity game engine	They are maximizing energy efficiency with DTs, AI, and IoT sensors. They use real-time data to optimize and assess building energy performance. DTs for buildings are shown in three dimensions for an overview and insights
Kaewunruen et al. (2019)	Case study	Revit Energy +	Prioritize Net Zero Energy Buildings (NZEB) for existing buildings. BIM and hierarchy flow charts are used for evaluation. A prospective framework for NZEB implementations in existing buildings using renewable technology. Feasibility of DT in NZEB buildings for renewable technology
Lu et al. (2020a)	Case study	Autodesk Revit AWS DynamoDB Autodesk Forge API	Monitoring of assets in O&M asset monitoring, Anomaly detection system, and a data integration technique based on extended IFC.
Jafari et al. (2020)	Case study	PMC	Predictive modeling control
Cespedes-Cubides and Jradi (2024)	Case study	Building Energy information systems	Monitor components, detect anomalies, optimize operations, perform predictive maintenance, and create scenarios
Tan et al. (2022)	Experimental	Autodesk Revit Tensorflow used for YOLOv4	Surveillance systems, intelligent lighting systems, and DT lighting systems use the integration of data from multiple sources
Balali et al. (2023)	Case study	OSIsoft WebCTRL server Modbus IP	Energy management, forecasting, and controlling of indoor temperature for buildings and integration of IoT devices and DT.

(Continued on the following page)

TABLE 4 (*Continued*) Recent applications of DT for energy efficiency.

References	Research method	Tools used	Applications
Jradi and Bjornskov (2023)	Experimental	FIWARE TRNSYS EnergyPlus DOE-2	Smart buildings, DT platform applications, comfort, safety, and energy efficiency
Bortolini et al. (2022)	Case study	VOSViewer Excel	Design optimization, occupant comfort, simulation of energy consumption, and building maintenance and management
Dave et al. (2018)	Case study	IoT Sensors BIM Otaniemi3D	IoT sensor for energy consumption, occupancy, and user comfort data. A campus-wide platform for connecting IoT devices and building information models. IoT integration with the built environment is demonstrated through real-world usage scenarios
Fathy et al. (2021)	Case study	IoT smart gateway	Energy efficient home production by optimizing consumption. Efficient energy use using a home-centric energy management system. Real IoT dataset trials for energy optimization were conducted on 17 households

Volatile Organic Compounds (VOCs) (Arsiwala et al., 2023; Chiesa and Vigliotti, 2024a).

DT integrates real-time data from several sensors, essential for monitoring and improving indoor environmental quality in existing buildings. To develop a user-friendly platform that monitors indoor environmental quality parameters like thermal comfort and indoor air quality and pollutants like e CO_2 and TVOC, a DT solution can integrate IoT, BIM, and ML. To create healthier indoor environments, this technology provides real-time insights into the indoor environment and enables future emissions to be predicted. It allows adequate ventilation and air purification systems to be implemented (Arsiwala et al., 2023). Furthermore, the use of DT for adaptive management of HVAC systems increases energy efficiency and guarantees adherence to indoor air quality regulations, protecting both building integrity and occupant comfort (Zhang et al., 2023). Controlling and improving the indoor environmental quality of existing buildings has advanced significantly with the use of DT.

DT technologies have positively impacted various phases of the architecture, engineering, and construction (AEC) sector, incorporating case studies into buildings indoor environments. However, the prevailing scholarly discussion focuses primarily on built infrastructure and urban settings while demonstrating comparatively reduced rigor concerning the landscape sector (Liu et al., 2023). It is crucial to design DT systems, specifically those for indoor building environmental conditions and DT with BIM technologies. In this case study, the model emphasizes using sensors and cameras for data collection to provide real-time identification and dynamic representation of building components. The framework developed is relevant to case studies of indoor settings as it is the basis for effective building management and operational efficiency (Wang et al., 2022). The authors introduce parametric DT for using ontology to model indoor environments in manufactured buildings. DT is combined with deep learning methods in a case study of historic buildings in Osterg, Otland, Sweden. It focused on building indoor temperature and relative humidity prediction models. It demonstrates the potential of a time series dense encoder model for multi-horizon predictions, underscoring the promise of DT technology for indoor environmental optimization (Ni et al., 2023). The authors do not directly cover DT for building indoor environments, but they focus on a case study of a university campus, emphasizing the layered integration of multi-functional models for infrastructure and building lifecycle management. The research demonstrates digital twinning (DODT), highlighting several applications, including condition assessment, construction management, and environmental planning (Chen et al., 2024).

Prior studies have addressed the main barriers to using DT to improve IEQ through integrating several technologies, including real-time data capturing systems, IoT, and BIM. For example, the DT framework was built to monitor and optimize indoor conditions, which addresses data integration and visualization challenges by combining BIM and IoT (Opoku et al., 2024). Furthermore, the accuracy of indoor mapping, which is essential for effective environmental monitoring, has increased with the use of LiDAR-based SLAM to generate high-fidelity point clouds (Hu and Assaad, 2024a). The use of DT optimizes energy performance and operational efficiency. It also gives facility managers insights into energy consumption trends and can enable proactive changes to improve sustainability and comfort (Renganayagalu et al., 2024). A computational framework that analyzes human-generated aerosol and CO_2 buildup in classrooms using CFD simulations and confirmed by *in-situ* observations. It investigates how individual heat sources and breathing momentum flux affect air stratification and aerosol dispersion in a stale air environment. The study highlights the significance of accurate exhaled aerosol and CO_2 modeling (Mahmoud et al., 2024a). A new classification and weighting scheme for IEQ assessment models aimed at improving the relevance and accuracy of assessments. An ensemble hierarchical clustering method is introduced to improve HVAC management practices based on occupancy variety, with the potential to save energy. Using hidden random variables and physical process equations, thermal comfort systems are argued to maximize occupant satisfaction and incorporate lower energy consumption (Karatzas et al., 2024).

