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REVIEW ARTICLE

Integrating BIM and AI for Smart Construction Management: Current Status and Future Directions

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Abstract
At present, building information modeling (BIM) has been developed into a digital backbone of the architecture, engineering, and construction industry. Also, recent decades have witnessed the fast development of various AI techniques in reliably tackling a huge amount of data under complex and uncertain environments. Since both BIM and artificial intelligence (AI) have attracted sustainable attention, the integration of BIM and AI can demonstrate newly added value in handling construction projects with inherent complexity and uncertainty. For a clear understanding of BIM-AI integration in boosting smart construction management, the goal of this paper is to make a comprehensive investigation and summary of its potential value and practical utility to drive the construction industry to catch up with the fast pace of automation and digitalization. Through both the bibliometric analysis and information analysis, this paper provides a deep insight into the status quo and future trends for leveraging AI during the entire lifecycle of a BIM-enabled project. It is worth noting that keywords that are highly cited in the latest two years contain deep learning, internet of things, digital twin, and others, which means AI is evolving as the next frontier to accelerate the revolution in the traditional civil engineering. According to keyword clusters derived from the log-likelihood ratio, we determine six advanced research interests and discuss the state-of-the-art research, including automated design and rule checking, 3D as-built reconstruction, event log mining, building performance analysis, virtual and augmented reality, and digital twin. Besides, a growing force can be put on three potential directions to more broadly adopt the BIM-AI integration, including synthesis of human–machine intelligence, civil-level digital twin, and blockchain, aiming to make BIM and AI live up to expectations.

1 Introduction

Building information modeling (BIM), known as a shared database and knowledge center, has been proven useful in visualizing, integrating, and analyzing the physical and functional characteristics of built objects across the whole building lifecycle, including the phase of design, construction, operation and maintenance (O&M) [1]. It is worth noting that BIM is more than a high-fidelity 3D model, which permits multi-disciplinary information to be superimposed into virtual prototyping for more efficient collaboration and communication [2]. Through exploration of the available project data, BIM has opportunities to inform valuable decisions concerning different management aspects, such as sustainable design, schedule planning, cost estimation, construction monitoring, building performance analysis, and others. Since the BIM-centric project delivery has shown its outstanding performance in digital management, it has been widely adopted to drive a high degree of automation, intelligence, and reliability of the architecture, engineering, and construction (AEC) industry in the digital era [3].

According to a survey from the McGraw-Hill Construction, the adoption of BIM is accelerating in many countries, which has gradually evolved as a central part of governmental policies in infrastructure development in the last decade [4]. For example, the United States and the United Kingdom have the highest awareness of BIM, where BIM is forced to use. Germany and France also

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witness a surge in BIM implementation, and thus BIM will be mandatory in the near future. Particularly, 87% of BIM users in these four leading countries have confirmed that they experience great business value from BIM, who highlight three top benefits of BIM, including the reduced conflicts and errors, the better field coordination, and the flexible adjustment in construction [5]. Therefore, it is evident that continuous efforts will be made to promote the growth of BIM implementation around the world, which can bring significant technological innovation to facilitate a digitalization process in the construction domain.

Motivated by the popularity of BIM, previous studies have made great contributions to reviewing BIM usage in tackling AEC problems. For example, Zhao [6] conducted a scientometric review to gain a snapshot of the global BIM research during the year 2005–2016. Li et al. [7] provided an objective summary of BIM knowledge and highlighted the evolution of BIM-related research. Wen et al. [8] adopted the visualization analysis method to draw the mapping knowledge to present the research progress and development trend of BIM. However, these generic studies mainly relied on the bibliometric approach to perform co-author, co-word, and co-citation analysis, which were insufficient in qualitatively discussing the practical applications and future development. To achieve a more thorough analysis, some papers have attempted to examine the contribution of BIM on a certain topic under the interaction of objective investigation and subjective interpretation, which can make a more detailed analysis of the resulting articles and the corresponding research directions to be resolved in the future. For example, Lu et al. [9] studied BIM in supporting green building development in terms of applications, functions, and assessments. Wang et al. [10] reviewed the combination of BIM and geographical information systems (GIS) in a sustainable built environment and introduced four relevant applications in data integration, lifecycle project management, energy management, and urban governance. Tang et al. [11] presented a comprehensive review of the current situation of BIM and internet of things (IoT) device integration along with the examination of limitations and prediction of future trends. Gao et al. [12] examined the current BIM abilities in supporting O&M activities of facilities and offering new functionalities for facility managers. Yin et al. [13] carried out a bibliometric-qualitative review approach to reveal the research needs of BIM for off-site construction. However, these reviews have mainly uncovered the practicality of BIM for specific purposes or processes. It clearly lacks emphasis on promoting BIM development throughout the project to a higher level of intelligence. Since the construction industry needs to embrace greater digitalization, an essential task is to reveal the meaningful relationship between BIM and the popular artificial intelligence (AI) for further guiding the smart development of civil engineering. This has not been summed up yet in the existing literature.

Notably, AI has been regarded as the next potential frontier in the AEC industry. Generally, the core idea behind most AI algorithms, such as machine learning, deep learning, cognitive computing, and others, is to simulate human thinking, which is able to deeply learn and analyze a large amount of data for tasks of clustering, prediction, and optimization. Compared to conventional analytical approaches, AI is superior to tackle complex problems in the real-world in a more automated and reliable way. It is helpful to facilitate a smarter decision-making process under less dependency on human experience and knowledge, aiming to maximize the chance of success in realizing the project goal [14]. Hence, the nature of AI makes it to be a suitable tool to well cope with challenges in construction projects that are highly complex and unnecessarily tedious. As a result, the adoption of various AI technologies is expected to bring sustainable benefits in terms of automation, risk mitigation, improved efficiency and safety to the construction industry [15]. Although the high applicability of AI has led to an upward trend of research on the AI-powered AEC industry since the start of the twenty-first century, the research topic concerning AI in the construction sector is still at an early stage, which is expected to bolster its rapid growth in the coming years. The reasons for the low-level AI adoption in construction probably lie in high cost, trust, security, talent shortage, internet connectivity, project uniqueness, and others [16]. Meanwhile, the fragmented nature of the industry is another critical reason to impede AI incorporation into construction, which will lead to issues of data acquisition, retention, and interpretation [17]. That is to say, AI has not reached its full potential in the construction domain. The foregoing limitations inspire this study to focus on the integration of BIM and AI techniques. Since the unique property of BIM lies in holding rich sources of historical data to deliver information throughout the project lifecycle, it can impose a new demand on making sense of these increasing BIM data by AI-enabled solutions for accelerating the digitalized process. The engineering informatics under the BIM-AI integration is believed to bridge the gap of digital transformation in construction management over the full lifecycle chain.

Currently, the technical premise of BIM entails digital information management to produce data-rich models for use in a project's life cycle [18], while AI is paving an intelligent way to shift the vision model to realization for decision-making purposes [19]. Since BIM and AI can show their own advantages in their individual fields, a digital practice can be reasonably centered on the enormous potential of seamlessly integrating a variety of fast-growing AI methods into BIM-related projects. That is to say, the motivation behind BIM-AI integration is to maximize great value from both BIM and AI, which creates the possibility of easily getting great access to available information and automatically bringing deep insights into a complex project with less manual work. Therefore, the combination of these two powerful techniques is bound to grow in the future, which can act as a digital assistant to improve the productivity, quality, and safety of a construction project. As reviewed. the connection between BIM and various AI methods has turned out to be an emerging area of research for the purpose of revolutionizing the AEC industry. Although Zabin et al. [20] summarized the use of BIM data through machine learning, its main weakness is that it only focuses on machine learning applications to BIM-generated project data. It is restricted to the data analysis aspect. In other words, machine learning can be treated as a specific subcategory of AI to maximize the value of big data [21], which is responsible to retrieve hidden patterns and unknown relationships from large quantities of data [22, 23]. In fact, the AI techniques that refer to a border idea to imitate human behavior are far more than machine learning algorithms. Accordingly, the review on the topic of BIM-AI integration is previously unstudied. Therefore, the interests need to fall into more kinds of AI methods beyond machine learning for decision making. Additionally, the adoption of AI into BIM is still in a nascent phase, which has not yet reached its full potential. In light of the above-mentioned issues, it is necessary to carry out a systematic and thorough review to narrow the gap in providing a full picture and understanding of the state-of-art development of BIM and AI along with their linkages.

To sum up, the goal of the present research is to perform a more comprehensive and scientific review of papers about the practical synthesis between BIM and AI in the last decades. More specifically, the BIM-AI integration can be understood to flexibly leverage various AI technologies in BIM-based projects, ultimately achieving significant contributions to the revolution and improvement of the AEC industry in terms of efficiency, profitability, safety, intelligence, and others. As for the scientific value, it is helpful to keep abreast of the current development status and ascertain the future research directions about BIM-AI integration. As for the reference value, our review can enhance the knowledge of researchers and decision-makers in the construction domain and then guide them to perform AI-driven applications far more than machine learning algorithms in wide application ranges of BIM projects. There are four open questions to be answered: (1) What is the current situation of BIM-AI integration and the development over time. (2) What is the potential area of BIM-AI integration for improving project management. (3) What is the advanced research concerning BIM-AI integration that is worth discussing. (4) What are the prominent research trends in the future study. For seeking answers to these questions, we intend to perform a comprehensive review based on a mix of bibliometric analysis and information analysis to study the existing research works on the BIM-AI integration. For one thing, the bibliometric analysis as a statistical evaluation is responsible to convert text into quantitative data, which can not only measure the influence of articles, authors, and others within the scientific community but also capture the development process of the targeted topic. For another, the information analysis focuses on interpreting the content of representative papers in detail, enabling to make the summary and inference for assurance of in-depth investigation in certain key domains.

Towards the objective of our literature review, Fig. 1 visualizes a general framework to critically review the synthesis of BIM and AI, which can make the best use of both the quantitative and qualitative approaches to eliminate biased conclusions. Observably, the transparent process begins

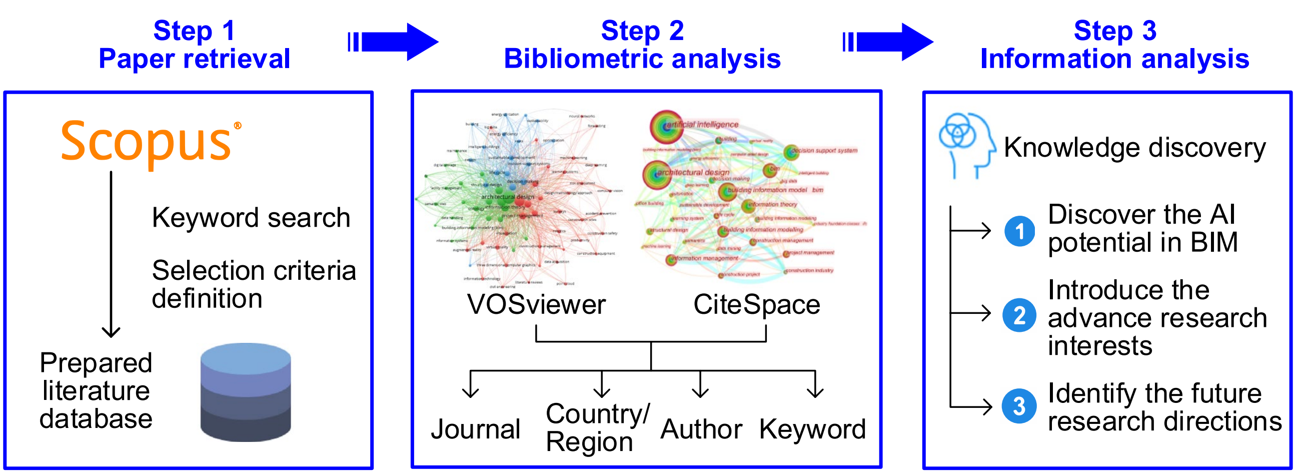


Fig. 1 Framework of the proposed literature review

with the web search of relevant scientific articles from the Scopus database for paper retrieval. Some up-to-date pieces of literature that are satisfied with the pre-defined selection criteria are selected and gathered in a database serving as the knowledge basis for further exploration. Subsequently, two software packages named VOSviewer and CiteSpace are deployed to produce informative conceptualizations, which can systematically map and discover the structural and dynamical aspects of the prepared literature dataset. Finally, information analysis is carried out for knowledge discovery from three perspectives, resulting in conclusions to offer a deeper insight into the potential of AI in developing new BIM-related topics. As a result, a roadmap as an overall understanding of the reviewed topic about BIM-AI integration can be objectively created to help other researchers easily capture the status quo, identify popular research interests, and trace future frontiers.

2 Bibliometric Analysis

2.1 Data Acquisition

In the stage of data acquisition, the following three criteria are adopted to search for the most relevant papers: (1) We select Scopus containing comprehensive scientific data and literature as the practical database. It has been proven that Scopus combines the advantages of both PubMed and Web of Science, which can provide 20% more publication coverage [24]. Moreover, Scopus acts as an ideal tool in searching inter-disciplinary research topics [25], and thus it is more proper for our review work on BIM and AI integration. (2) A set of keywords are determined to retrieve the most relevant previous literature. The search period is set from Jan 2000–Apr 2021, aiming to consider the development of the targeted topic in the recent two decades. The keyword search strategy is tabulated in Table 1, where three major concepts (including BIM, AI, and construction industry) are taken into account and each concept is described by several synonyms or similar phrases. The determination of keywords mainly refers to [15, 16]. To be more specific, the two complementary terms BIM and AI are research objectives in this review, and the topic concerning the construction industry aims to limit the scope of papers in the engineering field. (3) There are four key points in the process of publication search, aiming to prepare a high-quality dataset for ensuring the reliability of analytical results. At first, the scope of keyword search is within the full article, which can reduce the likelihood of omitting related papers. Second, a query statement is formulated based on the Boolean operator to sufficiently cover the target topic. Third, result filtering is performed to limit a large number of papers. For example, the document type should be refined as "Article", and thus review papers are excluded from the prepared dataset. The subject area is limited to "Engineering", "Computer Science", and "Environmental Science". Fourth, the manual screening process is necessary to further refine papers within the research area. We quickly check the journal name, article title, and highlight to remove irrelevant papers due to query misinterpretation and ambiguity. As a result, a total of 2,766 scientific publications coupling three topics together are relevant to our review topics. which are extracted as our targeted database for the bibliometric analysis. This publication number is still limited accounting for only 0.21% of AI-related studies, 0.43% of construction-related studies, and 12.75% of BIM-related studies. Accordingly, substantial research has concentrated on three separate topics about AI, construction, and BIM. Nevertheless, it can be concluded from the limited number of publications that efforts in applying AI to BIM for handling complex construction projects are still at an initial stage. Since BIM-AI integration is envisioned to play key roles in speeding up the digital development in the construction field, it appears to be an emerging topic deserving more attention.

