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The impact of digital technologies on energy-efficient buildings: BIM and AI-based study

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A B S T R A C T

The building and construction sector significantly contributes to global energy consumption and carbon emissions, necessitating the exploration of innovative solutions for sustainability. This study investigates the transformative impact of digital technologies, specifically Building Information Modelling (BIM) and Artificial Intelligence (AI), on the development of energy-efficient buildings. By conducting a comprehensive scientometric and systematic review of 559 publications from 2010 to 2023, the research identifies prevailing trends, significant advancements, and existing challenges in the field. The findings reveal that BIM and AI hold substantial potential for enhancing energy efficiency during the early design and construction stages, facilitating better decision-making, reducing errors, and optimizing resource use. The study also highlights 14 specific categories of significant barriers to widespread adoption. These categories include interoperability issues, knowledge gaps, process complexity, lack of standards, data unavailability, industry resistance, low client interest, high service costs, trust deficits, technical issues, inflated technology costs, workflow inefficiencies, design errors, and role ambiguities. Particularly, interoperability issues, data integration challenges, and high initial costs emerged as the most severe challenges, hindering the smooth implementation of these technologies. These challenges underscore the need for developing robust standards and fostering a culture of innovation within the industry. This paper synthesizes current research, offering valuable insights into the critical role of digital construction technologies in advancing sustainable building practices and outlining directions for future research to overcome existing limitations.

Keywords: building information modelling (BIM); artificial intelligence (AI); energy-efficient buildings; digital construction technologies

Introduction

Humanity faces numerous planetary crises, such as global warming, resource depletion, and environmental degradation [1]. Considering the significant contribution of the building and construction industry to these issues, it is vital to advance sustainable construction approaches, such as energy-efficient buildings [2]. Buildings and the construction sector significantly influence social and economic developments. However, diverse research findings highlight the vast energy and natural resource usage resulting in negative environmental impacts. Globally, the buildings and construction sector generates around 37% of energy-related carbon emissions and over 34% of global energy demand [3]. Addressing this problem requires energy efficiency in the building and construction sector, which involves minimizing consumption to meet necessary environmental requirements. Developing energy-efficient buildings can be perceived as the most direct and effective solution for mitigating the adverse energy consumption by the sector. Khosla & Singh [4] noted that energy-efficient buildings optimise resource use and reduce the negative impact on human health and the environment throughout the building's lifecycle.

The development of various digital technologies in the construction industry offers significant benefits for advancing the construction of energy-efficient buildings [5, 6]. Increasing adoption of these technologies will be beneficial for the industry to understand how digital construction methods, such as Building Information Modelling (BIM) and Artificial Intelligence (AI), have been deployed for developing energy-efficient buildings. Though slower compared to other sectors, the building and construction sector is experiencing an increasing use of various digital technologies [7, 8]. Achieving enhanced integration in construction through advanced Information and Communication Technologies (ICT) is known as digital construction. Deploying digital construction enhances decision-making, reduces rework and waste, and ensures improved quality of work [9]. Considering the increasing adoption of digital technologies in the building design and construction stages, buildings' energy usage can be reduced during operation. Digital technologies such as BIM, AI, and Virtual Reality (VR) are increasingly impacting the development of sustainable buildings. Using digital construction technologies has significant potential to improve the energy efficiency of buildings and achieve sustainability [10-12]. Accordingly, dominant academic fields have outlined the need for digital technologies to decrease the energy use of buildings. However, there is a gap in knowledge and limited literature on the impact of digital construction on energy-efficient buildings. Most existing studies have focused solely on technologies and tools for improving energy efficiency during building operations [2, 13].

Considering the increasing demand for sustainable buildings, a review of existing literature is vital to understand the impact of digital construction on the development of energy-efficient buildings. Thus, this paper aims to identify research trends by examining existing literature on the impact of digital construction, particularly BIM and AI, on the development of energy-efficient buildings. The paper assessed the current state of research, identified different challenges, and analysed the influence of BIM and AI on developing energy-efficient buildings during the design and construction stages. The scope of the research involved a comprehensive review of the literature published between 2010 and 2023, using secondary data and a quantitative methodology combining scientometric and systematic reviews. This paper will critically assess the impact of BIM and AI on energy-efficient buildings and explore practical challenges in deploying digital construction to improve energy efficiency.

Literature review

Digital Construction

There is an urgent need for improved efficiency, sustainability, quality, and productivity in the building and construction sector. However, disappointedly, the construction industry has been slow to adopt new technologies compared to the pace seen in the Fourth Industrial Revolution in other sectors [14-16]. The stagnation in technology adoption is largely attributed to the industry's tendency to resist change. A study by Schober & Hoff [17] showed that 93% of construction stakeholders agree that their construction processes will eventually be affected by new technology, specifically digitalization. The construction industry is currently undergoing a wave of digital technologies aimed at enhancing efficiency and effectiveness, while simultaneously reducing costs and environmental impact [7, 18].

BIM has enabled real-time information interchange and collaboration among different project stakeholders, ensuring visualization, progress simulation, and project optimization. In addition to information management, BIM can be deployed to optimize building performance through building performance simulation and energy efficiency using sensors [19, 20]. Merschbrock & Munkvold [21] and Toyin & Mewomo [22] highlight that BIM improves collaboration and coordination among project stakeholders, leading to more effective project delivery. Shishehgarkhaneh et al. [23] emphasize that to enhance communication among project stakeholders, the deliverables of BIM are categorized into various 'levels of development' to indicate the amount of information and details to be included in the BIM model. The adoption of BIM for building energy simulations is gaining momentum, driven by the increasing demand for enhanced building energy analysis. Pereira et al. [24] conducted a literature review of revolutionary technologies for improving building energy efficiency. The study identified that BIM allows building designers to achieve energy-efficient solutions, enables building owners to maintain them effectively, and helps construction stakeholders to build efficiently. BIM and associated energy simulation tools have been researched to offer different methods to standardize 3D architectural modeling of existing buildings [25]. These technologies can create an interoperable model that facilitates quicker and more reliable energy performance simulations throughout the building's life cycle, with a particular focus on the management phase [26]. The integration of BIM with these simulation tools is increasingly becoming critical for enhancing the efficiency of energy performance assessments in both new and existing buildings. Homayouni et al. [27] outlined that using BIM for design and construction analysis can help project teams achieve energy-efficient targets. However, these studies focused solely on BIM, overlooking the capabilities of other relevant digital construction technologies.