IEQ in buildings has been significantly improved by combining AI techniques with DT technologies using real-time data and predictive analytics. By providing an all-inclusive framework that integrates IoT, BIM, and ML. DT facilitates IEQ monitoring and enables efficient data integration and visualization (Qian et al., 2024a). This approach enables rapid assessment and management of air pollution, guaranteeing prompt resolution of IEQ issues. In addition, data from multiple sensors is analyzed using AI technologies such as supervised and unsupervised learning to increase energy efficiency and occupant comfort (Karatzas et al., 2024). Ultimately, managers can bridge the gap between problem identification and subsequent resolution using a DT platform by enhancing the overall welfare and functionality of internal environments. Table 5 represents recent DT applications for indoor environmental quality in buildings.

6 Discussions

The review results illuminate the application of AI and ML in improving preexisting architectural structures. The prevalence and widespread terminologies associated with DTs, AI, BIM, smart urbanism, architectural design, energy efficiency and consumption, and indoor environmental quality parameters corroborate this claim. Moreover, the results emphasize the need for additional research in underexplored domains such as smart grids, energy storage systems, augmented and virtual reality, 5G connectivity, and edge computing. Ongoing investigations in these domains are imperative to comprehensively utilize AI and ML capabilities to optimize intelligent building systems.

The significant number of citations in the seventeen research papers, as indicated in Table 3, demonstrates the depth of research on applying DT for energy efficiency and indoor environmental quality. Although IEQ has received more attention than energy efficiency, the issue of indoor air quality in existing buildings requires additional attention. Figure 8 illustrates that extensive scholarly research has been undertaken in various global regions, including China, Italy, the United States, the United Kingdom, Germany, Singapore, Spain, and India. In future efforts, enhanced international collaboration is hoped to further advance this research area. Urbanization exacerbates the energy consumption problem, which impacts resource depletion and climate change. BIM and DT technologies are essential in increasing energy efficiency in existing buildings. Building energy efficiency has evolved with design and technological advances. DT supports nearly zero-energy buildings (Kaewunruen et al., 2019), which combines real-time data and smart sensors to increase building efficiency. BIM enhances design and compliance. Using advanced simulations and energy trading, AI can further improve energy efficiency. However, to realize the full potential of these technologies, barriers such as industry fragmentation and the need for specialized training must be overcome.

Preserving the environmental integrity of historic buildings has become an essential priority as urban development shifts from constructing new buildings to renovating older buildings. These historic buildings often have IEQ issues due to old materials and systems that negatively affect people's health and wellbeing. Integrating advanced technology such as DT and adaptive HVAC systems is recommended to overcome these issues. IoT, BIM, and ML are combined in DT to use real-time sensor data to monitor and improve IEQ accurately. This technology provides information about indoor variables, including humidity, temperature, and pollution levels. At the same time, it enables predictive analytics, which can improve ventilation and air purification system management. According to empirical studies, DT significantly improves energy efficiency, operational effectiveness, and compliance with IEQ laws. Furthermore, LiDAR-based SLAM for accurate indoor mapping and CFD simulations for aerosol and CO2 modeling can further improve environmental monitoring and ventilation practices. In summary, the integration of AI and DT has the potential to significantly improve indoor environmental quality by enabling real-time building condition monitoring and optimization, which ultimately leads to improved energy efficiency and occupant comfort.

In addition, DT offers many advantages regarding enhancing IEQ and energy efficiency. It offers several benefits over conventional building management techniques. DT allows for the incorporation of real-time data from IoT devices. It allows for ongoing building performance monitoring, which enhances IEQ and energy efficiency and facilitates improved decision-making. With its emphasis on communications and sustainable cities, DT supports the SDGs and encourages inexpensive, renewable energy and health and wellbeing. DT promotes environmental science, engineering, and construction. In addition, the preventive maintenance methods made possible by DT save maintenance costs and interruptions. Finally, DT is a valuable tool for improving performance compared to traditional approaches.

7 Limitations

It is important to acknowledge several limitations when discussing a systematic review of Digital Twin technology for improving energy efficiency and indoor environmental quality. This review focused on English-language publications, potentially omitting key findings from research disseminated in alternative languages. This analysis makes it clear that the use of DT technology in different typologies and geographical settings has not been adequately examined. This study was limited to specific academic disciplines, raising concerns about the representativeness of the research. This may have overlooked significant contributions from different fields, potentially obscuring important insights and applications of DT in different contexts. Synthesis of results proved problematic due to the different methods used in this study. Since different methods may lead to different results, this discrepancy undermines the reliability of the findings derived from the review.

The prominent use of sensors in the reviewed research focuses primarily on baseline data, thereby complicating comprehensive environmental assessments. This suggests that the full potential of DT technology cannot be realized without sophisticated sensor

TABLE 5 Recent applications of DT for indoor environmental quality.