Regarding the annual number of public studies, it can be seen from Fig. 2 that interests in the individual topic and the integrated topic all experience significant growth during the past 20 years. Specifically, the papers for BIM exhibit an overall upward trend, while there is the main burst of publications about AI and the construction

Table 1 Keyword search strategy and result for pieces of literature in the period of Jan 2000–Apr 2021

Concept	Keyword and phrase	Number of documents
AI	AI OR "artificial intelligent" OR "artificial intelligence" OR "computational intelligent" OR "computational intelligence" OR "data mining" OR "machine learning" OR "deep learning" OR "neural network"	1,297,116
Construction industry	"construction industry" OR "construction engineering" OR "construction management" OR "architecture engineering" OR "structural engineering"	647,804
BIM	BIM OR "building information modeling" OR "building information modelling" OR IFC OR "industry foundation classes"	21,695
BIM and AI in construction industry	Combine the keywords from the abovementioned three concepts by "AND" operator	2,766

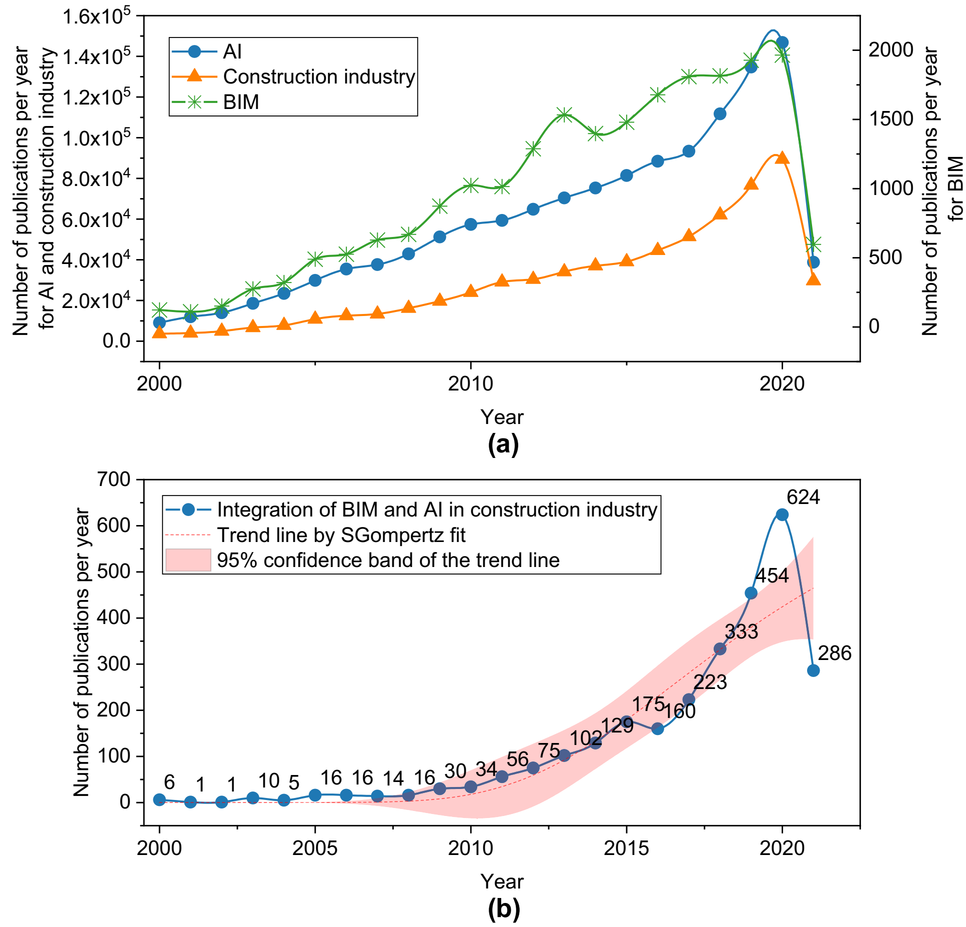


Fig. 2 Variation of publication number per year during Jan 2000–Apr 2021: **a** individual topic about AI, construction industry, and BIM; **b** our review topic about the integration of BIM and AI in the construction industry

industry in 2016. Accordingly, the rising tendency of publications concerning our reviewed topic roughly matches the development of advanced AI and BIM techniques and the ever-increasing attention in the construction industry. The publication trend can be generally divided into three stages. In the first 10 years, the annual growth was relatively slow under an average of 12 publications every year. From the year 2010 to 2015, this discipline field began to receive increased attention, and thus the average publication number per year had risen to 95. Since 2016, a pretty steep increase occurs, leading to a jump in the publication number from 160 (the year 2016) to 624 (the year 2020). It is observed that the shape of the curve in Fig. 2b generally follows the Gompertz function, where the growth is slowest at the beginning. Therefore, such a type of function is fitted along with a 95% confidence band to quantitatively capture the growing trend of relevant publications, resulting in a considerably high R^2 value of 0.849. It should be noted that the publication number has reached 286 in the first four months of the year 2021 taking up around 45.8% of the previous whole year, which even exceeds the annual number before 2017. That is to say, there has been a surge of interest in our reviewed topic about progressively integrating AI and BIM for pursuing intelligent civil engineering, and thus a promising rise of related published works will keep going.

Table 2 The top 10 majority journals with the most publications about BIM-AI integration in the construction industry

Journal	Number of publications
Automation in construction	340
Journal of Computing in Civil Engineering	96
Advanced Engineering Informatics	91
Journal of Construction Engineering and Management	90
Engineering Construction and Architectural Management	79
Journal of Information Technology in Construction	47
Sustainability	46
Applied Sciences	44
Journal of Cleaner Production	39
Buildings	38

2.2 Journal, Country/Region, and Author Analysis

Most published papers about the reviewed topic come from the top 10 majority journals, as listed in Table 2. Among these journals, *Automation in construction* accounting for 12.3% of publications makes the greatest contribution, which is followed by *Journal of Computing in Civil Engineering*, *Advanced Engineering Informatics*. Besides, the top 10 journals with the most direct citations are summarized in Table 3, which tend to exert more impacts on the targeted topic. It is evident that 5 of the top 10 most cited journals are listed in the top 10 majority journals providing the greatest number of publications, which are *Automation in Construction*, *Journal of Construction Engineering and Management*, *Advanced Engineering Informatics*, *Journal of Computing in Civil Engineering*, *Journal of Cleaner Production*. Particularly, the first four journals under a total citation of 3922 are also ranked at the top four in Table 2.

Table 3 The top 10 most cited journals about BIM-AI integration in the construction industry

Journal	Number of citations
Automation in Construction	1570
Journal of Construction Engineering and Management	947
Advanced Engineering Informatics	752
Journal of Computing in Civil Engineering	653
Building and Environment	421
Procedia Engineering	352
Energy and Buildings	308
Construction Management and Economics	290
Expert System with Applications	287
Journal of Cleaner Production	217

That is to say, journals owning more related publications have more opportunities to be cited. In short, the scope of all these top journals in Tables 2 and 3 can cover issues related to the integrated application of BIM and AI within civil engineering, and thus they can serve as the best sources for researchers.

From the view of the country/region, Figs. 3 and 4 disclose the distribution of publications. Evidently, the United States, China, United Kingdom, and Australia stand out to be the four greatest contributors to this specific research field, which are all prominent in the number of publications and citations. Especially for the United States, its published papers (622) and citations (11319) are far more than others. Hence, it can be assumed that the United States takes the leading position in exploring the BIM-AI integration for smart construction. Besides, all the 9 top-ranked countries/regions in Fig. 3 are the same, which are all more active in conducting relevant research and play a greater influence. The difference lies in the last country. Spain is ranked at the 10th place to provide the most publications, while Belgium owns more citations than Spain. To study cross-country collaboration, an optimum co-authorship network is established under the criterion that the minimum number of publications of a country/region is 20 and the minimum number of citations of a country/region is 20. Therefore, 35 of the 99 countries/regions meeting the threshold are incorporated in Fig. 4, where the bigger node donates the more influential the country/region, the thicker link represents the stronger relationship between the two countries/regions, and the color stands for the average citations. There is a high level of cooperation among all these 35 selected countries/regions.

In addition, these selected published papers can be analyzed from the author's side. The top 8 most productive authors from Australia, Netherland, Hong Kong (China), United States, Italy, and China are listed in Table 4, who

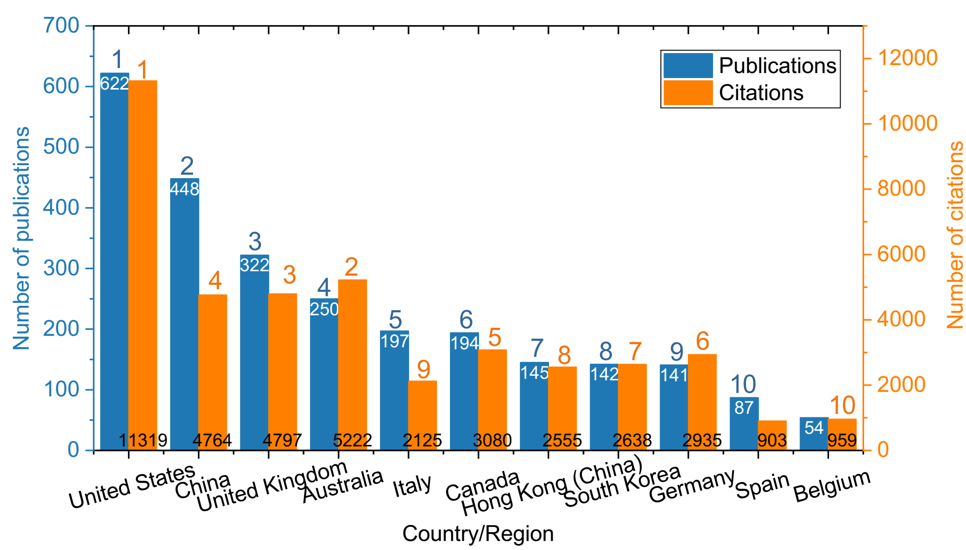


Fig. 3 Top 10 countries/regions with the largest number of publications and citations. (Note: the number above each bar stands for the top N ranking.)

Fig. 4 Co-authorship network based on the country/region

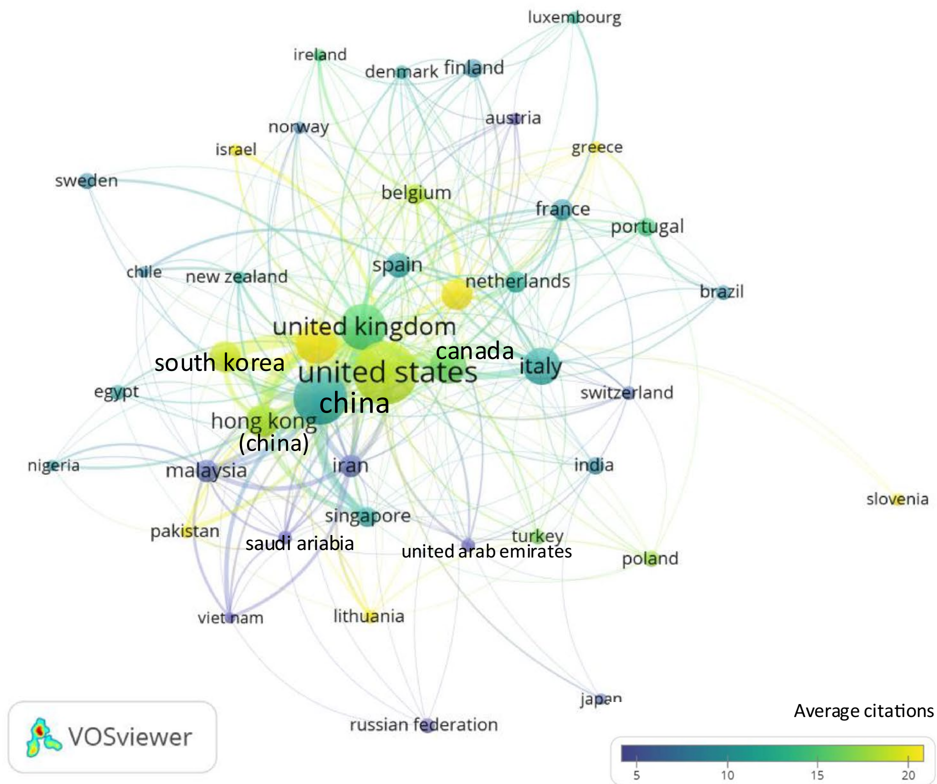


Table 4 The top 8 more productive authors

Author	Country/ Region	Institute	Number of publi- cations	Number of citations
Xiangyu Wang	Australia	Curtin University	52	1513
Pieter Pauwels	Netherland	Eindhoven University of Technology	40	825
Heng Li	Hong Kong (China)	The Hong Kong Polytechnic University	38	655
Jun Wang	Australia	Deakin University	36	491
Martin Fischer	United States	Stanford University	31	530
Jack C.P. Cheng	Hong Kong (China)	The Hong Kong University of Science and Technology	26	659
Luigi Barazzetti	Italy	Politecnico di Milano	24	517
Hanbin Luo	China	Huazhong University of Science and Technology	22	489

have contributed over 10% of related publications in the latest two decades. Also, their papers are very influential reaching a number of citations above 489, and thus they can be regarded as the highly cited authors in the targeted research area. To be more specific, Pieter Pauwels puts a special emphasis on smart architectural design based on semantic web techniques. Luigi Barazzetti concentrates on computer vision and laser scanning for mapping and 3D modeling. The rest of the authors have made great efforts in implementing BIM along with AI towards a high degree of digitalization and intelligence in infrastructure management during its entire lifecycle.