The integration of BIM with other digital technologies, such as AI and digital twins, unlocks enhanced benefits. Craveiroa et al. [28] outline that integrating BIM with AI improves decision-making, conflict management, and structural safety during project development. Long & Li [29] also established that integrating BIM with other digital technologies during design and construction enables energy analysis and recommends alternatives for optimising building design to achieve energy efficiency. Combining VR or Augmented Reality (AR) with BIM can enhance decision-making, manage conflicts, reduce errors, and ensure structural safety through on-site design visualisation before construction commences [30, 31]. Digital construction, in particular, contributes to achieving sustainable building design and construction. A literature review by Bortolini et al. [32] examined the application of digital twins for energy-efficient buildings. The study found that using digital twins can increase buildings' energy efficiency and help maintain appropriate comfort levels for occupants. Deploying the Internet of Things (IoT) and sensors to update the digital twin also optimised building energy efficiency [32, 33]. Deploying AI in the construction industry has increased in recent years due to the need for stakeholders to leverage the capacity of technology to improve the efficiency and performance of construction projects. AI is projected to disrupt the business model of the construction industry, particularly in managing logistics, stakeholders, information, finance, capacity development, safety, waste, and construction workflow [34-36]. Currently, the adoption of AI in construction is still limited compared to other sectors like transportation and manufacturing [37, 38]. However, Pan & Zhang [39] project that more deployments and investments in AI within the construction sector are expected. Companies and industry stakeholders are anticipated to advance AI to increase productivity, prevent cost overruns, enhance site safety, and streamline processes [40]. Implementing AI in construction can be enhanced using BIM as the digital backbone for integrating various systems. Digital construction technologies, like AI, can build and deliver value on the foundation of BIM, providing information that extends beyond the boundaries of a project [41, 42]. Researchers have explored integrating both BIM and AI for design review [43, 44], developing smart buildings [45, 46], waste management [47], construction cost simulation [48, 49], smart construction management [50-52], and energy-efficient buildings [53-55]. AI, when combined with BIM, enables an integrated system that can improve the energy efficiency of buildings. In recent energy efficiency projects, the interactions of integrated design play a more crucial role in making life-cycle energy-saving decisions [56, 57]. This is because, when evaluating design options, it is necessary to consider the results from various simulation tools (e.g., energy, daylighting) within the context of the 3D model [58, 59]. Traditional communication methods can hinder efficient decision-making, making integrated modeling approaches like BIM increasingly important. These approaches visualize energy modeling assumptions and metrics, facilitating the evaluation of suitable alternatives and enhancing stakeholder collaboration.

Energy Efficiency in Buildings

The operations and maintenance of buildings represent the highest energy demand and carbon emissions, with decisions made during building design and conception influencing up to 80% of life cycle energy consumption [53]. This percentage underscores the importance of integrating energy efficiency strategies during the design and construction stages to promote sustainable buildings. Various solutions and systems have been proposed to enable energy efficiency in buildings, particularly during the pre-construction and construction stages. Among others, these include architecture and design solutions [60, 61], building components and envelopes [62-64], decision optimization systems [65, 66], information technology (IT) innovations [67-69], environmental policy instruments [70, 71], and the use of renewable energies [72-74].

Digitalisation is projected to enable a 10% reduction in energy use of buildings by 2040 [75]. Building energy consumption and carbon emissions can be reduced by leveraging digital technologies [5]. Various research outputs have considered the application of new technologies, such as digital construction, for energy efficiency [5, 13, 76]. Otte et al. [2] analysed various case studies and incorporated findings from best practices interviews and government policies. They assessed challenges and opportunities from deploying digitalisation for energy efficiency of building operations. Their research findings affirmed that digitalisation plays a significant role in achieving energy efficiency in the building industry. Kramers & Svane [13] observed that digital technologies could decrease buildings' energy use by gathering information and monitoring energy use and supply. Using a systematic literature review, Casquiço [5] identified technologies that can enhance the energy efficiency of buildings, such as energy simulations, smart grids, IoT, and AI. However, these stud Stumpf ies primarily focus on building operation, often neglecting the design and construction stages.

Deep learning of BIM data through AI can explore alternative approaches to low-energy building management as well as the construction process. Previous studies [15, 36, 46] have primarily focused on integrated systems for energy use management within buildings. However, recent research is evolving to determine optimal operational strategies by integrating AI-learned BIM simulation data [29, 74, 77], not only for energy but also for the entire building management system, including HVAC and ventilation [41, 78]. For the development of energy-efficient buildings, various levels of building energy simulations are necessary, ranging from simple static calculations to sophisticated dynamic simulations. Especially for building retrofits, many assumptions must be made regarding construction, materials, etc., which increases the uncertainty of simulation results [79]. Consequently, various analytical methods, such as an integrated design workflow combining distributed dynamic simulation [80, 81] and statistical analysis using BIM as the base platform [82, 83], are being studied. The experiments generated through this methodology can identify the effects and interaction strengths of various design factors on selected performance indicators, allowing the application of passive design or high-efficiency building materials at the early design stage.

The efficient selection of building envelope components, which directly impacts energy use, plays a crucial role in low-energy building development. Various studies have been conducted in the field of building envelopes, including automated/semi-automated comprehensive energy [48, 52, 84] and whole life-cycle cost analysis using BIM simulations [85, 86]. Research ranges from evaluating energy and economic performance through a series of steps from basic 3D BIM models to final assessment and decision-making, to economic evaluation of construction and operating costs using cost-optimal methodologies. Advanced BIM simulations, such as 5D BIM, are facilitating the development of systems that enable optimal decision-making for energy and cost-efficient envelope components. Many studies [29, 41, 51] are being conducted on how AI and Big Data can provide energy-efficient construction processes in the construction industry and how they can be used to design and operate low-energy buildings [34, 36]. Different researchers focus on recent applications of AI and Big Data to energy-efficient buildings, with an emphasis on the use of machine learning and large databases.