References	Research method	Tools used	Applications
Hu and Assaad (2024a)	Experimental	Arduino UNO Wi-Fi REV2, MQ7 Gas sensor, Insta 360 × 2 360 panoramic camera, ESP32 UWB	DT framework for indoor air quality monitoring and visualization integrates LiDAR, indoor location, sensing, and autonomous robots
Karatzas et al. (2024)	Experimental	ANN, SVM, RF, DT Gradient boosting, XGB, NB, KNN, and Multilayer perception	DT with real-time control and monitoring for energy-efficient buildings. AI/ML methods to optimize indoor conditions and predict thermal comfort
Nair et al. (2022)	Experimental	Air quality sensor Generalized additive model (GAM)	Techniques to improve IEQ through ventilation. Methods for purifying and filtering air to reduce the risk of viral transmission
Cony Renaud Salis et al. (2017)	Experimental	Modeling tools Field measurements	Developing an IAQ metric for residential low-energy buildings. Evaluating contaminants IAQ using a subset of pollutants
Chiesa and Vigliotti (2024b)	Experimental	Energy simulation software, Calibration signature approach	DMV application of control algorithms to improve IAQ in school buildings. In the school building, mechanical ventilation system monitoring and simulation
Yuan et al. (2024)	Case study	Genetic algorithm, Structural Similarity, CFD simulations, Tecplot	Optimizing sensor placement for IEQ monitoring over wide areas. A genetic method for sensor placement optimization in complex indoor settings
Oh et al. (2023)	Empirical	Data-driven IEQ reports, Statistical analysis, IoT-based sensor network	IEQ reports based on data on changes in office occupant behavior. A health-related real-time indoor environmental quality monitoring system
Mucha et al. (2024)	Experimental	Gravimetric method Andersen impactor	IAQ improvement strategies have been modified for use in different types of buildings. They improve IAQ by influencing building design and retrofitting processes—significant technological advances in advanced filtration systems for motorized air conditioning systems
Qian et al. (2024b)	Case study	BLE Sensors MATLAB WeChat Trimble x7 3D laser scanning	Indoor Air Quality Management with IoT-based DT platform. Rapid prediction models for real-time indoor environmental conditions. BLE sensors and BIM are combined to track the location of interior occupants' algorithms for intelligent control of indoor environments in real-time
Opoku et al. (2024)	Experimental	Autodesk Revit, TogoIO API MultiTech Conduit AP for LoRa Technology	The university library uses a DT to monitor internal conditions. They are combining building information modeling with IoT to obtain real-time data

(Continued on the following page)

TABLE 5 (*Continued*) Recent applications of DT for indoor environmental quality.

References	Research method	Tools used	Applications
Babich et al. (2023)	Case study	Mass balance equation Box (EQ-OX)	Assess IAQ and thermal comfort in school buildings based on established criteria. Analyze data on indoor environmental quality and thermal comfort
Mahmoud et al. (2024b)	Experimental	CFD, TSI sensor, BuoyantPimpleFoam solver	They assessed indoor air quality in the classroom environments with CFD. They examined aerosol dispersion, air stratification, and structure with CO_2

applications that capture a diverse range of data. As a result, the findings of this review may soon be outdated, and further research is needed to accelerate progress in this field. This limitation suggests that the research may not have universal applicability, obscuring key opportunities from different contexts. The review highlights the challenges posed by the heterogeneity of study methods. This inconsistency hinders the synthesis of results and negatively impacts the reliability of conclusions drawn from the review. The effectiveness of the DT methodology primarily depends on the efficiency and accessibility of real-time data. The DT technology domain is undergoing rapid evaluation, making the review impractical in a short time. The manuscript recognizes the need for ongoing research to address these developments, suggesting that the conclusions require urgent reevaluation.

The review highlights the need for a multidisciplinary framework to thoroughly investigate the applications of DT technology. However, achieving effective collaboration across different fields can be challenging, leading to oversimplified conclusions that fail to capture the complexity inherent in the topic.

8 Future scope

Future applications of DT technology in optimizing energy efficiency and improving indoor environmental quality in existing buildings are highly encouraging. However, this requires significant technological advances. Recent scholarly research emphasizes the need for better synthesis of real-time data obtained from different sensors to create more accurate digital models of buildings, thus enabling superior monitoring and control of energy consumption and indoor environments. Moreover, expanding sensor usage beyond basic metrics such as temperature and humidity is imperative for holistic environmental assessments. There is a need for research efforts tailored explicitly to specific architectural typologies and geographic contexts. Realizing the operational capability of DT in different climatic conditions and by varying construction regulations will significantly improve its relevance and efficiency. Although the review describes shortcomings in the existing literature, it does not provide comprehensive guidelines for correcting them. Further research should produce clear methodological frameworks for future inquiries in this dynamic domain.

LiDAR technology improves the accuracy of DT by supporting high-resolution spatial information, facilitating indoor mapping, and enabling real-time surveillance and visualization. Implementing advanced predictive algorithms, including deep learning and reinforcement learning methodologies, can significantly enhance energy management strategies. Furthermore, promoting global collaboration and cross-disciplinary studies is crucial to reduce knowledge gaps and optimize DT implementations in practical contexts. These advances ultimately contribute to more sustainable construction practices and improved occupant satisfaction in the former.

9 Conclusion

According to a systematic review, DT technology holds great promise for improving building indoor environmental quality and energy efficiency. DT can be used to create real-time simulations that optimize building efficiency and improve occupant comfort by integrating with various digital technologies, including the Internet of Things and building information modeling. The review findings suggest that integrating DT can lead to significant energy savings and improved construction performance in various building types. The assessment highlights the potential of digital transformation technology to provide analytical insights derived from real-time data to support more informed decision-making at every stage of the buildings life cycle, from design to operation management. However, the analysis also points to several difficulties and limitations of the current application of DT technology. The narrow significance of current research, mainly limited to studies published in English and specific academic subjects, is a serious cause for concern. This can show how broadly the results can be applied and obscure critical perspectives from other fields and geographies. To fill these gaps, we anticipate the need for more research into how well DT works in different building types and locations. To ensure that anyone can use the benefits of DT technology, future research will work to provide standardized procedures for evaluating its effects.

Finally, DT offers a revolutionary opportunity to improve buildings indoor environmental quality and energy efficiency. However, to fully realize its potential, additional research is mandatory to overcome existing challenges. The findings described in the article illustrate the complex interrelationships between technological processes, sustainability theories, and health outcomes, thus underscoring the need for ongoing scholarly exploration and application of DT in the built environment. Conclusions drawn from the review form a framework for further research and advocate for a multidisciplinary perspective to examine different applications of DT in the built environment, ultimately facilitating the advancement of more sustainable and efficient construction technologies.