2.3 Keyword Analysis

A popular way to map the research hotspots and trends is drawing a network of co-occurrence keywords by feeding the bibliographic data from Scopus into the VOS viewer tool. Under the full counting, a total of 14,748 keywords are retrieved from a body of the selected literature, which could unnecessarily increase the complexity of the network. To attain a more readable and representative graph, we set the minimum frequency of keyword occurrence to be 50, and thus only 77 out of 14,748 keywords remain. The created network for knowledge mapping is shown in Fig. 5, which consists of 77 nodes and 2534 links under a total link strength of 23,913. As an explanation, such a network is proven useful to intuitively uncover the knowledge structure behind the target research topic. A node stands for a specific keyword and its size is in direct proportion to the frequency of the keyword. A pair of nodes stand for the co-occurrence of two keywords. The thickness of a line indicates the closeness of the relationship between two nodes in terms of co-occurrence. That is to say, the two connected keywords will appear at the same time and their link strength indicates the co-occurrence frequency. Herein, two informative ways of visualizing the keyword co-occurrence network are provided in Fig. 5, which are discussed below.

One is a static representation in Fig. 5a with a clustering view, where the entire network is automatically divided into three clusters in the color of red (cluster 1), green (cluster 2), and blue (cluster 3). The VOSviwer tool supports a network clustering method named the smart local moving algorithm to provide insights into the structure of the established network, which has shown the advantages of automatically discovering meaningful clusters with higher modularity values [26]. As a result, a set of closely related keywords can be reasonably gathered into the same clusters. Totally, 37, 23, and 17 keywords are assigned to the clusters 1–3, respectively. In particular, these extracted clusters correspond to the leading research interest. For example, the cluster 1 is centered around the advanced AI techniques. The cluster 2 is associated with the purpose of BIM. The cluster 3 is related to decision making. Keywords grouped into the same cluster are more likely to occur at the same time and belong to a similar research field. Additionally, the identified high-frequency keywords in Fig. 5a are listed in Table 5 under descending order of frequency of occurrences. For an easier understanding, Table 5 merges some keywords with similar meanings into one record, where the total link strength measures the summation of a node's link strength over other nodes connected to it. It can be seen that the keywords that appear most frequently are basic concepts about BIM and construction. Apart from these two keywords, the top keyword "architecture design" appears frequently under the highest frequency of 975 and the largest total link strength of 4928, revealing that an in-depth investigation has been conducted on the research focus of architecture design. Meanwhile, architecture design demonstrates a close interrelatedness with BIM, which can therefore be regarded as a major application domain for BIM-AI integration.

The other network is from the viewpoint of keyword evolution over time, as given in Fig. 5b. The keywords are colored by the average publication year in which they had been studied in papers. That is to say, nodes in the bluer color represent keywords to be noted and discussed earlier, while keywords marked in yellow color have recently captured the great attention of researchers in recent years. Hence, Fig. 5b can visually demonstrate the development trend of research hotspots. Based on cluster results and

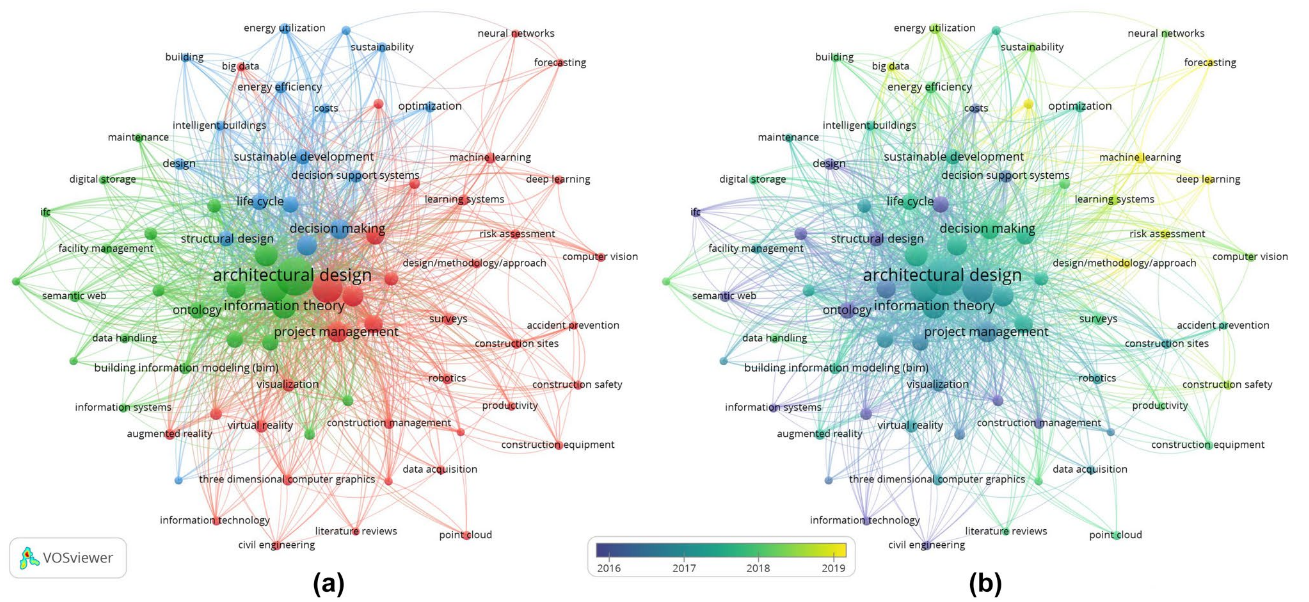


Fig. 5 Keyword co-occurrence network about BIM-AI integration in the construction industry during Jan 2000–Apr 2021: **a** By clusters; **b** By time

Table 5 Top keywords with the most frequent occurrence

Top	Keyword	Occurrence	Total link strength	Cluster	Top	Keyword	Occurrence	Total link strength	Cluster
1	Building information modeling/bim	1281	6501	2	14	Buildings	192	991	3
2	Construction industry/construction/construction projects	1117	5038	1	15	Ontology	190	853	2
3	Architecture design	975	4928	2	16	Structural design	170	851	3
4	Information theory/information management	624	3583	2	17	Sustainable development	167	769	3
5	Decision making/decision support systems	395	1907	3	18	Office buildings	139	849	2
6	Project management	310	1437	1	19	Automation	139	644	1
7	Artificial intelligence	219	1048	1	20	Visualization	122	592	1
8	Life cycle	196	1102	3	21	Interoperability	113	567	2
9	Semantics	196	1012	2	22	Industry foundation classes-ifcsystems	102	650	2

The cluster in this table is derived from Fig. 5a

temporal information in Fig. 5, it is interesting to find that the development of BIM-AI integration in construction can be basically broken down into three main phases. It can be observed that the early research interests before 2017 are related to keywords in cluster 2. Researchers mainly regard BIM as an information system for the basic task of architecture/structure design. During 2017–2018, more research interests are placed on keywords in cluster 3, which highlight the major benefits of BIM-AI integration in application value, such as cost analysis, decision making, energy efficiency, optimization, scheduling, and sustainable development. From 2018 till now, the latest research focus has shifted to keywords mainly in cluster 1, meaning that sustainable efforts continue to be dedicated to implementing various AI methods for speeding up the digitalization of construction management in Industry 4.0.

To further uncover the cutting-edge development, a citation burst analysis is performed to identify keywords that are most frequently cited in papers. As shown in Fig. 6, the keywords in the top three longest bursts are computer-aided design, structural design, and information technology, whose popularity has lasted for the first 15 years. Since 2010, research content incorporating the concept of AI along with digital technology, like the algorithm, radio frequency identification, data handling, natural language processing system, point cloud, neural network, IoT, have obtained surging citations. That is to say, the latest publications attempt to seek digital solutions in construction engineering and management largely based upon BIM-AI integration. To further retrieve the knowledge domain, we implement a statistic method named the log-likelihood ratio (LLR) to cluster keywords in a more accurate manner. As summarized in Table 6, 8 co-citation clusters can be identified, which provide references for the deeper investigation of advanced research of BIM-AI integration later. The value of Silhouette for each cluster is larger than 0.66, indicating the high degree of homogeneity and meaningfulness embedded in these extracted clusters.

3 AI Potential in the Full Lifecycle of the BIM Project

Currently, BIM is playing a leading role in revolutionizing the construction industry, which incorporates technological, agential, and managerial components to continuously digitalize the building representation process [27]. That is to say, BIM can serve as a multifunctional set of instrumentalities for specific purposes that are increasingly integrated [28]. Beyond the 3D model, BIM can offer a pool of information to support project management and exert substantial impacts on aspects of economic, social, and environment. According to a survey [29], BIM brings project delivering benefits in the phase of planning and design, construction, and O&M accounting for approximately 55%, 35%, and 10% of BIM adoption, respectively. In other words, BIM has gone far beyond the design phase. Since BIM helps digitalize every aspect of the building's lifecycle, a lot of data will be accumulated in a single phase. It is believed that the integration of BIM and AI will be more and more common.

Due to the nature of BIM in providing data-rich 3D visualizations and solid data about projects, AI is an ideal solution to be easily integrated with BIM to facilitate fast information retrieval and analysis across the full lifecycle of construction projects. It is worth noting that the great potential of AI is to offer smarter and more informative insights

Fig. 6 Results of the top 25 keywords with the strongest citation bursts

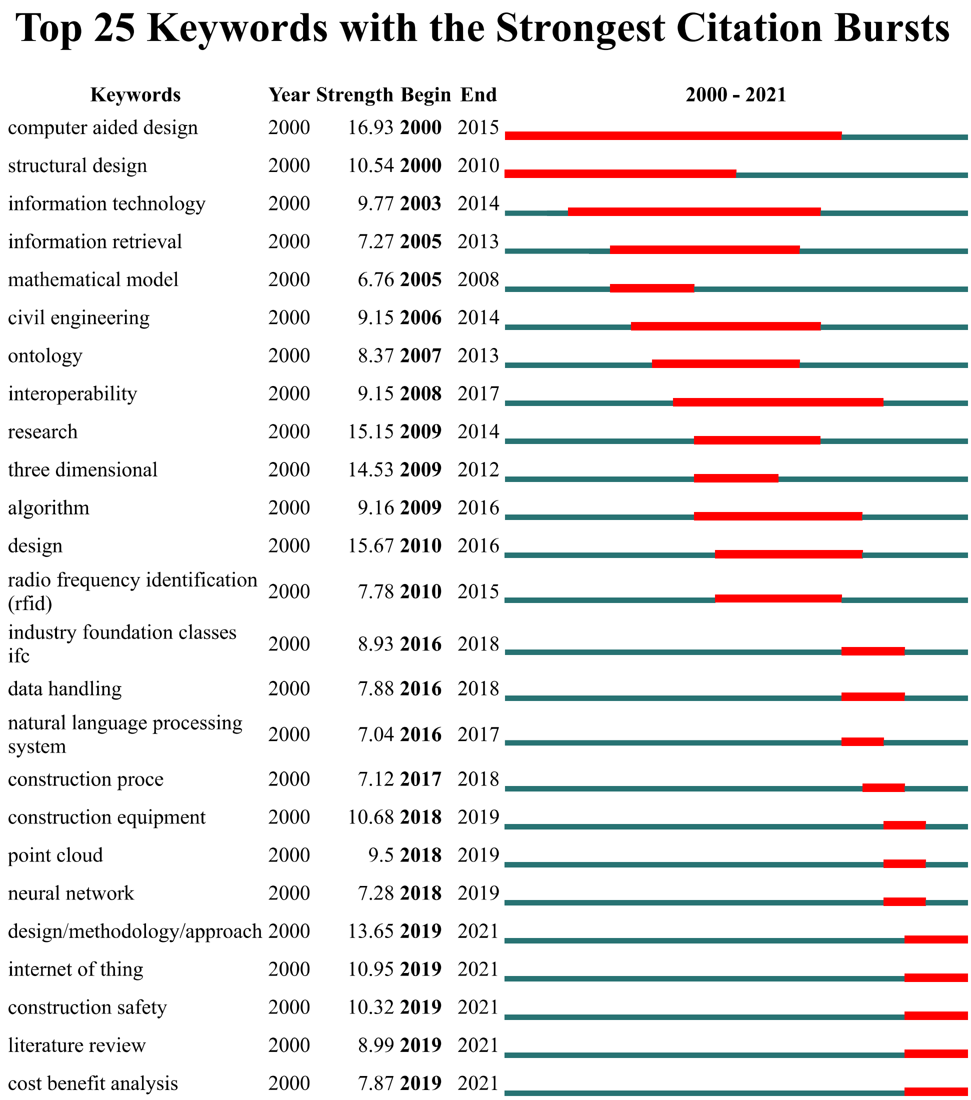


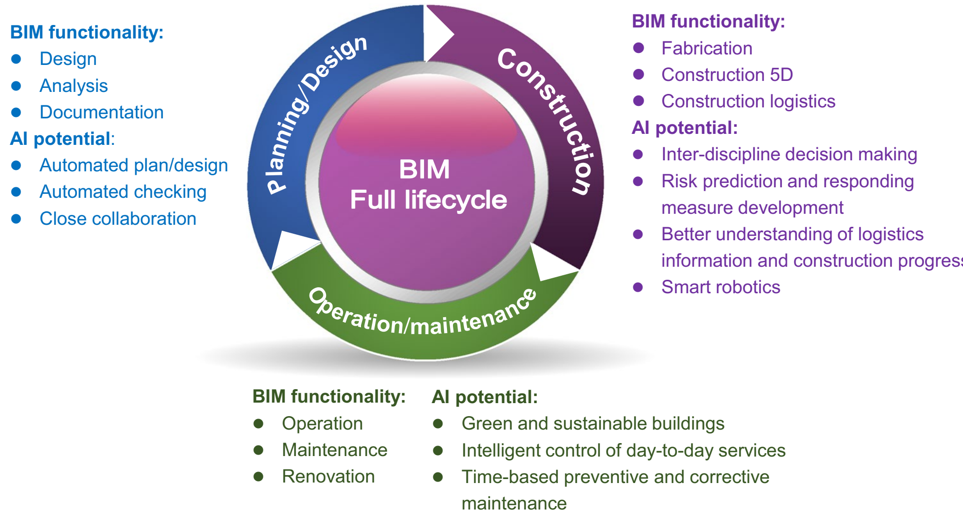
Table 6 Summary of the identified clusters by LLR