The focus of building owners and users on cost efficiency often prevents them from investing in initial capital costs to ensure building energy efficiency. Implementing energy efficiency requires upfront investments in capacity development, technology installation, and maintenance [87]. In addition to the initial costs associated with achieving energy efficiency in buildings, there is also a lack of knowledge, information, and access to climate-friendly technologies. Hafez et al. [88] indicate that energy efficiency challenges in buildings include a lack of experience, data, models, methods, and systems. The conservative institutional characteristics of the construction sector have led to a low priority being given to sustainability, thus hindering the implementation of energy efficiency policies [89]. Given these challenges in achieving energy efficiency in buildings, there is an urgent need for innovative tools and methods to facilitate improvements.

Research Methodology

This paper utilizes secondary data and adopts a quantitative methodology that involves visual and logical analysis of a large corpus of publications to assess, map, and identify structural patterns in a research domain. In the first stage, the study conducts a scientometric review of existing literature to identify the use of digital construction, particularly BIM and AI, for energy-efficient buildings. Using scientometric review is crucial for synthesizing patterns, understanding research directions and frontiers, extracting outcomes from published research, and analyzing the performance of authors within a research area [90, 91]. The combination of the following keywords is used to derive an all-encompassing result from the scientometric review.

Criteria keywords

1. “Digital Construction” AND “Building” AND “Energy Efficiency”
2. “BIM” AND “Building” AND “Energy Efficiency”
3. “Artificial Intelligence (AI)” AND “Building” AND “Energy Efficiency”
4. “Building Information Modelling (BIM)” AND “Artificial Intelligence (AI)” AND “Energy-Efficient Buildings”

The study refined the results to include only literature published in English between 2010 and 2023 under a global geographical scope (no country restrictions). Multiple scientific databases were used for the literature search, including Scopus, Web of Science, and ProQuest. The search included only three publication types: journal articles, conference proceedings, and e-book sections. Other publication types, such as government documents and technical reports, were excluded to avoid ambiguity in the metric research data. These literatures were analyzed using various software, including EndNote (20), Microsoft Excel, and VOS viewer (version 1.6.19). A total of 1,810 publications were found from the initial search within the three scientific databases. These publications were collated and indexed into EndNote (20) as seen in Figure 1.

Later, 278 publications were removed as overlapping duplicates from the databases. Subsequent manual review of the titles and abstracts resulted in the exclusion of 973 less related publications. After removing these duplicates and less related publications, the research data of 559 publications were finally exported from EndNote into Microsoft Excel to create charts for publication year, journal ranking, and conference ranking. The research data of 559 publications were also exported to VOS viewer (version 1.6.19). Using VOS viewer, the visualization of analyzed data from the scientometric review includes co-occurring keywords and author analysis. After that, a systematic review was conducted, including detailed analysis of the abstracts, titles, and conclusions of the 559 publications, with three criteria for selecting the publications as below.

1. Review all the contents to identify the strongly related research to the theme of this study.
2. Conduct a search of challenges and limitations to identify the literature that outlined the challenges of digital construction on energy-efficient buildings.

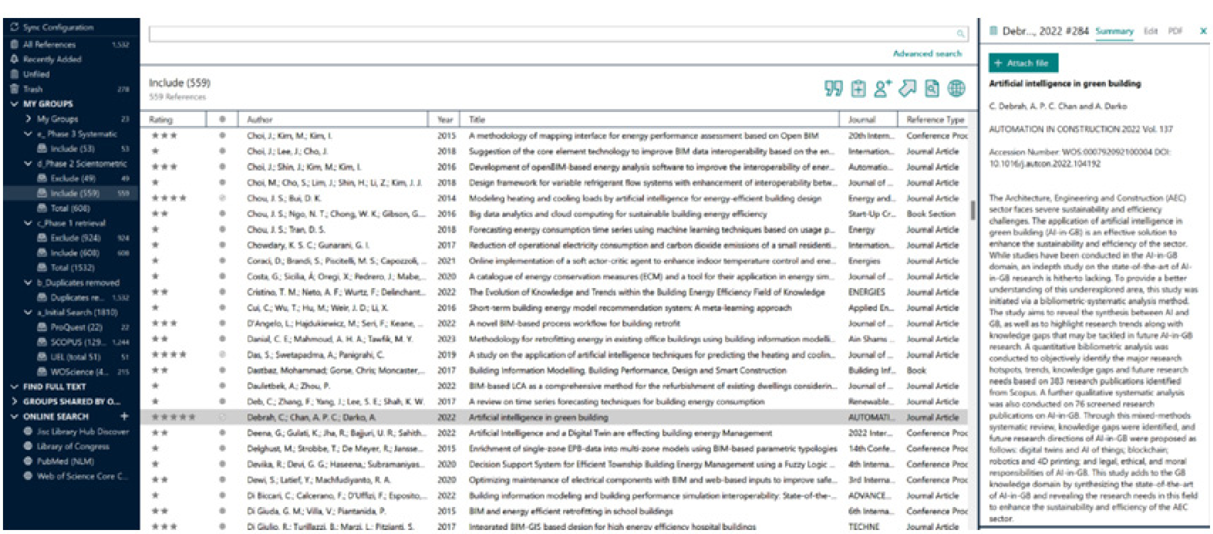

Figure 1. EndNote to collate and index the literature from scientific databases.

3. Evaluate the literature based on their relevance to this study (Figure 1 indicates the approach for rating related literature in EndNote. Only literature with two stars and above are included in the systematic review).

As a result, a total of 53 research publications were selected for the systematic review. The selected publications are outlined in the Appendix. The outline of the literature selection process is detailed in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) chart in Figure 2 below. After identifying the literature for the systematic review, an additional in-depth review was conducted to identify the challenges and limitations of BIM and AI on energy-efficient buildings. The review generated and categorized the challenges outlined in the different literature. The overlapping usage of BIM and AI for energy efficiency was also identified to outline the frequently adopted roles that these technologies influence. The outcomes were analyzed using frequencies, percentages, and rankings and are presented in tables, figures, and texts.