Author contributions

NV: Conceptualization, Data curation, Methodology, Software, Visualization, Writing–original draft. MS: Investigation, Supervision, Validation, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2025.1523464/full#supplementary-material

References

Abanda, F. H., Jian, N., Adukpo, S., Tuhaise, V. V., and Manjia, M. B. (2024). "Digital twin for product versus project lifecycles' development in manufacturing and construction industries," in *Journal of intelligent manufacturing* (Springer). doi:10.1007/s10845-023-02301-2

Agostinelli, S., Cumo, F., Guidi, G., and Tomazzoli, C. (2021). Cyber-physical systems improving building energy management: digital twin and artificial intelligence. *Energies* 14 (8), 2338. doi:10.3390/en14082338

Agouzoul, A., Simeu, E., and Tabaa, M. (2023). "Enhancement of building energy consumption using a digital twin based neural network model predictive control," in International conference on control, automation and diagnosis, ICCAD 2023, Rome, Italy, 10-12 May 2023. doi:10.1109/ICCAD57653.2023.10152308

Agouzoul, A., Tabaa, M., Chegari, B., Simeu, E., Dandache, A., and Alami, K. (2021). Towards a digital twin model for building energy management: case of Morocco. *Procedia Comput. Sci.* 184, 404–410. doi:10.1016/j.procs.2021.03.051

Aguilera, J. J., Meesenburg, W., Markussen, W. B., Zühlsdorf, B., and Elmegaard, B. (2024). Real-time monitoring and optimization of a large-scale heat pump prone to fouling - towards a digital twin framework. *Appl. Energy* 365, 123274. doi:10.1016/j.apenergy.2024.123274

Akanmu, A. A., Olayiwola, J., Ogunseiju, O., and McFeeters, D. (2020). Cyber-physical postural training system for construction workers. *Automation Constr.* 117, 103272. doi:10.1016/j.autcon.2020.103272

Alhamami, A., Petri, I., Rezgui, Y., and Kubicki, S. (2020). Promoting energy efficiency in the built environment through adapted BIM training and education. *Energies* 13 (9), 2308. doi:10.3390/en13092308

Almusaed, A., and Yitmen, I. (2023). Architectural reply for smart building design concepts based on artificial intelligence simulation models and digital twins. *Sustain. Switz.* 15 (6), 4955. doi:10.3390/su15064955

Alshammari, K., Beach, T., and Rezgui, Y. (2021). Cybersecurity for digital twins in the built environment: current research and future directions. *J. Inf. Technol. Constr.* 26, 159–173. doi:10.36680/j.itcon.2021.010

Angjeliu, G., Coronelli, D., and Cardani, G. (2020). Development of the simulation model for Digital Twin applications in historical masonry buildings: the integration between numerical and experimental reality. *Comput. Struct.* 238, 106282. doi:10.1016/j.compstruc.2020.106282

Arowoiya, V. A., Moehler, R. C., and Fang, Y. (2024). Digital twin technology for thermal comfort and energy efficiency in buildings: a state-of-the-art and future directions. *Energy Built Environ.* 5 (5), 641–656. doi:10.1016/j.enbenv.2023.05.004

Arsiwala, A., Elghaish, F., and Zoher, M. (2023). Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings. *Energy Build.* 284, 112851. doi:10.1016/j.enbuild.2023.112851

Asif, M., Naeem, G., and Khalid, M. (2024). Digitalization for sustainable buildings: technologies, applications, potential, and challenges. *J. Clean. Prod.* 450, 141814. doi:10.1016/j.jclepro.2024.141814

Author Anonymous (2024). Digital Twins The Convergence of Multimedia Technologies. Available at: https://www.computer.org/multimedia.

Babich, F., Torriani, G., Corona, J., and Lara-Ibeas, I. (2023). Comparison of indoor air quality and thermal comfort standards and variations in exceedance for school buildings. *J. Build. Eng.* 71, 106405. doi:10.1016/j.jobe.2023.106405

Balali, Y., Busch, A., and O'Keefe, S. (2023). "Modelling and prediction of energy efficient building climate toward digital twin integration," in *Asia-pacific power and energy engineering conference* (APPEEC). doi:10.1109/APPEEC57400.2023.10561934

Bekele, M. T., and Atakara, C. (2023). Residential building energy conservation in mediterranean climate zone by integrating passive solar and energy efficiency design strategies. *Buildings* 13 (4), 1073. doi:10.3390/buildings13041073

Bonomolo, M., Testasecca, T., Buscemi, A., Alberto Munafo, F. L., and Beccali, M. (2024). "Digital twin-based assessment framework for monitoring visual comfort," in 2024 IEEE 22nd mediterranean electrotechnical conference, MELECON 2024, Porto, Portugal, 25-27 June 2024, 1139–1145. doi:10.1109/MELECON56669.2024.10608560

Borja-Conde, J. A., Witheephanich, K., Coronel, J. F., and Limon, D. (2023). Thermal modeling of existing buildings in high-fidelity simulators: a novel, practical methodology. *Energy Build.* 292, 113127. doi:10.1016/j.enbuild.2023.113127

Bortolini, R., Rodrigues, R., Alavi, H., Vecchia, L. F. D., and Forcada, N. (2022). Digital twins' applications for building energy efficiency: a review. *Energies* 15 (Issue 19), 7002. doi:10.3390/en15197002

Cai, J., Chen, J., Hu, Y., Li, S., and He, Q. (2023). Digital twin for healthy indoor environment: a vision for the post-pandemic era. *Front. Eng. Manag.* 10 (2), 300–318. doi:10.1007/s42524-022-0244-y