Cluster	Silhouette	Three representative keywords in each cluster	Description
1	0.663	Machine learning, deep learning, convolutional neural network	Various machine learning algorithms
2	0.724	Visualization, point cloud, laser scanner	Computer vision
3	0.744	Computer-aided design, structure design, intelligent design	Design phase management
4	0.693	Information technology, collaboration, decision	Information technology and its purpose
5	0.680	Automated compliance checking, semantic system, natural language text	Text data mining
6	0.667	Construction safety, risk management, safety	Safety management
7	0.782	Radio frequency identification, internet of thing, smart technology	Advanced technology
8	0.944	As-built documentation, facility management, energy utilization	Operation & maintenance management

p value for clusters 1–7 is 1.0×10^{-4}, and p-value for cluster 8 is 1.0×10^{-3}

into the digitally built environment created by BIM, allowing for intelligent exploration and optimization in different stages of the BIM-based project to reach higher project efficiency, quality, collaboration, and sustainability. Moreover, the summary of AI potential in Fig. 7 is determined according to two pieces of evidence. One is three major phases of BIM utilization, including planning/design, construction, and operation/maintenance. The other is three extracted

Fig. 7 Potential of BIM-AI integration in three phases throughout a project's lifecycle



clusters in the keyword network of Fig. 5. Cluster 1 in red color indicates that AI is outstanding in its self-learning ability for construction safety management. Cluster 2 in green color shows that AI is beneficial for intelligent design work. Cluster 3 in blue color presents that AI contributes to sustainable development. To sum up, the AI potentials in the three project phases that are worthy of special attention are briefly introduced as follows:

(1) Planning and design phase: Before the start of physical construction, it is necessary to create detailed plans for the project development concerning resources, schedule, budget, dependencies, and others. BIM can be introduced as a design tool to more efficiently formulate well-prepared plans and design schemas fitted to the desired client demand, time scale, and workflow, which is expected to reduce errors, cost, duration, and irrational processes in the practical project. BIM relying on commercial software (i.e., Revit, Synchro, etc.) plays a vital role in transforming simple drawings to be digital models under the functionalities of visualization, navigation, and parametric modeling [30]. When the AI techniques are integrated into the BIM software, the AI potential lies in automating both the design/review process and then reducing dependency on expert knowledge and judgment. On one hand, AI provides opportunities to realize the automatic plan and design through generative design, which is expected to investigate possible permutations of solutions and then produce design alternatives. On the other hand, AI is capable of automatically checking and analyzing the detailed 3D model/animation with semantic information, which can eventually offer a comprehensive overview of the project for easier understanding and modification. To be more specific, there have been a few attempts to leverage BIM and AI to support the automated design and drafting at different levels of detail (LoD) [31]. LoD standing for the complexity of a 3D model has developed from LoD 100 to LoD500, and thus more building information in terms of orientation, location, shape, size, quantity, and some non-graphic information will be enriched in BIM [32]. An issue in basic 3D modeling is that it is a little far away from the actual project due to the lack of accurate project plans and estimates. Many efforts have been made to turn the concept of 3D BIM into 4D/5D BIM by incorporating the additional dimension of schedule and cost, enabling better-planned and more cost-effective construction [33]. Meanwhile, it is also necessary to refer to rule inferencing and machine learning algorithms for code compliance checking [34]. Therefore, the problem about whether the established model meets the design standards and requirements can be automatically checked, which helps to lead to a high-quality and efficient BIM-enabled design phase. Moreover, the BIM-based collaborative design is another advantage to be noted. To maximize the value of improved project delivery and efficiency from collaboration, implementation of AI has potential to further boost the co-design practice through exchanging design information in the standard data format among a group of participants.

(2) Construction phase: This is a phase of executing physical construction. BIM helps to create a solid link between the design and construction, aiming to carry out the plan made in the previous phase with fewer unnecessary reworks, conflicts, and errors on site [35]. The great potential of AI is highlighted in the following three points. Firstly, with the help of machine learning algorithms, rich data about the ongoing project from BIM can be continuously explored by various machine

learning algorithms to predict and prioritize high-risk issues, and then prevention measures can be taken at an early stage to ensure construction safety. Various techniques of IoT, such as unmanned aerial vehicles (UAVs), augmented reality (AR), location tracking, and others, can also be combined with BIM to improve identification and analysis of potential field safety risks and enhance the real-time communication in managers and workers. That is to say, such integration of BIM and AI contributes to automated construction monitoring and control, which is experiencing fast growth in site safety management to proactively address potential issues and prevent casualties. It has been proven to overcome limitations of manual safety checking, such as low accuracy, discontinuity, inefficiency, and labor-intensive [36]. Secondly, the 4D BIM simulations of construction schedules and activities are applicable to handle construction logistics for the improvement of construction productivity. More specifically, the adoption of BIM and AI can provide a better understanding of logistics information, detection of conflicts, supervision of construction progress and supply chains, and coordination of different activities [37, 38]. As expected, the inefficiencies and mistakes that slow things down can be eliminated, and thus the construction process will run more smoothly [39]. Thirdly, smart robotics equipped with different knowledge can be developed to replace humans for taking semi-automatic or full-automatic construction activities. They are beneficial in decreasing worker exposure to hazardous environments, reducing labor costs, and streamlining the construction process, which can further guarantee the safety, efficiency, and sustainability of construction.

(3) O&M phase: When the construction is completed, the project will enter a new phase called O&M to operate and maintain a constructed facility to not only meet the anticipated functions over its lifecycle but also ensure the safety and comfort of users. It is known that O&M takes the most of the time within the lifecycle, leading to a large amount of cost accounting for around 60% of the total project budget [40]. However, BIM applications for effectively operating and maintaining facilities are still insufficient. It is well known that traditional decision-making in facility management is largely based on facility managers, but it is error-prone and costly. To tackle this issue, AI has great potential to provide an efficient solution for informing more reliable decisions. For example, the joint deployment of BIM, smart IoT devices, and data mining methods under the existing BIM Application Programming Interface (API) has been proven useful in integrating the standardized information inherited from the design and construction phase along with additional information pertaining to the O&M phase into as-built models [41]. A generic BIM-based framework encompassing the BIM model, relational database, and cloud computing can be established to maximize the value of the collected time-series data by the full exploration and BIM model updating towards the goal of green and sustainable buildings. In other words, the AI application in the O&M phase holds the opportunities to visualize various aspects of the facility and comprehensively analyze the building's operational performance, which helps to automatically recognize and predict the risk of error or failure before its occurrence. Accordingly, a wide range of O&M activities, like maintenance and repair, emergency management, energy management, and others, can be conducted in a data-driven manner to further embrace the benefits of BIM [12]. As a result, the day-to-day services can be controlled in an efficient, economical, and reliable manner. Time-based preventive maintenance detects the potential risks and adjusts the ongoing operation prior to unexpected events. Corrective maintenance implemented after the occurrence of problems strives to repair the problematic parts and get them back to the normal status as quickly as possible.

4 Advanced Research Interests of BIM-AI Integration

According to LLR-based keyword clustering in Table 6, we will focus on six advanced research interests to demonstrate the effectiveness of BIM-AI integration in various aspects of the civil engineering realm. For a clear understanding, Fig. 9 displays the logic for the determination of targeted research interests, where the goal of each research interest along with the most relevant clusters of keywords are highlighted. In other words, a total of six emerging research topics regarding the BIM-AI integration are selected on a basis of the captured 8 clusters (see Table 6) from Sect. 2. Bibliometric analysis. Those research topics include BIM automated design and rule checking, 3D as-built reconstruction, event log mining, building performance analysis, VR/AR, and digital twin. Also, key points of the six determined research interests have been summarized in Fig. 8. It should be noted that the application range of all six topics covers the full lifecycle of a BIM-based project, including the phase of design, construction, and O&M. All the representative pieces of literature discussed in this section and listed in the tables have high citations over 100 or they are published in the last five years. Therefore, these selected papers can be highly representative in BIM-AI integration, which can offer a valuable reference for digital transformation in the construction industry.

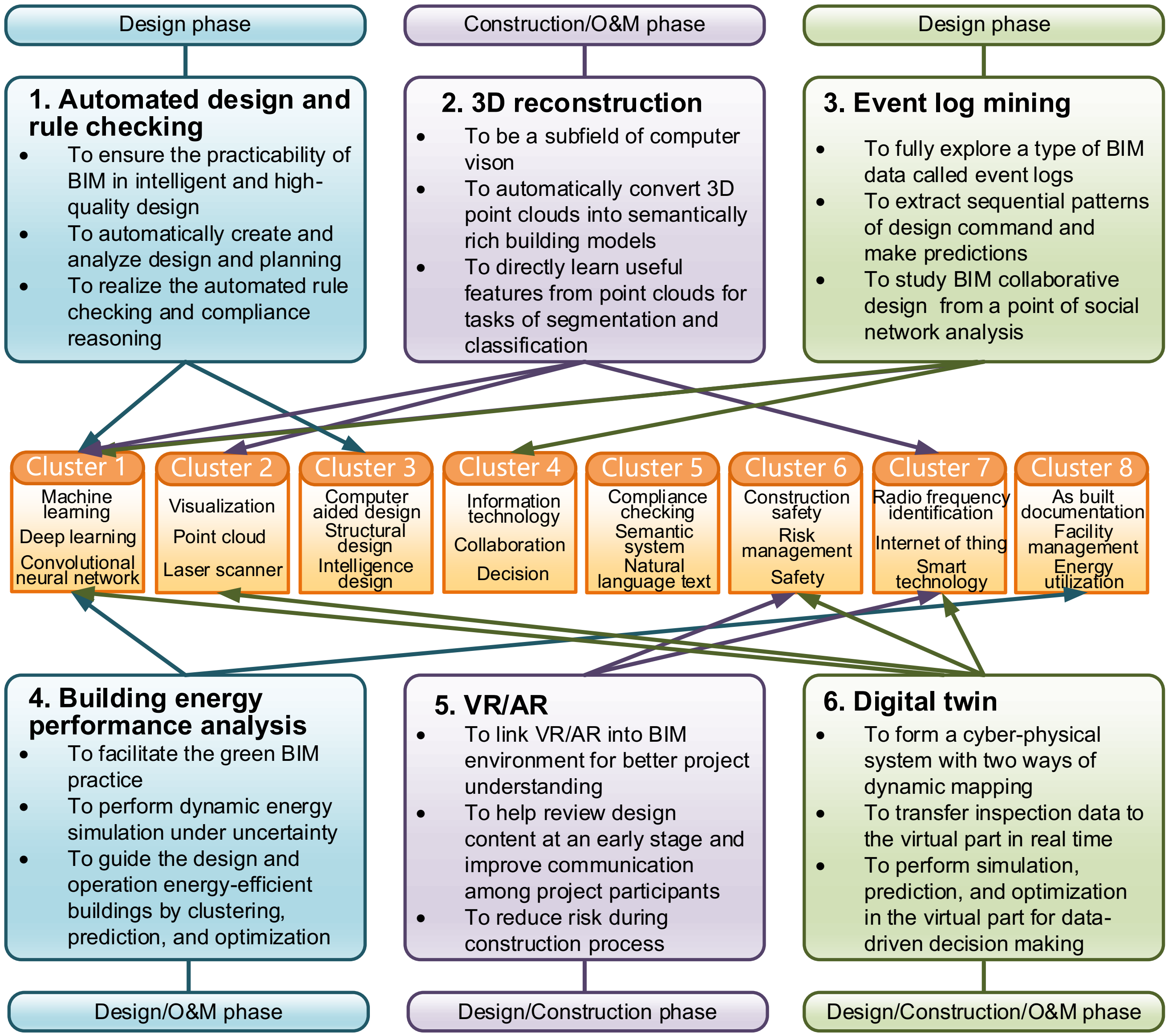


Fig. 8 Logic diagram about the selection of six advanced research interests

4.1 BIM Automated Design and Rule Checking

It is known that one of the most significant advancements provided by BIM is to extend and enhance the computer-aided design. Far more than the simple use of creating a building model, BIM acting as a shared knowledge center provides mass information at different levels of detail to enrich the model. Therefore, it is meaningful to properly leverage the flow of design-related information incorporating geometric and semantic aspects, which can potentially facilitate the automated creation and checking of drawings. It is worth noting that the necessity of developing BIM-AI integration in the design phase comes from two main parts. For one thing, the manual modeling process relying on intuitive knowledge could be time-consuming, laborious, and error-prone. Meanwhile, the modeling process exactly follows the plan, which is unable to automatically adjust to the ever-changing conditions. Thus, with the help of data-driven approaches, it is desired to develop an intelligent modeling framework with a higher degree of automation and flexibility. For another, design models under a high degree of inherent complexity need to comply with sets of well-defined building regulations, codes, and standards as well as project requirements. The current model checking process largely depends on manual inspection in the nature of unreliability and subjectivity, which has become a costly bottleneck causing undesired delays and errors during the project execution. To ameliorate the problem, it is essential to develop the automated rule-based compliance checking approaches to perform the design assessment of a building model, which is expected to add additional value to the BIM practical applications. The research question can be raised as: how to carry out automated design and rule checking with less manual effort and high efficiency. The advantage of this topic is to ensure the practicability of BIM level 3 with intelligent and high-quality alternative design generation and error elimination.