Analysis

Keywords Co-occurrence Analysis

The analysis of keyword co-occurrence was conducted in VOS Viewer based on a selected pool of 559 literature pieces, using a minimum occurrence threshold of four, a method similarly employed by Wu et al. [92] and Aghimien et al. [93]. Keyword co-occurrence analysis is an effective analytical tool for gaining insights into various research domains, specific research

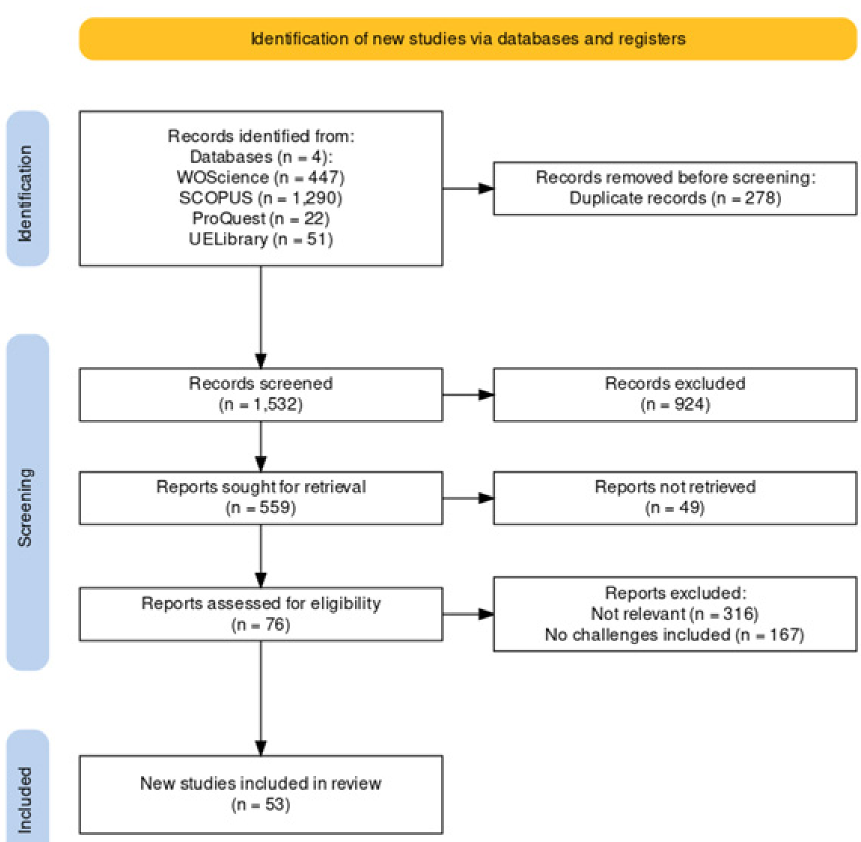

Figure 2. PRISMA flow diagram for the literature.

methodologies, and even interdisciplinary fields being explored, allowing for a comprehensive understanding of a large body of literature at a glance [94, 95]. Out of the 3,545 keywords in the research dataset, 367 keywords met this threshold. Figure 3 below depicts the network visualization of the total link strength for the keywords' co-occurrences. Colors, circles, and lines visualize the interrelationships between the keywords. The frequency of a keyword occurrence is represented by the size of the circle, with larger circles indicating higher frequency. The thickness of connecting lines indicates the link strength, while distance indicates affinity strength. Multiple lines between keywords indicate multiple co-occurrences, and the colors represent clusters.

According to VOS analysis, the keyword with the largest occurrence is "Energy Efficiency", appearing 472 times with a total link strength of 4,992 in the red cluster. The next keyword with the highest occurrence is "Architectural Design", appearing 336 times with a link strength of 3,904 in the blue cluster. Other keywords with high occurrences within the research data include "Building Information Model", "Sustainable Development", "Artificial Intelligence", and "Buildings". Out of the 367 keywords that met the threshold, the keywords with the lowest total link strength include "semantic web", "computer aided analysis", "emerging technologies", and "comfort". The low link strength indicates that these keywords are rarely used in research regarding BIM and AI for energy-efficient buildings.

Interestingly, the frequency of occurrences of keywords in "building information model" (BIM) and "artificial intelligence" research was found to be lower

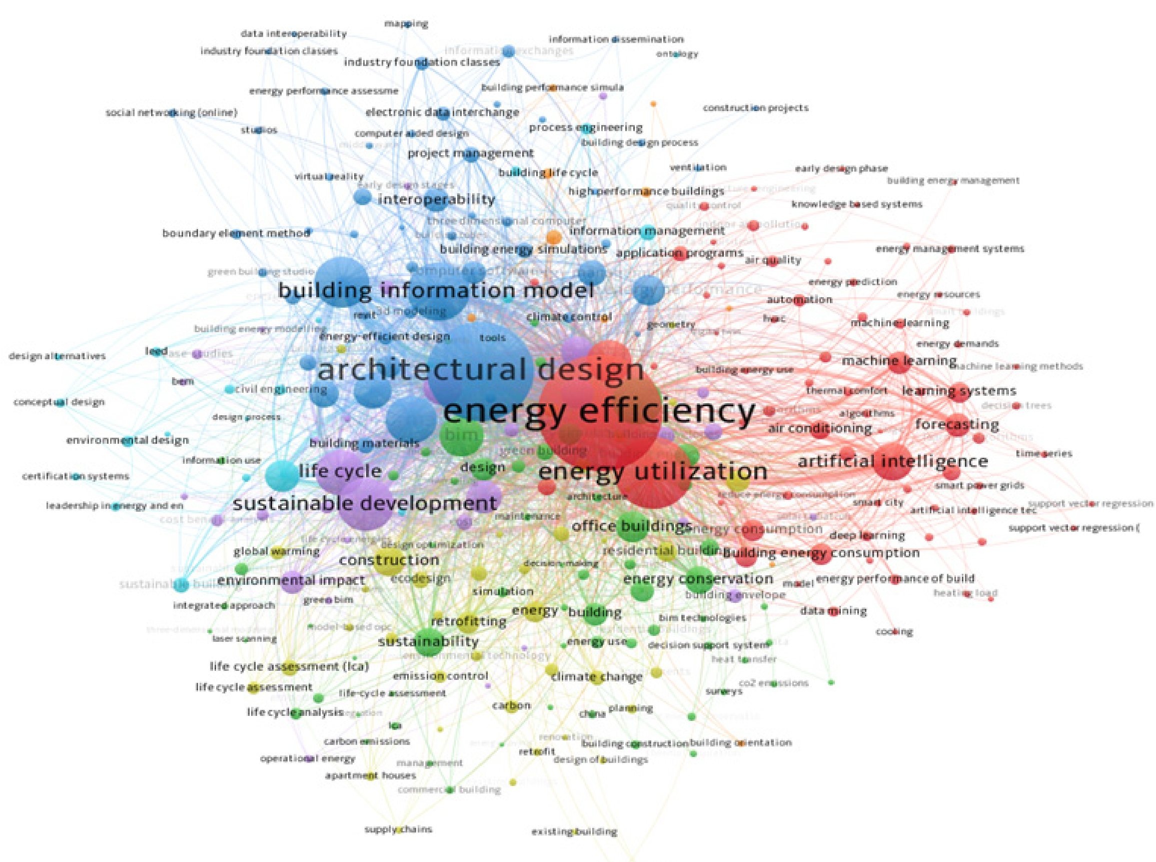

Figure 3. Network visualization of the total link strength for the keywords co-occurrences.