Cespedes-Cubides, A. S., and Jradi, M. (2024). A review of building digital twins to improve energy efficiency in the building operational stage. *Springer Nat.* 7 (1), 11. doi:10.1186/s42162-024-00313-7

Chen, G., Alomari, I., Taffese, W. Z., Shi, Z., Afsharmovahed, M. H., Mondal, T. G., et al. (2024). Multifunctional Models in Digital and Physical Twinning of the Built Environment—A University Campus Case Study. *Smart Cities* 7 (2), 836–858. doi:10.3390/smartcities7020035

Chiesa, G., and Vigliotti, M. (2024a). Comparing mechanical ventilation control strategies for indoor air quality: monitoring and simulation results of a school building in northern Italy. *Energy Build.* 322, 114665. doi:10.1016/j.enbuild.2024.114665

Chiesa, G., and Vigliotti, M. (2024b). Comparing mechanical ventilation control strategies for indoor air quality: monitoring and simulation results of a school building in northern Italy. *Energy Build.* 322, 114665. doi:10.1016/j.enbuild.2024.114665

Clausen, A., Arendt, K., Johansen, A., Sangogboye, F. C., Kjærgaard, M. B., Veje, C. T., et al. (2021). A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings. *Energy Inf.* 4, 40. doi:10.1186/s42162-021-00153-9

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., and Herrera, F. (2011). Science mapping software tools: review, analysis, and cooperative study among tools. *J. Am. Soc. Inf. Sci. Technol.* 62 (7), 1382–1402. doi:10.1002/asi.21525

Conroy, M. (2010). Modeling, simulation, information technology and processing roadmap. Available at: https://www.researchgate.net/publication/280310295.

Cony Renaud Salis, L., Abadie, M., Wargocki, P., and Rode, C. (2017). Towards the definition of indicators for assessment of indoor air quality and energy performance in low-energy residential buildings. *Energy Build.* 152, 492–502. doi:10.1016/j.enbuild.2017.07.054

Corrado, C. R., DeLong, S. M., Holt, E. G., Hua, E. Y., and Tolk, A. (2022). Combining green metrics and digital twins for sustainability planning and governance of smart buildings and cities. *Sustain. Switz.* 14 (20), 12988. doi:10.3390/su142012988

Dave, B., Buda, A., Nurminen, A., and Främling, K. (2018). A framework for integrating BIM and IoT through open standards. *Automation Constr.* 95, 35–45. doi:10.1016/j.autcon.2018.07.022

Deng, M., Menassa, C. C., and Kamat, V. R. (2021). From BIM to digital twins: a systematic review of the evolution of intelligent building representations in the AEC-FM industry. *J. Inf. Technol. Constr.* 26, 58–83. doi:10.36680/J.ITCON.2021.005

Desogus, G., Frau, C., Quaquero, E., and Rubiu, G. (2023). From building information model to digital twin: a framework for building thermal comfort monitoring, visualizing, and assessment. *Buildings* 13 (8), 1971. doi:10.3390/buildings13081971

Drobnyi, V., Li, S., and Brilakis, I. (2024). Connectivity detection for automatic construction of building geometric digital twins. *Automation Constr.* 159, 105281. doi:10.1016/j.autcon.2024.105281

El-Gohary, M., El-Abed, R., and Omar, O. (2023). Prediction of an efficient energy-consumption model for existing residential buildings in Lebanon using an artificial neural network as a digital twin in the era of climate change. *Buildings* 13 (12), 3074. doi:10.3390/buildings13123074

Es-haghi, M. S., Anitescu, C., and Rabczuk, T. (2024). Methods for enabling real-time analysis in digital twins: a literature review. *Comput. Struct.* 297, 107342. doi:10.1016/j.compstruc.2024.107342

Fathy, Y., Jaber, M., and Nadeem, Z. (2021). Digital twin-driven decision making and planning for energy consumption. *J. Sens. Actuator Netw.* 10 (2), 37. doi:10.3390/JSAN10020037

Ghansah, F. A., and Lu, W. (2024). Major opportunities of digital twins for smart buildings: a scientometric and content analysis. *Smart Sustain. Built Environ.* 13 (Issue 1), 63–84. doi:10.1108/SASBE-09-2022-0192

Ghenai, C., Husein, L. A., Al Nahlawi, M., Hamid, A. K., and Bettayeb, M. (2022). Recent trends of digital twin technologies in the energy sector: a comprehensive review. *Sustain. Energy Technol. Assessments* 54. doi:10.1016/j.seta.2022.102837

Greif, T., Stein, N., and Flath, C. M. (2020). Peeking into the void: digital twins for construction site logistics. *Comput. Industry* 121, 103264. doi:10.1016/j.compind.2020.103264

Grieves, M., and Vickers, J. (2016). "Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary perspectives on complex systems: new findings and approaches* (Springer International Publishing), 85–113. doi:10.1007/978-3-319-38756-7_4

Hadjidemetriou, L., Stylianidis, N., Englezos, D., Papadopoulos, P., Eliades, D., Timotheou, S., et al. (2023). A digital twin architecture for real-time and offline high granularity analysis in smart buildings. *Sustain. Cities Soc.* 98, 104795. doi:10.1016/j.scs.2023.104795

Han, F., Du, F., Jiao, S., and Zou, K. (2024). Predictive analysis of a building's power consumption based on digital twin platforms. *Energies* 17 (15), 3692. doi:10.3390/en17153692

Hosamo, H. H., Nielsen, H. K., Alnmr, A. N., Svennevig, P. R., and Svidt, K. (2022). A review of the Digital Twin technology for fault detection in buildings. *Front. Built Environ.* 8. doi:10.3389/fbuil.2022.1013196