Some existing studies have attempted to answer the question of how to automate and optimize the design task. As listed in Table 7, the object of BIM-based automated design is not limited to the architecture components, which can be extended to the structure of a building and the construction site. For example, from the architectural aspect, Liu et al. [31] integrated the rule-based algorithm in consideration of trades' know-how with an optimization algorithm to realize the automated design and planning for boarding layout of light-frame buildings, and thus various design alternatives could be assessed continuously to generate an optimal boarding design under the minimized material waste. Deng et al. [42] developed a BIM-enabled framework to automatically integrate graphic and non-graphic drawing information and generate readability fabrication drawings for façade panels, which was proven useful in better representing the curved panels using a new flattening algorithm. From the structural aspect, Hamidavi et al. [43] raised a workable BIM-based solution to realize the automated creation and analysis of optimized structural design meeting a set of criteria, allowing for building stronger ties with disciplines of architects and structural engineers and greatly reducing design time. From the aspect of the construction site layout planning. Kumar et al. [44] presented an automated framework to exploit information from BIM for building dynamic layout models under the accurate estimation of required facility size and space availability, and then an optimization algorithm was implemented to lower the total cost and travel distance. It has been studied that BIM automated design is beneficial for both the architecture design and structure design tasks. There are great opportunities to speed up the design procedure and eliminate errors from manual planning.

After model generation, how to automatically detect the potential design flaws hidden in the model with fewer manual interventions is another topic of interest. To check whether a model fulfills a wide spectrum of requirements stipulated by design standards and codes, a critical step lies in the rule interpretation. However, evaluation of a model against design codes and guidelines is not a straightforward task due to the challenges from the inherent complexity of building design rules and the incapability of computers in directly understanding the natural language-format rule and efficiently capturing key information from disorganized documents. Currently, most checking tasks are still performed manually, leading to costly, cumbersome, and error-prone procedures [53]. To fill the practical and technical gap, some studies concerning the automation of rule-checking procedures have been performed, as outlined in Table 7. For example, Zhang et al. [49] combined the NLP techniques with the semantic analysis and logic-based reasoning to facilitate the automated information processing and compliance reasoning, contributing to checking the compliance of BIM-based building designs with building codes in an automated manner. Ghannad et al. [50] deployed an emerging open-standard schema named LegalRuleOn one hand (LROn one hand) to formalize the design rule sets with rich semantics, ontologies, and parameters and then applied the Visual Programming Language (VPL) under a graphical notation to capture required information for the rule implementation, aiming

Table 7 Some previous studies about BIM automated design and rule checking

Purpose	Method	Achievement	Related reference
Automatic architecture design	Rule-based design algorithm; Evolutionary algorithm	It can provide automated design support for boarding, façade, floor tile, and others, and make optimization according to the customized and changeable requirements.	[42, 45, 46]
Automatic structure design	Mathematical functions	It can automatically generate optimized structural design based on the architectural model and enhance collaboration among team members.	[43]
Automatic site layout planning	Metaheuristic algorithms	It can facilitate more rational arrangements for a higher degree of efficiency and safety in on-site operations.	[44, 47, 48]
Automatic code compliance checking	Natural Language Processing (NLP); Semantic enrichment; Unsupervised learning; Visual programming language	It can reduce manual efforts in extracting regulatory information from documents to form logic rules and then automatically provide reliable checking results at the early stage of design.	[49, 50, –52]

to execute the rule-checking process against a BIM model automatically and assess design quality iteratively. What's more, Sydora et al. [51] proposed an integrated framework to bridge the task of automated BIM model checking and automated interior design, where a more user-friendly rule language based upon the BIM standard Industry Foundation Classes (IFC) was developed to express rules under logic operations for examining the model compliance and generating several alternative interior designs. Accordingly, Natural Language Processing (NLP) and semantic web technology are two new solutions to improve the flexibility of information extraction and the reusability of regulatory representations. Both of them can effectively assist in decreasing the cost and time in encoding rules for the automated rule checking process. More specifically, NLP is responsible for translating human-readable rules into the computer-processable rule format, while semantic web language, like resource description framework (RDF), web ontology language (OWL), and others, is used to describe the complex knowledge of schema, instance, and relevant rules through creating a graph, and thus extracted information from regulatory documents can be expressed in a logic-based manner. For an intuitive understanding, Fig. 9 provides a technical framework based on semantic web to perform knowledge extraction and discovery from a BIM-based data platform.

4.2 BIM and 3D As-Built Reconstruction

Apart from the as-designed BIM, another type called the as-built BIM acts as a semantically enriched digital model to truly reflect the as-built conditions of a facility, where the details cannot match the available designed models. It should be noted that laser scanning and photogrammetry have been extensively adopted to make a survey of existing facilities. These popular yet inexpensive measurement technologies have given easy access to a bunch of point-cloud data containing metric information through distance measurability or multi-view imagery. These acquired point clouds serve as evidence to locate and identify various objects in complex and irregular shapes. Based upon the point clouds, there are three typical tasks to be implemented for the creation of as-built models, including (i) to model the component geometry, (ii) to assign categories and materials, and (iii) to build interrelationships among components. However, these collected point clouds show the characteristics of randomness, sparsity, and non-structure, which will inevitably suffer from a lot of noise and occlusion [55]. The current solution for noise removal is largely dependent on manual procedures. Meanwhile, expert modelers often subjectively explain the point clouds and then manually build the model and enrich its semantics. Such manual methods could be inefficient and unreliable. Moreover, the commonly used BIM software, like Autodesk Revit, Synchro, Tekla, etc., is incapable of managing point clouds and linking them to the BIM model. To fill the research gap, a critical problem to be addressed is how to make full use of rich data sources from the raw point clouds to reproduce the 3D parametric as-built model automatically and accurately. Since computer vision falls into an interdisciplinary scientific field to gain a detailed understanding of visual data by computers, the ongoing research about BIM and 3D reconstruction can be treated as a subfield of computer vision to drive the Scan-to-BIM process to be more automatic and accurate [56].

Semantic segmentation is an important step in understanding 3D scenes, aiming to classify similar point clouds into homogeneous regions [57]. But point cloud segmentation requires prior rules about the semantic labels, and in the meantime, it is insufficient for irregular-shaped objects and complicated scenes. To address these weaknesses, recent researchers have endeavored to develop numerically robust and fast algorithms including mathematical models, machine learning, and deep learning approaches, as listed in Table 8. To be more specific, the mathematical model is the early stage for reconstructing semantically rich BIM from 3D

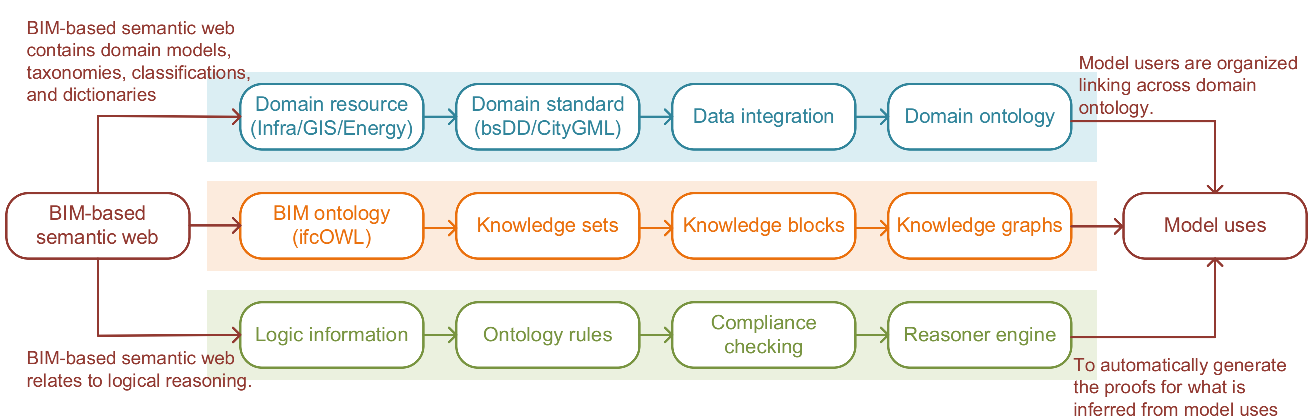


Fig. 9 Framework of knowledge extraction and discovery in BIM [54]

Table 8 Some previous studies about BIM and 3D as-built reconstruction

Purpose	Method	Achievement	Related reference
Automatic interpretation and reconstruction of BIM models from point cloud data	Mathematical model	It can convert point clouds into BIM models with accurate geometries and rich semantics, and thus it can handle complex scenes with irregular-shaped and repetitive objects.	[58–60]
	Machine learning	It can cluster and classify segments to reconstruct BIM model objects and their topology.	[61]
	Deep learning	It can find a direct mapping from point cloud to object labels under less feature engineering, which helps to achieve better performance in point cloud segmentation and classification in complex 3D scenes.	[62, 63, –65]

point clouds. For example, Barazzetti et al. [58] presented a semi-automated method based on a mathematical function named NURBS (Non-Uniform Rational B-Splines), which could generate a set of NURBS surfaces as a reconstruction of external object surfaces along with their geometric anomalies from point clouds. Then, Jung et al. [59] turned the as-built modeling into a fully automated process through room segmentation from point-cloud inputs, floor-wall boundary extraction under the offset-space noise filtering, floor-wall boundary refinement by linear regulation under the constrained least-squares method, the inside- and outside-wall component modeling. They focused on modeling the building interiors containing multiple rooms rather than just the surface representation, and thus the 3D output model contained volumetric wall components with detail-rich objects, such as windows and doors. Instead of semantic segmentation, Xue et al. [60] proposed a novel semantic registration method for semantically rich BIM reconstruction, bringing two opportunities in enhancing the effectiveness and efficiency of modeling performance. One is that multimodal optimization (MMO) algorithms for finding all optimal solutions were carried out to handle the complex scenes incorporating irregulated and repetitive objects; the other is that the architectural design knowledge hidden in point clouds, like symmetry, parallelism, repetition, etc., was fully utilized to eliminate noise and limit search space. In general, the data-driven algorithms mentioned above can well process the inherently noisy, sparse, and unstructured point cloud data, which benefit in driving the automated process of converting dense point clouds into 3D volumetric models. However, these methods too heavily rely on the combinations of hand-crafted features, and they may lack the capability of extracting neighboring information of points.

Currently, more special attention has centered on the use of deep learning to directly learn predictive features from point clouds, which is particularly useful for large-scale datasets with no need for feature preprocessing. In particular, the PointNet proposed in 2017 [66] is the pioneering work to accelerate the development of point cloud segmentation, which can directly operate on the raw point cloud to derive high-quality features. After that, a lot of studies for automatic as-built BIM creation are developed based upon the improvement of PointNet. For instance, Chen et al. [62] performed a modified PointNet architecture to understand the indoor point cloud scene following the combined tasks of edge-based segmentation, classification with context, and component merging for building element recognition. Ma et al. [63] verified the viability of two state-of-the-art algorithms named PointNet and Dynamic Graph Convolutional Neural Network (DGCNN) in semantic segmentation of point clouds of building interiors, which could augment the pre-existing 3D BIM for as-built modeling. Xu et al. [64] developed a new 3D object detection network named CorDet to concurrently extract the object-level and corner-level features using deformable convolutions and represented BIM objects of indoor building primitives by class-specific, oriented, and symmetric 3D bounding boxes, whose overall performance was proven to surpass the segmentation approaches. For an intuitive understanding, Fig. 10 provides an example of the deep learning-based reconstruction results. Since deep learning is superior in learning high-level features from point data itself, it has paved a more appropriate way to semantically segment point clouds for reaching great efficiency and satisfactory results. That is to say, deep learning-enabled approaches are more powerful and robust for the automatic process of creating detail-rich models from the point cloud data, which can meet the demand for efficient and accurate as-built BIM. Overall, it has been seen that the increasing automated 3D reconstruction has gradually taken the place of laborious operations in the scan-to-BIM process.