than the frequency of occurrences in "architectural design" research. Although architectural design is not included in the combination of four criteria keywords, it appeared as the second highest frequency. This may indicate that digital technologies for energy-efficient buildings in these literatures are applied or analyzed at the architectural design stage, which is the early stage of projects. Just as passive and active design are both considered and applied at the design stage for sustainable buildings [96], it can be understood that digital technologies such as BIM or AI for energy-efficient buildings should also be analyzed and simulated at the architectural design stage to achieve optimal performance [44, 97].

Occurrences of keywords over time were also analyzed using Overlay Visualization as seen in Figure 4. Here, keywords are indicated with the level of co-occurrence growth over the years. Keywords within the yellow circles had higher occurrences around 2017, while keywords around the red circles have had higher occurrences in recent years. The absence of data from 2021 to 2023 indicates that no significant changes have been observed in recent years regarding the keywords' co-occurrences. According to Overlay visualization analysis, before 2020, general studies such as 'sustainable development' and 'energy conservation' were conducted in relation to energy efficiency. The keyword 'building information model − BIM' was the only one studied in collaboration with energy efficiency research prior to 2020. However, as seen in Figure 4, since 2020 (highlighted by the red circle), more practical digital technologies such as 'neural network,' 'deep learning,' 'internet of things,' and 'smart building' have been integrated into energy efficiency research.

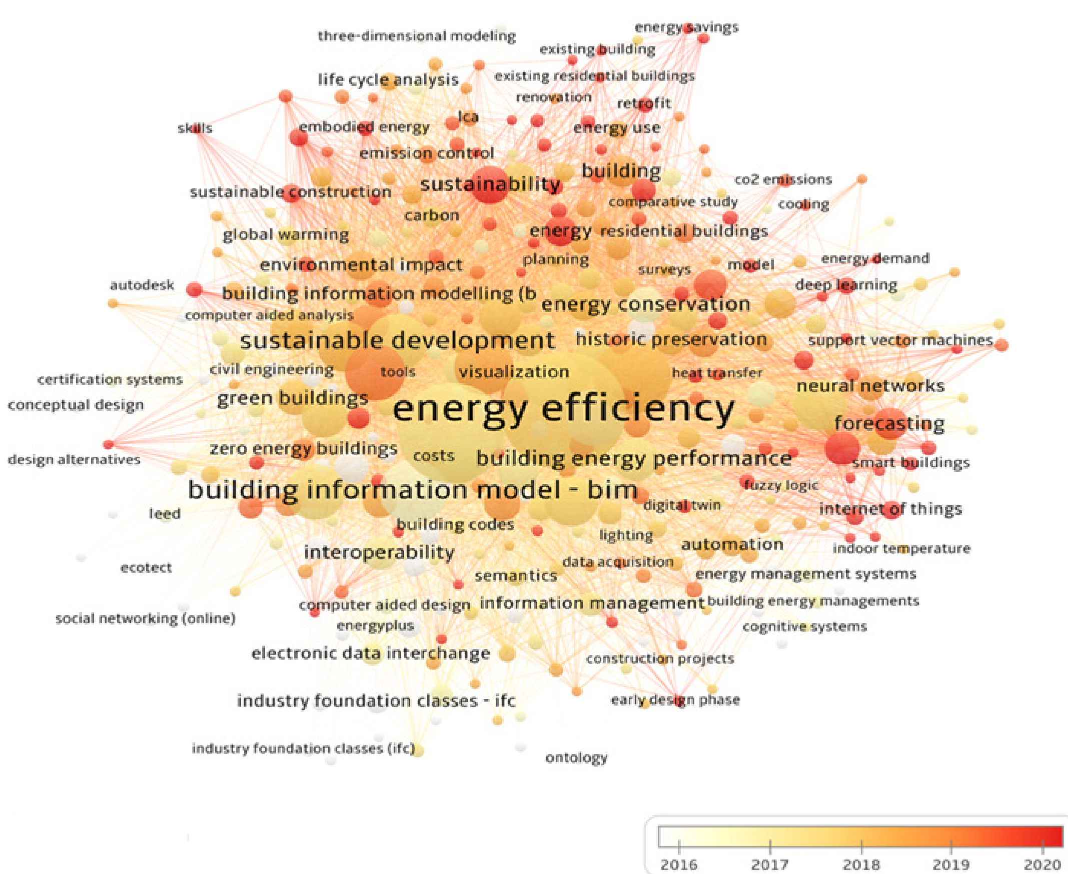

Figure 4. Overlay visualization of the keywords co-occurrence.

Systematic Review

Through the analysis of keyword co-occurrences above, it was observed that, besides BIM, other digital technologies are not yet fully integrated and cooperative in energy efficiency research (the size of circles representing these technologies is not as large as that of BIM research circles). Hence, it is necessary to analyze the barriers hindering this integrated research at the current stage.

The systematic review focused on identifying the challenges and limitations of digital technologies for developing energy-efficient buildings. For this, only strongly relevant 53 publications out of 559 research data were selected using robust selection criteria. Selected publications explored the deployment of BIM or AI for energy-efficient buildings, or combined them for digital construction technologies. An outline of the research topic, literature type, publication year, and authors of selected literature for the systematic review is presented in the Appendix. The in-depth study of the literature for the systematic review revealed challenges identified in the deployment of BIM and AI in energy-efficient buildings. During the detailed study of the publications, it was observed that the terminologies used to indicate the challenges in each publication might differ but refer to similar challenges. The systematic review outlined closely related challenges from all the research publications and classified them into 14 categories. Many of the 53 publications were classified into multiple categories based on the types of challenges identified in their research. The categories of challenges and barriers identified are presented in Table 1.