Hosamo, H. H., Nielsen, H. K., Kraniotis, D., Svennevig, P. R., and Svidt, K. (2023a). Digital Twin framework for automated fault source detection and prediction for comfort performance evaluation of existing non-residential Norwegian buildings. *Energy Build.* 281, 112732. doi:10.1016/j.enbuild.2022.112732

Hosamo, H. H., Nielsen, H. K., Kraniotis, D., Svennevig, P. R., and Svidt, K. (2023b). Improving building occupant comfort through a digital twin approach: a Bayesian network model and predictive maintenance method. *Energy Build.* 288, 112992. doi:10.1016/j.enbuild.2023.112992

Hu, X., and Assaad, R. H. (2024a). A BIM-enabled digital twin framework for real-time indoor environment monitoring and visualization by integrating autonomous robotics, LiDAR-based 3D mobile mapping, IoT sensing, and indoor positioning technologies. *J. Build. Eng.* 86, 108901. doi:10.1016/j.jobe.2024.108901

Hu, X., and Assaad, R. H. (2024b). A BIM-enabled digital twin framework for real-time indoor environment monitoring and visualization by integrating autonomous robotics, LiDAR-based 3D mobile mapping, IoT sensing, and indoor positioning technologies. *J. Build. Eng.* 86, 108901. doi:10.1016/j.jobe.2024.108901

Jafari, M. A., Zaidan, E., Ghofrani, A., Mahani, K., and Farzan, F. (2020). Improving building energy footprint and asset performance using digital twin technology. *IFAC-PapersOnLine* 53 (3), 386–391. doi:10.1016/j.ifacol.2020.11.062

Jamil, H., Jian, Y., Jamil, F., Hijjawi, M., and Muthanna, A. (2024). Digital twin-driven architecture for AIoT-based energy service provision and optimal energy trading between smart nanogrids. *Energy Build.* 319, 114463. doi:10.1016/j.enbuild.2024.114463

Jradi, M., and Bjornskov, J. (2023). "A digital twin platform for energy efficient and smart buildings applications," in 2023 5th international conference on advances in computational tools for engineering applications, ACTEA 2023, Zouk Mosbeh, Lebanon, 05-07 July 2023, 1–6. doi:10.1109/ACTEA58025.2023.10194071

Kaewunruen, S., Rungskunroch, P., and Welsh, J. (2019). A digital-twin evaluation of Net Zero Energy Building for existing buildings. *Sustain. Switz.* 11 (1), 159. doi:10.3390/su11010159

Karatzas, S., Papageorgiou, G., Lazari, V., Bersimis, S., Fousteris, A., Economou, P., et al. (2024). A text analytic framework for gaining insights on the integration of digital twins and machine learning for optimizing indoor building environmental performance. *Dev. Built Environ.* 18, 100386. doi:10.1016/j.dibe.2024.100386

Koltsios, S., Katsaros, N., Mpouzianas, N., Klonis, P., Giannopoulos, G., Pastaltzidis, I., et al. (2022). Digital twin application on next-generation building energy performance certification scheme. *ISC2 2022 - 8th IEEE Int. Smart Cities Conf.*, 1–7. doi:10.1109/ISC255366.2022.9921821

Koo, J., and Yoon, S. (2024). Simultaneous *in-situ* calibration for physical and virtual sensors towards digital twin-enabled building operations. *Adv. Eng. Inf.* 59, 102239. doi:10.1016/j.aei.2023.102239

Kritzinger, W., Karner, M., Traar, G., Henjes, J., and Sihn, W. (2018). Digital Twin in manufacturing: a categorical literature review and classification. *IFAC-PapersOnLine* 51 (11), 1016–1022. doi:10.1016/j.ifacol.2018.08.474

Kurniawan, T. B., Dewi, D. A., Usman, F., and Fadly, F. (2023). Towards energy analysis and efficiency for sustainable buildings. *Emerg. Sci. J.* 7 (6), 2226–2238. doi:10.28991/ESJ-2023-07-06-022

Lin, Y.-C., and Cheung, W.-F. (2020). Developing WSN/BIM-Based environmental monitoring management system for parking garages in smart cities. *J. Manage. Eng.* 36. doi:10.1061/(asce)me.1943-5479.0000760

Lin, Y. W., Tang, T. L. E., and Spanos, C. J. (2021). "Hybrid approach for digital twins in the built environment," in *E-energy 2021 - proceedings of the 2021 12th ACM international conference on future energy systems*, 450–457. doi:10.1145/3447555.3466585

Liu, C., Zhang, P., and Xu, X. (2023). Literature review of digital twin technologies for civil infrastructure. *Elsevier B.V* 2 (Issue 3), 100050. doi:10.1016/j.iintel.2023.100050

Lu, Q., Chen, L., Li, S., and Pitt, M. (2020a). Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Automation Constr.* 115, 103183. doi:10.1016/j.autcon.2020.103183

Lu, Q., Xie, X., Parlikad, A. K., and Schooling, J. M. (2020b). Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Automation Constr.* 118, 103277. doi:10.1016/j.autcon.2020.103277

Lydon, G. P., Caranovic, S., Hischier, I., and Schlueter, A. (2019). Coupled simulation of thermally active building systems to support a digital twin. *Energy Build.* 202, 109298. doi:10.1016/j.enbuild.2019.07.015

Madni, A. M., Madni, C. C., and Lucero, S. D. (2019). Leveraging digital twin technology in model-based systems engineering. *Systems* 7 (1), 7. doi:10.3390/systems7010007

Madubuike, O. C., Anumba, C. J., and Khallaf, R. (2022). A review of digital twin applications in construction. *J. Inf. Technol. Constr.* 27, 145–172. doi:10.36680/j.itcon.2022.008