4.3 BIM and Event Log Mining

During the BIM-enabled design process, an important type of data called BIM event logs can be automatically generated by BIM modeling software, such as Autodesk Revit, Tekla,

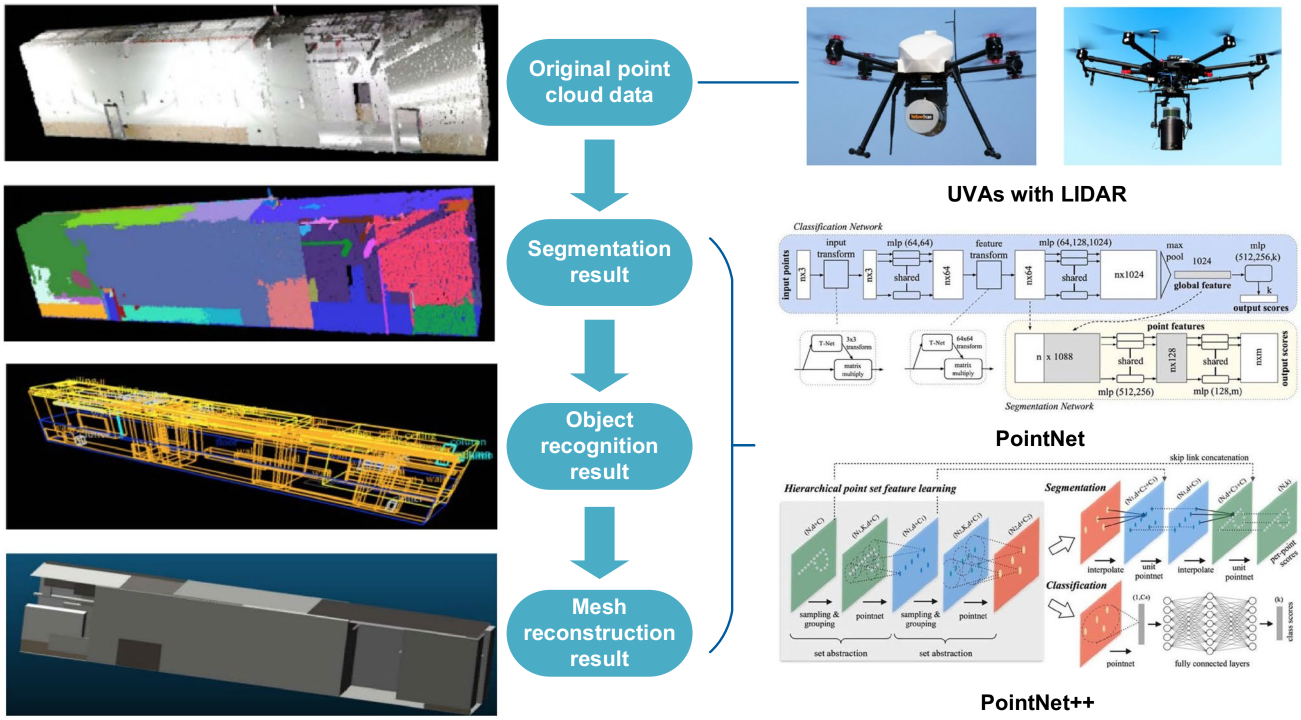


Fig. 10 Example of automated scan and 3D reconstruction [62]

and others, which will be heavily accumulated into a large volume to bring some characteristics of "big data". Notably, event logs in the format of pain text are similar to the web server logs. It is known that web logs can be interpreted as the detailed and objective recording of all operations and events in an information system in a chronological order, which has been developed to maturity for mining web usage, content, and structure. That is to say, valuable information derived from web log mining has been adopted to develop web content personalization and recommendation systems for web intelligence and greater surfing experiences. In the same way, the BIM event log is made up of process-specific sequences related to the modeling activities, including cases, persons, time stamps, and others, which is the value-added data to track the executed procedure that has occurred in the entire design session. However, BIM itself is incapable of manipulating and exploring these rich event logs for knowledge discovery. In this regard, the research question is how to implement proper data mining algorithms to reveal meaningful insights into the model evolution embedded in these logs. To narrow the gap between BIM event logs and data science, existing studies have leveraged different data mining approaches to investigate the ever-increasing availability of BIM event logs. It has been found that BIM event log mining is a comparatively new research topic, which has the potential to return promising results to better understand and improve the overall design process for the following crucial purposes. Its practical value is to inform data-driven decision-making towards better management of the design phase. The basic framework of BIM event log mining has been displayed in Fig. 11. There are mainly three types of functions in the event log mining, including design performance evaluation, design activity prediction, and social network analysis, as listed in Table 9.

The first main task is to extract sequential patterns of design command, which is helpful in assessing the design performance. Yarmohammadi et al. [67] firstly conducted sequential pattern mining to discover the presence of common command sequences by Generalized Suffix Trees (GST) and then estimated the average time required to finish these patterns for characterizing the designer's performance and determining the difference among designers. Zhang et al. [68] retrieved the most frequent patterns of command sequences using a process mining algorithm named the customized PATRICIA, which could serve as the baseline to measure design productivity. Apart from the statistical methods, Pan et al. [69, 70] referred to the novel clustering algorithm under the integration of Kohonen clustering network (KCN) and fuzzy C-means (FCM) to obtain design behavioral patterns, which could easily distinguish design productivity at different time periods into the high, medium, and low level and group designers exhibiting similar efficiency into the same cluster. In short, these high-quality extracted patterns can bring two great benefits in practical applications.

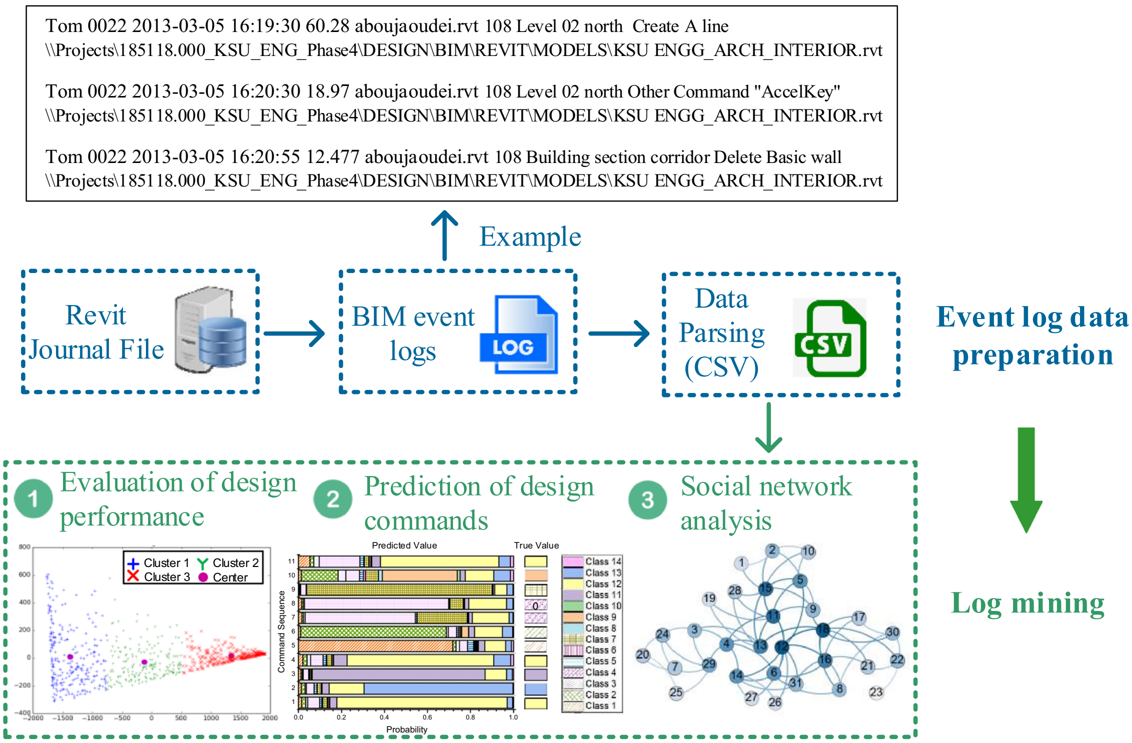


Fig. 11 Framework of BIM event log mining

Table 9 Some previous studies about BIM and event log mining

Purpose	Method	Achievement	Related reference
Design performance evaluation	Process mining; Machine learning	It can extract patterns of sequential commands to objectively evaluate the design behavior of different designers and rationally arrange the work.	[67, 68, –70]
Design activity prediction	Deep learning	It can accurately predict the next possible design command, which generates data-driven command recommendations according to designers' preferences.	[71, 72]
Social network analysis	Statistical method; Deep learning	It can investigate characteristics of complex collaboration during the design process from the view of social networks for strategically arranging work.	[40, 73]

On one hand, the patterns reveal and highlight the important characteristics of the design behavior of different designers, contributing to measuring and comparing designers' productivity in an objective manner. On the other hand, they enable project managers to strategically arrange personalized and rational work, allowing for satisfying the demands of the project and enhancing the modeling efficiency.

Another point to address the concern about maximizing the strength of the growing amount of BIM event log data is the deep learning-based prediction of sequential design commands. Pan et al. [71, 72] carried out the recurrent neural network (RNN) and long short-term memory neural network (LSTM NN) to learn sequences of the designer's behavior from the abundant BIM event log, resulting in reliable predictions about the next possible design command that could be adaptable to the changing conditions. As a result, such a data-driven command recommendation can be provided to potentially guide the design phase and reduce the uncertainty and subjectivity in the modeling process. By simply following the recommended commands, it is possible for designers to speed up their work and avoid some unnecessary mistakes.

Moreover, since a group of designers will participate to ensure the success of the BIM collaborative design process, some efforts have emphasized social network analysis (SNA) to monitor and evaluate the complex cooperation. Zhang et al. [40] built a social network using implicit process and inter-organizational information extracted from BIM event logs to graphically describe the information exchange and behavior interaction among designers, aiming to achieve a better understanding of designers' performance and roles in collaborative organizations through analysis of network structural characteristics. Except for the commonly-used centrality metrics, Pan et al. [73] developed a novel community detection algorithm combining a graph embedding method named node2vec and a clustering method named Gaussian mixture model to extract the potential clusters of designers who work more closely. For one thing, the SNA results provide objective insights into the collaboration patterns, individual roles, and the possible work transmission for a better understanding the complex execution of BIM projects. For another, SNA offers a valuable opportunity to guide project managers in strategically arranging work, aiming to realize the goal of maximizing cooperation chances and ensuring the project success.

To sum up, BIM event log mining based on varying data analysis approaches, including the statistical methods, machine learning algorithms, and deep learning algorithms, paves a new way to understand the complicated design phase from a data layer, contributing to boosting the BIM-enabled design for higher design efficiency and quality. The practical value to be highlighted is that BIM event log mining can serve as a data-driven tool, which helps project managers define staffing strategy more objectively and helps designers to do the modeling process more smoothly.

4.4 Green BIM and Building Performance Analysis

Since sustainability turns out to be a key factor in the construction project, green BIM practice under the integration of BIM and building energy performance analysis has become a hot topic for green building development. The core concept of green BIM is to conduct a model-based process of generating and managing coordinated and consistent building data towards the goal of sustainability [2]. According to a report created by McGraw-Hill Construction Company [74], although green BIM practice is becoming an emerging trend, there remains a research gap between the full potential of BIM and the sustainable outcome. The research question that has aroused is how to use BIM to support the development of energy-efficient buildings during the entire project lifecycle. As expected, this topic can bring benefits in various aspects of sustainability, such as (i) to improve the building performance in the early design stage, (ii) to reduce waste at the construction stage, and (iii) to monitor the sustainability performance of building at the operational stage [9]. Notably, embodied phase and operational phase will take around 10–20% and 80–90% of energy demand in the entire project cycle, which require more focus for better energy control [75]. It has been found that the BIM-enabled energy analysis process is easy to follow for facilitating sustainable development, and thus a participant with no professional knowledge and simulation skills can perform it to formulate some environmental-friendly decisions [76]. With the advent of various AI techniques, BIM for building energy performance analysis has played critical roles in two perspectives as shown in Table 10, resulting in data-driven energy-efficient design described in Fig. 12.

The first important task is the building energy simulation, which is not straightforward due to a lot of uncertainty in the energy modeling process. A promising and popular solution is to integrate different kinds of probabilistic and statistical approaches into energy simulation, aiming to capture the dynamic behavior under uncertainty and understand the building performance objectively [85]. Chong et al. [77] developed the continuous-time Bayesian calibration of energy models using data from BIM and building energy management systems, which could dynamically update the established model and maintain high accuracy in predicting the monthly electrical energy consumption. However, this kind of method could be computationally expensive in some cases. As an alternative approach, some studies have referred to machine learning models instead of physical simulation to effectively predict energy demand in a data-driven manner. For example, Singh et al. [78] implemented the probabilistic prediction under BIM-integrated machine learning algorithms to estimate heating and cooling loads, and then statistical analysis was performed to determine the optimal design options. Geyer et al. [79] proposed a component-based machine learning approach for predicting the thermal energy performance of buildings under high accuracy, which provided design-supporting insights to interpret and adjust parameterized components of building for reaching desired performance. Hammad [80] trained a deep neural network

Table 10 Some previous studies about green BIM and building performance analysis

Purpose	Method	Achievement	Related reference
Building energy simulation	Statistical method; Machine learning	It can simulate and predict the building energy performance, which can provide instant feedback to managers.	[77, 78, –80]
Sustainable design development	Machin learning	It can generate optimal design strategies for energy-efficient and environmentally conscious design, achieving more sustainable outcomes.	[81, 82, –84]

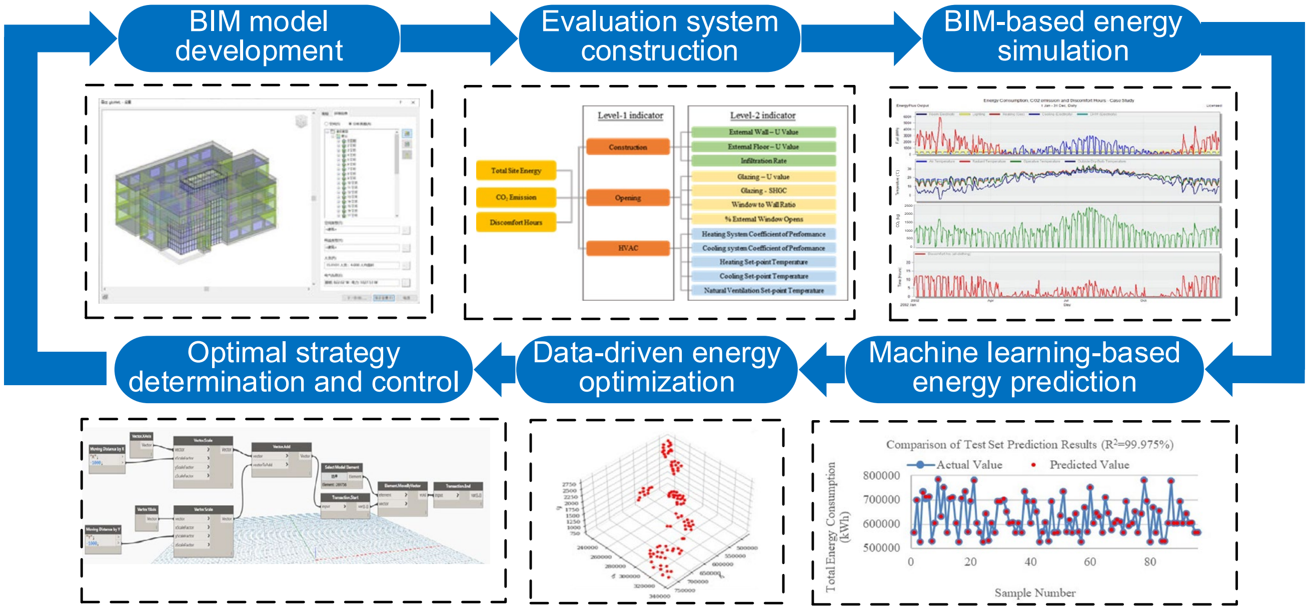


Fig. 12 Framework of data-driven green building design

to precisely predict the expected energy consumption of a given building in BIM during the operation phase, which could provide evidence to make operational measures. It has been found that the machine learning-based method can show the advantage in promising accurate energy prediction under decreased computational complexity. Also, it is more applicable to large-scale construction projects. Besides, in order to make these efficient and precise estimation tools for building energy more practical, it is expected to build them as a plugin in BIM software. The developed plugin helps to directly demonstrate the predicted results and give instant feedback to managers.