Table 1. Outline of categories of challenges and barriers

Categoty	Utilized Terminologies	References
Interoperability issues	- Interoperability issues, data extraction, loss of data, and discrepancies in data file software structure. - Lack of easy solutions for extending existing BIM schemas. - Software is relatively independent and lacks interactive operations. - Insufficiency in the desirable level of integration and interoperability. - Loss of semantic information. - Poor interoperability between different tools. - Geometry data transference flaws. - Varying parameters of data input.	Lu et al. [98], Marzouk et al. [99], Pereira et al. [24], Zhao et al. [84], Kamel & Memari [100], Carvalho et al. [101], Yang et al. [56], Wong et al. [102], Vilutienė et al. [85], Van Dessel et al. [82], Sanhudo et al. [6], Ramaji et al. [57], Onososen & Musonda [86], Mohanta & Das [103], Abdelazim et al. [104], Osello et al. [25], Cao et al. [105], Primasetra et al. [106], and Schlueter & Geyer [79].
Industry pushbacks	- Industry opposition to shifting from conventional methods. - Difficulties in embracing innovations. - BIM adoption hesitancy.	Marzouk et al. [99], Oloke [107], and Cao et al. [105].
Low client interest	- Owners and developers want designs to be completed quickly and at a low cost. - No client demands. - Satisfying different views of stakeholders regarding priorities.	Pereira et al. [24], Oloke [107], Lu et al. [98], and Kamel & Memari [100].
Process complexity	- Lengthy time of adjusting to novel technologies. - Complexity of traditional tools for energy simulation. - Creating simulation models is complicated and work intensive. - User-hostile processes. - Manual workflow and large models.	Węglarz [108], Lu et al. [98], Marzouk et al. [99], Gao et al. [109], Onososen & Musonda [86], Singh et al. [80], Remmen et al. [83], Zhang [110], and Singh et al. [111].
High service cost	- High training and consultancy fees. - Expensive skilful worker.	Oloke [107] and Wong et al. [102].

Table 1. Outline of categories of challenges and barriers (Continue)

Categoty	Utilized Terminologies	References
Lack of Trust	- Data protection and secrecy in the industry. - Lack of trust between multiple parties.	Gourlis & Kovacic [112] and Raouf & Al-Ghamdi [113].
Technical issues	- Software or hardware issues. - Poorly set-up database.	Gerrish et al. [114] and Oloke [107].
Knowledge gap	- Lack of necessary knowledge of the processes and workflows. - Users' lack of appropriate AI & BIM knowledge. - Require knowledge from many disciplines. - Extensive knowledge of HVAC systems is required to obtain accurate simulation results. - Insufficient BIM training.	Marzouk et al. [99], Pereira et al. [24], Oloke [107], Tien et al. [78], Węglarz [108], Cho et al. [115], Cao et al. [105], Abdelazim et al. [104], Schlueter & Geyer [79], and Primasetra et al. [106].
Lack of standards	- Lack of industry codes for green BIM applications. - Establish BIM technology-related standards. - Insufficiency of a standard for data exchange. - Lack of strict policies and guidelines. - Requirement for common standards. - Variations in the structure of models.	Oloke [107], Lu et al. [98], Kamel & Memari [100], Gerrish et al. [114], Marzouk et al. [99], Zhao et al. [84], Carvalho et al. [101], and Abdelazim et al. [104].
Bogus technology cost	- Substantial cost of software equipment. - Computational tools cost. - Expensive hardware.	Wong et al. [102], Tien et al. [78], Oloke [107], Abdelazim et al. [104], and Primasetra et al. [106].
Unavailable Data	- Lack of information for simulations. - Information availability. - Continuity and consistency of the data. - Lack of data availability and quality in models. - Constraints of data acquisition.	Onososen & Musonda [86], Lu et al. [98], Gerrish et al. [114], Wong et al. [102], Schlueter & Geyer [79], Tien et al. [78], Primasetra et al. [106], and Singh et al. [111].
Workflow Issues	- Lack of appropriate project delivery. - Workflow errors. - Unscientific intelligent processing method.	Zhao & Gao [81], Lu et al. [98], and Onososen & Musonda [86].
Design errors	- Insufficient design accuracy. - Difficulty in accurate modelling of complex high-performance features. - Modelling errors.	Gerrish et al. [114], Onososen & Musonda [86], and Zhao & Gao [81].
Clarity of roles	- Lack of defined responsibility. - Ambiguous ownership and stakeholder roles.	Raouf & Al-Ghamdi [113], Gerrish et al. [114], and Cao et al. [105].

Findings

Challenges and imitations

As a result of deeper analysis of the literature classified into 14 categories by the systematic review, the most frequent category can be further described as below.

Interoperability issues: Interoperability is broadly defined as the capacity of two or more technologies to share or exchange information seamlessly without losing data. 19 publications outlined that interoperability issues hinder the deployment of BIM and AI for energy-efficient buildings. Pereira et al. [24] outlined interoperability challenges between digital construction technologies and energy analysis tools for buildings. Other literature also outlined that this interoperability issues can manifest as challenges such as data extraction difficulties [100, 116], loss of semantic information [56], geometry flaws [101], and discrepancies in data file software structure [84, 117].

Regarding BIM for energy-efficient buildings, Lu et al. [98] indicated that it is challenging to utilize massive BIM data for sustainability analysis of buildings. AI technologies are also constrained by varying data input parameters in building energy-analysis software [102]. This interoperability issue between digital construction and energy simulation tools limits the potential for advancing energy efficiency in buildings and the broader construction sector [57, 82, 85].

Knowledge gap: 10 publications indicated that the lack of adequate knowledge is a major barrier to deploying digital construction for energy-efficient buildings. Technical skill problems and insufficient BIM training are obstacles to designing and constructing energy-efficient buildings [105, 106]. Tien et al. [78] also affirmed that despite the capabilities of AI models in AI methodologies, knowledge of building engineering and energy systems is still required. The inadequate capacity cuts across knowledge of processes and workflows [99], building forms and materials [115, 118], energy performance and design parameters [79], the applicability of BIM standards [104], and AI methods [108]. Oloke [107] observed that the construction sector lacks clarity regarding the application of digital construction for enabling energy efficiency and called for urgent actions through capacity development.