Mahmoud, M. M. A., Bahl, P. V. de A., Aquino, A. F., Maclntyre, C. R., Bhattacharjee, S., Green, D., et al. (2024a). A numerical framework for the analysis of indoor air quality in a classroom. *J. Build. Eng.* 92, 109659. doi:10.1016/j.jobe.2024.109659

Mahmoud, M. M. A., Bahl, P. V. de A., Aquino, A. F., Maclntyre, C. R., Bhattacharjee, S., Green, D., et al. (2024b). A numerical framework for the analysis of indoor air quality in a classroom. *J. Build. Eng.* 92, 109659. doi:10.1016/j.jobe.2024.109659

Manfren, M., James, P. A., Aragon, V., and Tronchin, L. (2023). Lean and interpretable digital twins for building energy monitoring – a case study with smart thermostatic radiator valves and gas absorption heat pumps. *Energy AI* 14, 100304. doi:10.1016/j.egyai.2023.100304

Manzoor, B., Othman, I., and Pomares, J. C. (2021). Digital technologies in the architecture, engineering and construction (Aec) industry—a bibliometric—qualitative literature review of research activities. *Int. J. Environ. Res. Public Health* 18 (11), 6135. doi:10.3390/ijerph18116135

Mata, O., Méndez, J. I., Ponce, P., Peffer, T., Meier, A., and Molina, A. (2023). Energy savings in buildings based on image depth sensors for human activity recognition. *Energies* 16 (3), 1078. doi:10.3390/en16031078

Meho, L. I., and Rogers, Y. (2008). Citation counting, citation ranking, and h-index of human-computer interaction researchers: a comparison of scopus and web of science. *J. Am. Soc. Inf. Sci. Technol.* 59 (11), 1711–1726. doi:10.1002/asi.20874

Moshood, T. D., Rotimi, J. O., Shahzad, W., and Bamgbade, J. A. (2024). Infrastructure digital twin technology: a new paradigm for future construction industry. *Technol. Soc.* 77, 102519. doi:10.1016/j.techsoc.2024.102519

Mucha, W., Mainka, A., and Brągoszewska, E. (2024). Impact of ventilation system retrofitting on indoor air quality in a single-family building. *Build. Environ.* 262, 111830. doi:10.1016/j.buildenv.2024.111830

Nair, A. N., Anand, P., George, A., and Mondal, N. (2022). A review of strategies and their effectiveness in reducing indoor airborne transmission and improving indoor air quality. *Environ. Res.* 213, 113579. doi:10.1016/j.envres.2022.113579

Neves-Silva, R., and Camarinha-Matos, L. M. (2022). Simulation-based decision support system for energy efficiency in buildings retrofitting. *Sustain. Switz.* 14 (19), 12216. doi:10.3390/su141912216

Ni, Z., Eriksson, P., Liu, Y., Karlsson, M., and Gong, S. (2021). Improving energy efficiency while preserving historic buildings with digital twins and artificial intelligence. *IOP Conf. Ser. Earth Environ. Sci.* 863 (1), 012041. doi:10.1088/1755-1315/863/1/012041

Ni, Z., Zhang, C., Karlsson, M., and Gong, S. (2023). "Leveraging deep learning and digital twins to improve energy performance of buildings," in 2023 IEEE 3rd international conference on industrial electronics for sustainable energy systems, IESES 2023, Shanghai, China, 26-28 July 2023. doi:10.1109/IESES53571.2023.10253721

Oh, J., Wong, W., Castro-Lacouture, D., Lee, J. H., and Koo, C. (2023). Indoor environmental quality improvement in green building: occupant perception and behavioral impact. *J. Build. Eng.* 69, 106314. doi:10.1016/j.jobe.2023.106314

Opoku, D. G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Bamdad, K., and Famakinwa, T. (2024). Digital twin for indoor condition monitoring in living labs: university library case study. *Automation Constr.* 157, 105188. doi:10.1016/j.autcon.2023.105188

Pavirani, F., Gokhale, G., Claessens, B., and Develder, C. (2023). Demand response for residential building heating: effective Monte Carlo Tree Search control based on physics-informed neural networks. Available at: http://arxiv.org/abs/2312.03365.

Petri, I., Rezgui, Y., Ghoroghi, A., and Alzahrani, A. (2023). Digital twins for performance management in the built environment. *J. Industrial Inf. Integration* 33, 100445. doi:10.1016/j.jii.2023.100445

Pregnolato, M., Gunner, S., Voyagaki, E., De Risi, R., Carhart, N., Gavriel, G., et al. (2022). Towards civil engineering 4.0: concept, workflow and application of digital twins for existing infrastructure. *Automation Constr.* 141, 104421. doi:10.1016/j.autcon.2022.104421

Qian, Y., Leng, J., Zhou, K., and Liu, Y. (2024a). How to measure and control indoor air quality based on intelligent digital twin platforms: a case study in China. *Build. Environ.* 253, 111349. doi:10.1016/j.buildenv.2024.111349

Qian, Y., Leng, J., Zhou, K., and Liu, Y. (2024b). How to measure and control indoor air quality based on intelligent digital twin platforms: a case study in China. *Build. Environ.* 253, 111349. doi:10.1016/j.buildenv.2024.111349

Renganayagalu, S. K., Bodal, T., Bryntesen, T. R., and Kvalvik, P. (2024). "Optimising energy performance of buildings through digital twins and machine learning: lessons learnt and future directions," in *2024 4th international conference on applied artificial intelligence, ICAPAI 2024*. doi:10.1109/ICAPAI61893.2024.10541224

Rosen, R., Von Wichert, G., Lo, G., and Bettenhausen, K. D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. *IFAC-PapersOnLine* 28 (3), 567–572. doi:10.1016/j.ifacol.2015.06.141