Another key task is to develop an intelligent framework for desirable energy design from the BIM data layer, which can be realized by various data mining approaches, like clustering, sensitivity analysis, and optimization methods. For example, Peng et al. [81] developed a hybrid BIM-based decision-making approach for extracting latent patterns in BIM records, resulting in useful management advice for the improvement of resource usage and maintenance efficiency in the O&M stage of buildings. Tushar et al. [82] quantitatively evaluated the impact of design variables on the building thermal performance to find out the optimal solutions of suitable input design parameters as the guideline of BIM-based design, which was proven useful to not only assure energy comfort to residents but also decrease energy costs and emissions during operation. Chen et al. [83] connected the NSGA-II algorithm with the fitness function from the LSSVM-based energy prediction, which can obtain the optimal combination of building envelope parameters to simultaneously minimize building energy consumption and maximize indoor thermal comfort. As a result, sustainable decisions about the passive design strategies and necessary design adjustments can be reasonably informed to improve design accuracy and efficiency, contributing to promoting the reduction of energy consumption and environmental contamination at an early stage. In addition, due to the availability of accumulated BIM data and the powerful analytical ability of AI techniques, it is suggested that more advanced and flexible data mining approaches need to further be incorporated into BIM to learn from energy-related data to reveal more comprehensive views of building energy consumption. These discovered pieces of knowledge are expected to offer more opportunities to establish a feedback loop for improving design and facility management in a BIM environment. Therefore, optimal strategies leading to less energy utilization in the building lifecycle can be quickly generated, which will reasonably guide the process to design and operate energy-efficient buildings.

4.5 BIM and VR/AR

Virtual and augmented reality (VR/AR) are two emerging digital tech developments to bridge the physical world and the cyber world. Acting as a computer-generated simulation, VR builds a synthetic environment to completely take the place of users' field vision, aiming to trigger interactions between the simulated world and users. Differently, AR is a mixture of computer-generated elements and the real world relying on common equipment, like smartphones, tablets, headsets, and others, which shows the information on the real-world scene to be less immersive than VR. Recent years have witnessed the surging trend of VR/AR applications in various domains, including entertainment, retail, healthcare, education, etc., which benefit from their strengths of 3D visualization, immersive and interactive environments, personalized content, cognitive enhancement, and others. Since there is a lot of geometric and semantic information about the 3D model hidden in BIM to support virtual simulation and information interoperability, it seems reasonable to link VR/AR techniques with the BIM environment [86]. Therefore, the research question focuses on the integration of BIM and VR/AR for enhancing project understanding and promoting better decision making during the entire lifecycle of the building facility, which can eventually make breakthroughs in the construction industry. The general workflow of BIM and AR/VR technology is summarized in Fig. 13.

Remarkably, since the heavy workload of the manual data processing and the delay of data transmission will, unfortunately, impede the adoption of VR/AR, a principal issue to be solved is to formulate a reliable mechanism for transferring the established BIM model along with relevant data into VR/AR engines in a fast and automated manner. That is to say, there is a pressing need to facilitate the automatic and simultaneous data exchange in BIM and VR/AR. The ideal conversion process is expected to perform real-time data synchronization and keep high data integrity between BIM design data and VR/AR environments. To actualize this goal, Du et al. [88] designed a BIM-VR real-time synchronization system (BVRS) incorporating BIM for gathering metadata, cloud servers for online calculating, game engine for offering immersive experiences, and VR headsets for improving interpersonal communication. Chen et al. [89] adopted an ontology-based approach to efficiently transfer BIM into VR/AR under the consideration of rich semantic information, which was outstanding in simplifying the geometric representation of the BIM model while trying to reserve the high consistency of the overall shape. In short, the real-time and automated data exchange between BIM model and VR platform is typically composed of three parts, including BIM data, metadata transfer, and game engine. This is the work basis for BIM and VR/AR integration, which needs to be written into commercial vendors for practicability.

Due to the nature of BIM and VR/AR, their joint usage is becoming a promising development to exert beneficial impacts in both the phases of design and construction, as outlined in Table 11. For one thing, it paves a novel way of reviewing the design schema in a realistic way from an early stage, enabling engineers and managers to conduct intuitive manipulation and interaction with large data. Based on the immersive experience in 3D architecture design, participants even in lack of specialized knowledge can gain a clear understanding of the model and easily detect design errors and weaknesses [90]. For example, Shiratuddin and Thabe [91] developed a virtual design review system for early and accurate 3D visualization of design within a federated BIM. Garbett et al. [92] created a multi-user BIM-AR system based on an Agile Scrum software development approach to reuse BIM data for achieving synchronous collaboration in an AR environment, which could provide a unique visualization experience for design support. It has been found that the AR implementation can improve the participants' responses in design by up to 20% compared to the BIM 3D visualization [93]. Khalek et al. [94] proposed a hybrid BIM-AR method to identify the maintainability concerns and make better maintainability decisions during the design stage. Lin et al. [95] combined BIM, game engine, and VR technologies for a design project, which was proven useful in improving the comprehension of the design content and minimizing communication gaps among clients, stakeholders, and designers.

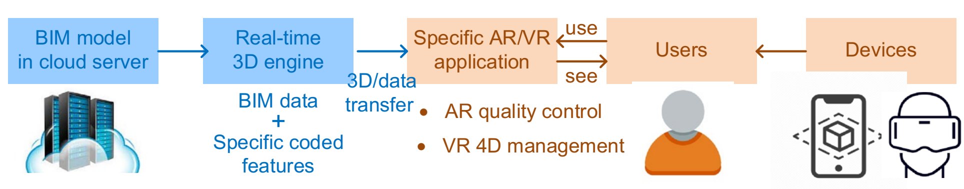


Fig. 13 Framework of BIM and AR/VR integration [87]

Table 11 Some previous studies about BIM and VR/AR

Purpose	Method	Achievement	Related reference
Data transfer between BIM and VR/AR	Cloud computing; Ontology method	It can efficiently facilitate data transfer and synchronization for semantic and geometric information.	[88, 89]
Design review	VR/AR techniques	It can improve design understanding and collaboration based on intuitive analysis and manipulation of 3D models.	[92, 93, –95]
Construction management	VR/AR techniques	It can pave a new way for project presentation and construction training, contributing to enhancing construction safety and ensuring the smoother progress of construction projects.	[19, 96, 97, 98, –100]

Reviewing the current studies, it has been found that the adoption of VR/AR and BIM outperforms the traditional 2D drawings by three major points. Firstly, the biggest advantage is to enhance the understanding of the design at its full scale with the help of advanced visualization techniques. Secondly, it can achieve the interaction between the virtual buildings and surrounding environments. Finally, it can provide an immersive and interactive experience to facilitate more efficient communication and decision making among designers and clients.

For another, since BIM-VR/AR contains first-hand knowledge about the lifecycle activities of the project, it is advisable to apply it in tackling issues in terms of scheduling, site planning, safety controlling, and others, contributing to ensuring the smoothness of the project execution under relatively low safety risk and high quality. For example, Boton [96] proposed a neutral comprehensive framework of the immersive VR-based collaborative BIM 4D simulation for carrying out the constructability analysis meetings. Getul et al. [97] performed BIM-based immersive VR under the steps of creating BIM-based modeling and planning, defining activity simulation environment, and analyzing data from VR simulations by two novel algorithms, which in turn provided suggestions for allocating workspaces on construction sites meeting the safety criteria. The topic of BIM-AR in the construction phase has been explored earlier than VR, and thus its practical applications are more mature and enjoy better usability. Jiao et al. [98] made AR work together with many advanced techniques, like cloud computing, web3D, business social networking service (BSNS), and others, to monitor the construction progress. Park et al. [99] connected BIM with AR and an ontology-based data collection template for defect inspection and analysis, aiming to give back a proactive reduction of defect occurrence during construction. What's more, Chen et al. [100] combined BIM, IoT, and VR/AR technologies to build a situation awareness system under an innovative immersive environment, which could realize three different purposes, including dynamic fire monitoring and alerting, AR-based real-time route navigation, and VR-based fire training. Accordingly, seamlessly integrating the best aspects of BIM, IoT, and VR/AR is envisaged to offer interactive renderings, spatial coordination, and virtual mockups. It is gaining more and more attention with the expectation of revolutionizing construction project management. What's more, this topic can extend to a higher level named BIM-enabled Extended Reality (XR), enabling to simulate construction projects in multidimensional digital models under the great immersion of visual, audio, touch, olfactory, and others.

4.6 BIM and Digital Twin

The concept of the digital twin originally arose from the National Aeronautics and Space Administration (NASA) in 2003 to better simulate the full life of the space capsule for mirroring and diagnosing problems that would occur in orbit [101]. This has been regarded as a precursor of the current digital twin under the ultimate vision of modeling and testing the physical entity in a virtual environment. After that, the digital twin is rapidly developing to facilitate Industry 4.0, and thus it is believed to be the top strategic technology trend. It can be explained as a virtual counterpart of the physical assets incorporating identical fidelity with the help of IoT devices and various AI methods. Based on its powerful capability of monitoring and synchronizing physical objects in real time, the digital twin provides deep insights into the system's performance and potential problems. As shown in Fig. 14, the digital twin is typically made up of a physical model, a digital model, and an essential database connecting the cyber-physical system, which can make the utmost of bi-directional data flows. To be more specific, a digital replica of a physical counterpart that is enriched with large volumes of data can dynamically imitate, model, and analyze real-world behavior. A lot of hidden knowledge is bound to embed in the virtual part, which can be deeply explored through various data mining approaches in terms of process simulation, pattern extraction, problem diagnosis, trend prediction, and others. In return, the analytical data

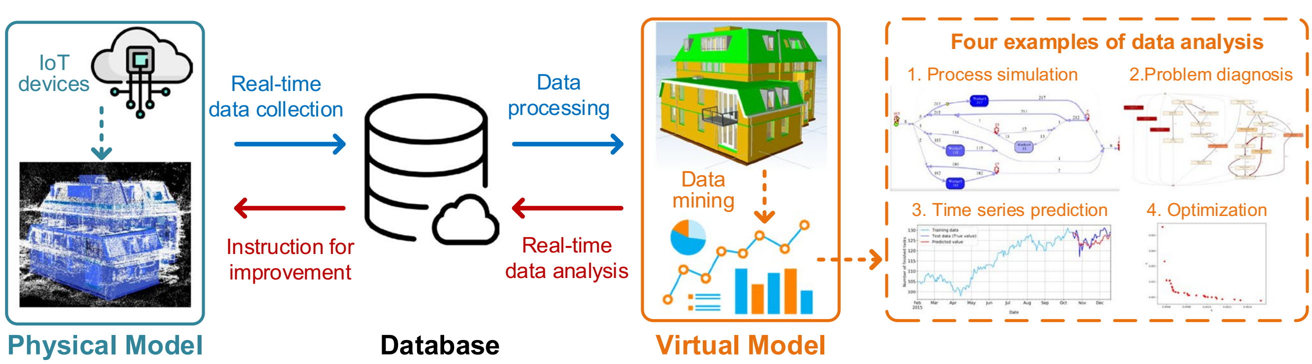


Fig. 14 Architecture of the digital twin

results can serve as the value-added evidence to guide the formulation of response and precaution for problem solving and process optimization, which can trigger the feedback decision loop to adjust the physical part constantly and optimally. In short, there are three important features in the digital twin that can distinguish the digital twin from BIM or VR/AR [102]. The first one is the emphasis on the existence of the physical model. The second one is the twin relationship between the physical world and the virtual world. The digital object can be regarded as a corresponding representation and controlling instance of the physical object, and thus any changes in one object's status can be concurrently reflected in another object's status. The third one is the full integration of rich and accurate data flow between the physical and digital objects.