Process complexity: Deploying digital construction technologies to achieve energy-efficient buildings is time-consuming and complicated [111]. 9 publications identified limitations regarding the complexity of the process. The need for knowledge from various professionals to achieve detailed energy simulation results in a work-intensive process [108]. The tools and technologies required for integrating energy efficiency in buildings also require necessitate large models, are user-hostile, and can be difficult to operate [83, 86, 98, 109]. Energy modelling at the preliminary design stage is also complicated since critical building details are unavailable and decision-making relies on multiple competing criteria [80]. Building stakeholders require extended periods to adjust to new technologies [99].

Lack of standards: 8 publications identified the challenge of unavailable standards when deploying digital construction for energy-efficient buildings. There is a lack of industry standards for managing various aspects of BIM application for energy efficiency [98, 99, 101]. Deploying BIM and AI for energy-efficient buildings requires better standardization and sophiscated guidelines for effective implementation [100, 107, 114, 119]. Stakeholders must accelerate the creation of technology-related standards for energy-efficient buildings [84].

Unavailable data: The lack of quality data and information impedes various processes for ensuring building energy efficiency [86]. 8 publications identified unavailable data as challenge in deploying digital construction for energy-efficient buildings. The absence of information for simulation, lack of large datasets, constraints in data acquisition, and inconsistencies in information hinder the use of BIM and AI for energy-efficient buildings [78, 79, 102]. Of the 53 publications, 36 explored the deployment of BIM, 12 explored the deployment of AI, and only 5 explored the combination of both digital construction technologies. This distribution indicates that the deployment of BIM for energy-efficient buildings is more widespread than the deployment of AI. Since research related to BIM was conducted first, a considerable number of challenges and barriers were classified based on BIM-related issues such as interoperability with BIM system or data, and lack of BIM knowledge and experience. These issues are anticipated to arise similarly when applying future research on energy-efficient buildings incorporating AI and other digital technologies. In particular, inadequate global standards, high initial investment costs, and lack of experience are considered challenges that will emerge whenever new digital technologies are integrated for energy-efficient buildings, regardless of the type [120, 121].

Strategies for Implementation of BIM and AI for Energy-Efficient Buildings

The advancement of data schemes should be prioritised to address the interoperability challenges experienced during the implementation of BIM and AI for energy-efficient buildings. Data schemes such as Industry Foundation Classes (IFC) and Green Building XML (gbXML) facilitate seamless information exchange and enhance interoperability between BIM, AI, and other digital tools [6, 24]. Other approaches to improve interoperability includes using open BIM frameworks and ensuring standardized file schema between BIM, AI, and energy modelling tools [85, 100, 101, 114]. Continuous practice and deployment are recommended to address the technical and workflow issues, inflated costs, and design errors experienced during the deployment of BIM and AI for energy-efficient buildings. Increasing the application these technologies will enhance designers' technical proficiency and facilitate their commercialisation to overcome these challenges [79]. Construction stakeholders would also gain mastery of these new technologies after extended periods of use [99]. Collaboration among designers, sustainability experts, software companies, building owners, and policymakers is essential to gather and share data in standardized parameters [99, 102]. This collaboration will help bridge the knowledge gap and address low client interest, which hinder the effective deployment of digital construction for energy-efficient buildings. Corporate organizations and civil society can jointly implement frequent training, advocacy, and capacity development initiatives [103]. These strategies for improving the effective deployment of BIM and AI for energy-efficient buildings rely significantly on collaboration and synergy among all industry stakeholders.

Conclusion

This study has investigated the transformative potential of digital construction technologies, particularly BIM and AI, in advancing energy-efficient buildings. Through a meticulous scientometric and systematic review of literature spanning from 2010 to 2023, the research illuminates the current state of digital construction's impact on energy efficiency within the building sector. Key findings underscore a pronounced trend towards adopting digital technologies, notably BIM and AI, in the early design phases of buildings, with a strong emphasis on improving energy efficiency. These technologies are pivotal in enabling informed decision-making, reducing errors, and optimizing resource utilization throughout the lifecycle of buildings. However, the study also identifies numerous challenges and limitations hindering the widespread deployment of digital technologies such as BIM and AI. Foremost among these challenges are interoperability issues, which denote the ability of different technologies to exchange information seamlessly without loss of data. This barrier persists due to difficulties in data extraction, semantic information loss, geometry discrepancies, and structural variations in software data files. Beyond interoperability, the study categorizes 14 distinct challenges from the literature. These encompass knowledge gaps, process complexity, lack of standards, data unavailability, industry resistance, low client interest, high service costs, trust deficits, technical issues, inflated technology costs, workflow inefficiencies, design errors, and role ambiguities. These challenges collectively reflect the current obstacles hindering the effective deployment of digital construction technologies aimed at achieving energy-efficient buildings.

Nevertheless, the study emphasizes the substantial benefits that integrating advanced digital tools can bring to the construction industry, including reduced environmental impact, enhanced building performance, and contributions to global sustainability goals. To fully realize these benefits, future research should prioritize overcoming identified barriers, establishing robust interoperability standards, and fostering an environment conducive to innovation within the industry. These efforts are crucial in harnessing the potential of digital construction technologies to achieve energy-efficient buildings. In conclusion, while challenges remain, the ongoing evolution and deployment of BIM, AI, and other digital tools present a promising pathway towards sustainable development and enhanced energy efficiency in the built environment. Addressing these challenges will be essential in realizing the full transformative potential of digital construction technologies in shaping the future of building practices.

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APPENDIX

Literatures included in the systematic review.