Saback, V., Popescu, C., Blanksvärd, T., and Täljsten, B. (2024). Analysis of digital twins in the construction industry: practical applications, purpose, and parallel with other industries. *Buildings* 14 (Issue 5), 1361. doi:10.3390/buildings14051361

Salihu, C., Hussein, M., Mohandes, S. R., and Zayed, T. (2022). Towards a comprehensive review of the deterioration factors and modeling for sewer pipelines: a hybrid of bibliometric, scientometric, and meta-analysis approach. *J. Clean. Prod.* 351, 131460. doi:10.1016/j.jclepro.2022.131460

Seo, H., and Yun, W. S. (2022). Digital twin-based assessment framework for energy savings in university classroom lighting. *Buildings* 12 (5), 544. doi:10.3390/buildings12050544

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., and Calinescu, A. (2022). Digital Twins: state of the art theory and practice, challenges, and open research questions. *J. Industrial Inf. Integration* 30, 100383. doi:10.1016/j.jii.2022.100383

Song, Y., Xia, M., Chen, Q., and Chen, F. (2023). A data-model fusion dispatch strategy for the building energy flexibility based on the digital twin. *Appl. Energy* 332, 120496. doi:10.1016/j.apenergy.2022.120496

Spudys, P., Afxentiou, N., Georgali, P.-Z., Klumbyte, E., Jurelionis, A., and Fokaides, P. (2023). Classifying the operational energy performance of buildings with the use of digital twins. *Energy Build.* 290, 113106. doi:10.1016/j.enbuild.2023.113106

Suleny Bojorquez-Roque, M., Garcia-Cabot, A., Garcia-Lopez, E., and Magdiel Oliva-Cordova, L. (2024). Digital competence learning ecosystem in higher education: a mapping and systematic review of the literature. *IEEE Access* 12, 87596–87614. doi:10.1109/ACCESS.2024.3416906

Tagliabue, L. C., Cecconi, F. R., Maltese, S., Rinaldi, S., Ciribini, A. L. C., and Flammini, A. (2021). Leveraging digital twin for sustainability assessment of an educational building. *Sustain. Switz.* 13 (2), 480. doi:10.3390/su13020480

Tahmasebinia, F., Lin, L., Wu, S., Kang, Y., and Sepasgozar, S. (2023). Exploring the benefits and limitations of digital twin technology in building energy. *Appl. Sci. Switz.* 13 (Issue 15), 8814. doi:10.3390/app13158814

Tan, Y., Chen, P., Shou, W., and Sadick, A. M. (2022). Digital Twin-driven approach to improving energy efficiency of indoor lighting based on computer vision and dynamic BIM. *Energy Build.* 270, 112271. doi:10.1016/j.enbuild.2022.112271

Tao, F., Xiao, B., Qi, Q., Cheng, J., and Ji, P. (2022). Digital twin modeling. *J. Manuf. Syst.* 64, 372–389. doi:10.1016/j.jmsy.2022.06.015

Tuegel, E. J., Ingraffea, A. R., Eason, T. G., and Spottswood, S. M. (2011). Reengineering aircraft structural life prediction using a digital twin. *Int. J. Aerosp. Eng.* 2011, 1–14. doi:10.1155/2011/154798

Wang, W., Guo, H., Li, X., Tang, S., Xia, J., and Lv, Z. (2022). Deep learning for assessment of environmental satisfaction using BIM big data in energy efficient building digital twins. *Sustain. Energy Technol. Assessments* 50, 101897. doi:10.1016/j.seta.2021.101897

Ye, X., Jamonnak, S., Van Zandt, S., Newman, G., and Suermann, P. (2024). Developing campus digital twin using interactive visual analytics approach. *Front. Urban Rural Plan.* 2 (1), 9. doi:10.1007/s44243-024-00033-2

Yoon, S. (2023). Building digital twinning: data, information, and models. *J. Build. Eng.* 76, 107021. doi:10.1016/j.jobe.2023.107021

Yoon, S. (2024a). Virtual building models in built environments. *Dev. Built Environ.* 18, 100453. doi:10.1016/j.dibe.2024.100453

Yoon, S. (2024b). Virtual building models in built environments. *Dev. Built Environ.* 18, 100453. doi:10.1016/j.dibe.2024.100453

Yuan, M., Geng, Y., Lin, B., Tang, H., and Yang, Y. (2024). Optimization of indoor temperature sensor deployment in large spaces for multiple building operation scenarios using the genetic algorithm. *J. Build. Eng.* 96, 110446. doi:10.1016/j.jobe.2024.110446

Zhang, J., Chan, C. C. C., Kwok, H. H. L., and Cheng, J. C. P. (2023). Multi-indicator adaptive HVAC control system for low-energy indoor air quality management of heritage building preservation. *Build. Environ.* 246, 110910. doi:10.1016/j.buildenv.2023.110910

Zhao, L., Zhang, H., Wang, Q., Sun, B., Liu, W., Qu, K., et al. (2022). Digital twin evaluation of environment and health of public toilet ventilation design based on building information modeling. *Buildings* 12 (4), 470. doi:10.3390/buildings12040470

Zhao, L., Zhang, H., Wang, Q., and Wang, H. (2021a). Digital-twin-based evaluation of nearly zero-energy building for existing buildings based on scan-to-BIM. *Adv. Civ. Eng.* 2021. doi:10.1155/2021/6638897

Zhao, T., Qu, Z., Liu, C., and Li, K. (2021b). BIM-based analysis of energy efficiency design of building thermal system and HVAC system based on GB50189-2015 in China. *Int. J. Low-Carbon Technol.* 16 (4), 1277–1289. doi:10.1093/ijlct/ctab051

Zhou, Y., and Liu, J. (2024). Advances in emerging digital technologies for energy efficiency and energy integration in smart cities. *Energy Build.* 315, 114289. doi:10.1016/j.enbuild.2024.114289