Year	Research title	Authors	Reference No.
2010	Developing energy efficient building design in machine learning *	Kim et al. (2010)	[36]
2011	Architecture data and energy efficiency simulations: BIM and interoperability standards *	Osello et al. (2011)	[25]
2012	Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures *	Lee et al. (2012)	[119]
2013	Usage of building information modelling for evaluation of energy efficiency *	Volkov et al. (2013)	[9]
2013	Lessons learned from developing immersive virtual mock-ups to support energy-efficient retrofit decision making *	Yang et al. (2013)	[56]
2014	Modeling heating and cooling loads by artificial intelligence for energy-efficient building design **	Chou & Bui (2014)	[34]
2014	Research on building energy technology based on BIM *	Song (2014)	[19]
2014	Application of BIM technology on energy efficiency building design *	Zhang (2014)	[110]
2015	An open framework for integrated BIM-based building performance simulation using modelica *	Remmen et al. (2015)	[83]
2017	BIM application to building energy performance visualisation and managementChallenges and potential **	Gerrish et al. (2017)	[114]
2017	Building Information Modelling for analysis of energy efficient industrial buildings – A case study **	Gourlis & Kovacic (2017)	[112]
2017	The promise of BIM for improving building performance **	Habibi (2017)	[15]
2017	Building Information Modeling (BIM) for green buildings: A critical review and future directions **	Lu et al. (2017)	[98]
2017	Investigation of leveraging BIM standards to facilitate sustainability evaluations from early stages of design *	Ramaji et al. (2017)	[57]
2017	Toward automatic review of building energy efficiency based on building information modelling *	Zhao et al. (2017)	[18]
2018	Use-case analysis for assessing the role of building information modeling in energy efficiency *	Alhamami et al. (2018)	[11]
2018	Component-based machine learning for energy performance prediction by multiLOD models in the early phases of building design *	Geyer et al. (2018)	[54]
2018	Building information modeling for energy retrofitting – A review **	Sanhudo et al. (2018)	[6]
2018	Linking BIM and Design of Experiments to balance architectural and technical design factors for energy performance **	Schlueter &Geyer (2018)	[79]
2018	Using Artificial Intelligence in energy efficient construction *	Węglarz (2018)	[108]
2019	A study on the application of artificial intelligence techniques for predicting the heating and cooling loads of buildings **	Das et al. (2019)	[46]
2019	BIM-based real time building energy simulation and optimization in early design stage *	Gao et al. (2019)	[109]
2019	Review of BIM's application in energy simulation: Tools, issues, and solutions **	Kamel & Memari (2019)	[100]
2019	A review of the applications of artificial intelligence and big data to buildings for energy-efficiency and a comfortable indoor living environment **	Mehmood et al. (2019)	[41]
2019	Building information modelling and green buildings: challenges and opportunities **	Raouf & Al-Ghamdi (2019)	[113]
2019	Statistical decision assistance for determining energy-efficient options in building design under uncertainty *	Singh & Geyer (2019)	[111]
2019	Information exchange scenarios between machine learning energy prediction model and BIM at early stage of design *	Singh et al. (2019)	[43]

Year	Research title	Authors	Reference No.
2019	BIM to building energy performance simulation: An evaluation of current transfer processes *	Van Dessel et al. (2019)	[82]
2019	BIM AND PARAMETRIC DESIGN APPLICATIONS FOR BUILDINGS' ENERGY EFFICIENCY: AN ANALYSIS OF PRACTICAL APPLICATIONS **	Zardo et al. (2019)	[33]
2020	A systematic review of the role of BIM in building sustainability assessment methods *	Carvalho et al. (2020)	[101]
2020	Energy and cost analysis of building envelope components using BIM: A systematic approach **	Pučko et al. (2020)	[48]
2020	Quick energy prediction and comparison of options at the early design stage **	Singh et al. (2020)	[80]
2021	TOWARDS SUSTAINABLE BUILDINGS USING BUILDING INFORMATION MODELLING AS A TOOL for INDOOR ENVIRONMENTAL QUALITY and ENERGY EFFICIENCY *	Abdelazim et al. (2021)	[104]
2021	A Comparative Study of Artificial Intelligence Models for Predicting Interior Illuminance **	Arbab et al. (2021)	[51]
2021	Transition from building information modeling (BIM) to integrated digital delivery (IDD) in sustainable building management: A knowledge discovery approach based review **	Liu et al. (2021)	[117]
2021	Research on energy-efficiency building design based on BIM and artificial intelligence *	Long & Li (2021)	[29]
2021	Deployment of Building Information Modelling (BIM) for Energy Efficiency in the UK ***	Oloke (2021)	[107]
2021	Using BIM to improve building energy efficiency − A scientometric and systematic review **	Pereira et al. (2021)	[24]
2021	How BIM contributes to a building's energy efficiency throughout its whole life cycle: Systematic mapping **	Vilutienė et al. (2021)	[85]
2021	Potential and limitation of AI system in building services and control management system *	Wong et al. (2021)	[102]
2021	BIM-based analysis of energy efficiency design of building thermal system and HVAC system based on GB50189-2015 in China **	Zhao et al. (2021)	[84]
2022	Green Building Construction: A Systematic Review of BIM Utilization **	Cao et al. (2022)	[105]
2022	Artificial intelligence in green building **	Debrah et al. (2022)	[77]
2022	Role of BIM and energy simulation tools in designing zero-net energy homes **	Habibi (2022)	[12]
2022	Green building system integration into project delivery utilising BIM **	Marzouk et al. (2022)	[99]
2022	Causal Analysis of Slow BIM Adoption in Eastern India with a Special Focus on Green Building Sector **	Mohanta & Das (2022)	[103]
2022	Barriers to BIM-Based Life Cycle Sustainability Assessment for Buildings: An Interpretive Structural Modelling Approach **	Onososen &Musonda (2022)	[86]
2022	BIM Utilization in Improving Energy Efficiency Performance on Architectural Design Process: Challenges and Opportunities *	Primasetra et al. (2022)	[106]
2022	Combining artificial intelligence and building engineering technologies towards energy efficiency: the case of ventilated façades **	Summa et al. (2022)	[52]
2022	Machine Learning and Deep Learning Methods for Enhancing Building Energy Efficiency and Indoor Environmental Quality - A Review **	Tien et al. (2022)	[78]
2022	Energy Consumption Prediction in Low Energy Buildings using Machine learning and Artificial Intelligence for Energy Efficiency *	Vijayan (2022)	[74]
2022	Research on Energy-Saving Design Method of Green Building Based on BIM Technology **	Zhao & Gao (2022)	[81]
2023	Data-driven estimation of building energy consumption and GHG emissions using explainable artificial intelligence **	Zhang et al. (2023)	[116]