To date, the application of the digital twin in civil engineering is still in its infancy, which falls behind the industry of manufacturing and aerospace. Since BIM is known as an information system, it owns the great potential to efficiently synchronize and store mass data that is continuously collected from IoT devices. In this regard, the research question can be formed as how to build a functional digital twin relying on BIM, which can facilitate a synchronized interaction between the physical and virtual entity for simulation, learning, and decision making. Some early efforts have been made to integrate BIM with IoT and advanced data analysis methods for developing more objective decision support in building facility management and maintenance from a data layer, as listed in Table 12. For example, Ma et al. [103] combined BIM, geographic information system (GIS), and reliability-centered maintenance (RCM) to support automatic data acquisition, updating, and analysis, which could reduce labor costs and increase objectivity in the decision-making of equipment maintenance in a business park. Cheng et al. [104] systematically utilized the functionality of BIM and IoT techniques along with machine learning algorithms to perceive the possible failure in mechanical, electrical, and plumbing components of facilities, which helped managers to schedule the maintenance plan and extend the lifespan of components in an evident-based manner. Clearly, such an emerging integration of BIM and IoT has proven to be a significant prototype of the data-driven system for decision making, allowing for automatic and real-time condition monitoring, evaluation, and improvement. Therefore, these existing works can serve as a foundation to further create a closed-loop paradigm for a complete set of digital twins. As expected, a developed digital twin-based model can be equipped with powerful abilities of constantly updating and learning real-time data for decision making.

Due to the great potential of the digital twin towards a high level of digitization and intelligence, some existing papers have attempted to build the BIM-IoT-based digital twin with intelligent functions, such as machine learning algorithms, data analysis methods, and others. As a result, information can be synced in real time between the as-designed and as-built models, aiming to support smart management throughout the whole lifecycle of the BIM-enabled projects. For example, in the design stage, Lu et al. [105] rapidly and reliably created a digital twin for an existing reinforced concrete bridge by extracting and adopting geometric features directly from the 3D point cloud in the IFC format, which could address the question of manual digital twinning. Lydon et al. [106] carried out the coupled simulation of thermally active building systems to support a digital twin, which could address building physics issues about energy performance at the design phase of a building project. In the construction stage, Pan et al. [108] developed a BIM-IoT-data mining-based digital twin framework for better understanding and optimization of the complicated construction work, where process mining and time series analysis were conducted in the virtual part to discover the bottleneck and predict the construction progress and then provide guidance to reasonably arrange work and staffing. Matthews et al. [109] designed and implemented a real-time object-oriented bi-directional system using cloud-based BIM, allowing for synchronizing information captured on-site and improving decision-making during the construction of a reinforced concrete structure. In the O&M stage, Lu et al. [110] proposed a digital twin architecture at building and city levels, which can successfully inform prompt

Table 12 Some previous studies aabout BIM and digital twin

Purpose	Method	Achievement	Related reference
Design management	IFC object fitting method; High-resolution model; Design structure matrix	It can support preliminary design with fewer design defects and higher design efficiency, which can also well predict and manage the design changes.	[105–107]
Construction management	Process mining; Time series analysis; Re-engineered method	It can perform real-time monitoring and control of construction quality and progress.	[108, 109]
O&M management	Machine learning; Deep learning	It can contribute sustainability to comprehensive asset management and structural health monitoring for risk mitigation and prevention.	[104, 110–112]

decisions for five services, including anomaly detection in pumps, ambient environment monitoring, maintenance optimization, maintenance task prioritization, and urban energy planning. Kang et al. [111] developed the twin-based service for bridge health monitoring, which could dynamically predict the defect of a deteriorating bridge and then create preventive maintenance plans. To sum up, the digital twin under BIM can create a high-fidelity and dynamic digital replica of a construction project, since it is able to bring together and provide insights into design, construction, and O&M data. Hence, such a digital twin model is actually responsive and continuous to evolve under the workflow of accurate monitoring, intelligent analysis, real-time response, which can potentially serve as a feasible solution to improve the entire lifecycle of a construction project. However, a noticeable problem is that the current research about digital twin development under the integration of BIM, IoT, and advanced data analysis for the AEC industry is still limited, and its practical application is at the primary stage. Since digital twin shows great potential in various service perspectives in promoting efficient design, smart construction comprehensive asset O&M, more attempts need to be put on the creation and implementation of the reliable digital twin for boosting digitalization, automation, and safety in civil engineering.

5 Future Research Directions

To date, construction project management is on the verge of digitalization, which has been greatly influenced by technological breakthroughs from the widespread adoption of AI approaches. Therefore, it is believed that the integration of BIM and AI will continuously be a hot area of research in the following years. According to the existing papers, it is worth noting that some challenges remain in the future development of BIM-AI integration. The first challenge is the excessive dependence on data-driven algorithms. Unfortunately, such a data-driven model cannot always ensure its robustness and application, which could draw conclusions that are contradicted to engineering mechanisms [113]. In fact, human also plays an integral role in decision making. In this regard, an open question is how to consider the importance of the human in cooperating with various algorithms, aiming to generate more reasonable results for project management. The second challenge is the application scope of the current research that is mainly limited to buildings. Technically, the leverage of BIM and AI can bring benefits in the real-world built environment and governance perspective from the city level. In particular, this is far more than the buildings, infrastructures, and traffic systems, which is outstanding to offer a holistic visualization of city infrastructure assets and gather actional insights into infrastructure performance improvement. It is therefore urgent to drive digitalization and increase innovation on an urban scale, which also meets the unprecedented tendency of urbanization. In other words, another open question to be solved is to promote smart city development, contributing to formulating optimized strategies and operations along with long-term resilience and ecological environment. The third challenge lies in the security and transparency of data shared across all participants with different roles. Since a key feature of BIM to be noted is collaboration and information management, an essential task to ensure the successful BIM implementation is to improve the transparency of data exchanges and contracts and keep trust among project participants. Hence, how to develop a more safe and collaborative way for information delivery under high efficiency and trust remains an open question, aiming to perform a transparent, secure, and traceable BIM process.

Notably, these three identified challenges can provide clues to determine future research directions. To tackle these challenges, we highlight the following three potential research directions, including the synthesis of human–machine intelligence, city-level digital twin, and blockchain, all of which will make great contributions to embracing the revolution in AEC industries. That is to say, it is desired to add more bodies of knowledge and practicability in these potential directions, aiming to maximize the intelligence and automation of project implementation and increase the probability of project success throughout its entire lifecycle. Although these potential directions currently meet some challenges and stay in their nascent stage, their practical and strategic value will be increasingly revealed and validated in the future.

5.1 Synthesis of Human–Machine Intelligence

This future research direction is the extension of smart project management. Although BIM and AI attempt to boost the high degree of automation and digitalization in construction projects, less consideration has been put on the human intervention and communication that is an indispensable part within the lifecycle of a project. Meanwhile, due to the complexity and uncertainty in practical engineering [114], the current BIM-AI approaches are still short of sufficient empirical knowledge and expert interpretation, leading to a lack of trust. In this regard, how to drive human-centered automation in construction management remains a great challenge. To deal with it, the reliable development of human–machine intelligence is in high demand. It is necessary to explore the human influence and take combined action with AI to facilitate more reliable and efficient construction. Its practical value lies in the increase of situation awareness and improvement of human performance, which will ultimately better instruct the participants in different roles to promote the project smoothly. The goal of this determined direction is to fully incorporate human factors, such as behavior and psychology, into the BIM-enabled project, resulting in a complicated socio-technical system for achieving human-automation interactive decision making.

As the potential solutions, it is suggested to adopt more advanced sensing technologies, such as NLP, computer-vision-based human tracking, wearable devices, and others, to monitor human activities from both the physical and cognitive aspects [115]. These collected data in large volumes offer a basis for understanding the uncertainty in human factors, which can be tightly integrated with BIM and data mining methods toward a human-in-the-loop cyber-physical system [116]. Such a close loop containing cyber parts and physical parts along with humans' cognitive thinking and reasoning capability can be reasonably regarded as the knowledge fusion from civil engineering, computer science, and psychology. Notably, the developed human-in-the-loop framework benefits in fully considering complex interactions in humans, tasks, and environments for more reliable simulation, analysis, and decision making. As reviewed, social-technical-based project management under human–machine intelligence is in the initial stage. Some studies have shown promise in topics of resilient nuclear power plant facility management [115], construction safety control [117], and infrastructure visual inspection [118]. It has been proved that the central role of human and human-related factors can potentially make the process of data acquisition and analysis more resilient and convincing. As a result, more promising decisions that feasibly adapt and respond to the participants, local conditions, and dynamic changing processes in real time can be informed. In conclusion, more future efforts can reasonably extend applications of the novel human-in-the-loop system into all phases of construction project management, contributing to better adapt to the changeable environment for various purposes of diagnosis, prediction, and optimization. It is expected to achieve proactive improvement for quality, safety, and efficiency assurance.

5.2 City-Level Digital Twin

This future research direction is the extension of the digital twin. The envisioned concept of the digital twin will not be restricted to an individual building, which has prospective potential to be extended to a higher level for augmenting smart city development and management based upon cyber-physical intelligence. Therefore, it is meaningful to combine the smart city concept and digital twin technique into a single platform, and thus the current data from the smart city can drive the data analysis in the digital twin for intelligent decision making [119]. Compared to a building, the city is a more complex living system with a wide range of aspects, including ecology, economic, social, culture, and others, which cause great difficulties in developing an effective framework of the city digital twin. Hence, a challenge to be resolved is how to maximize the utilization of digital twins to improve not only the operation and sustainability of cities but also the quality of life. The goal of this direction is to properly utilize the concept of digital twins to create a smarter city through digital simulation, analysis, and optimization in real time. As expected, the city-level digital twin can well reflect various functions of a city for different purposes, such as scenario planning, energy and waste management, mobility improvement, citizen satisfaction feedback, and others, whose practical value comes from enhancing the city's visibility and operability in support of sustainable city development [120].

As possible solutions, various IoT tools and AI methods can be integrated into BIM to map the physical truth and corresponding evolution of natural and built environments on a city scale. In other words, the real-time data collection from IoT devices for monitoring energy consumption, air pollution, traffic flow, and others provides valuable and rich foundations for the creation of a digital twin city [121]. Meanwhile, it brings new opportunities to capture spatiotemporal fluctuations about human activities and natural disasters across time and space as a complementary in situation evaluation, decision making, and coordination among different stakeholders. In other words, this proposed version of the digital twin can present a more comprehensive view of a city through real-time monitoring, simulation, and assessment to better understand the as-is condition of the city, which is practical in timely putting forward data-driven decisions for disaster prevention, response, and recovery to make the city smarter and resilient to extreme events [122]. Besides, the city digital twin has shown its superiority in performing large-scale analyses for near-real-time urban energy assessment and management over the traditional building energy methods, which can effectively determine and prioritize specific retrofit strategies for energy efficiency improvement [123]. It has been found that the USA, UK, Germany, and Switzerland have made some efforts to reveal the potential of the city digital twin in terms of data management, visualization, situational awareness, prediction, and collaboration [120, 124]. There are reasons to believe that more countries will focus on the establishment of digital twins at the city level to help governments form both short-term and long-term resilience strategies for better city control. In conclusion, the development of smart cities with digital twins is currently in its infancy. It is envisioned that more attempts in the future can make the utmost of a variety of IoT data along with socio-economic components and citizen feedback to generate a more completely mirrored city digital twin. Such a digital environment with AI-enhanced advanced analytics enables a more efficient and sustainable way for resilient city management across all phases of the lifecycle.

Moreover, it can potentially evolve into the urban brain with the powerful ability of self-perceiving, self-determining, and self-execution, which can more intelligently and adaptively support city operation and maintenance.

5.3 Blockchain

This future research direction is inspired by an emerging digital technology called blockchain, which is known as a distributed database to store data in blocks and then chain them together in chronological order. It is revolutionizing the business practice around the world, which is promised to secure a consensus on transactions under the significant advantages of high security, automation, and decentralization. Due to these inherent characteristics of blockchain, it is an ideal solution to manage the collaborative BIM platform in the nature of interdisciplinary, multiple data contributors, and decentralized project organizational structure. In particular, blockchain has developed to be an alternative approach for building trustworthy collaboration in the construction industry [125]. Therefore, it can play important roles in ensuring BIM information security through the deployment of three critical technologies, including smart contractors, distributed ledgers, and distributes-cryptographic indexing structure [126]. However, the integration of blockchain and BIM is not a straightforward task, which has remained a great challenge. In this regard, the goal of this direction is to develop an operational and efficient BIM-blockchain system. Its practical value is to reveal the potential value-added applications of blockchain with BIM, enabling a built environment under a high degree of trust for sustainable design, smart contracts and quality assurance, supply chain management, and others [127].

Some efforts have been made to extend the utilization of blockchain in BIM into the phases of pre-construction, construction, and post-construction for well saving the immutable changes, which can offer immediate benefits in enhancing the authenticity of records and confidence of stakeholders during the project execution. That is to say, the blockchain holds the data generated by IoT in a transparent, secure, and convenient environment, while BIM as a baseline tool promises to digitize the construction project and increase collaboration [128]. The potential role of blockchain in BIM can be performed from the following aspects. Firstly, the marriage of BIM and blockchain has shown its outstanding performance in securely tracing the revision of BIM data for the improvement of BIM data audit, provenance, and accountability, and thus each participant in a construction project is not allowed to change information retrospectively [129]. Secondly, since blockchain is proven effective in addressing problems of data security and privacy, transaction speed, modification tracking, and others, an potential application of blockchain with BIM is to develop a post-disaster recovery system based on the principle of decentralization, self-governance, and transparency, aiming to streamline a number of operations and enact prompt response for a better rebuilding process [130]. Thirdly, the blockchain-aided BIM can support sustainable building design collaboration and inform strategies towards sustainability goals. In particular, the blockchain is responsible for driving the smart contract to negotiate editing permissions and document immutable modifications to the BIM models [131]. In conclusion, the value of blockchain technology in a BIM-enable environment is highlighted to make construction management more transparent, efficient, automatic, and accountable among all participants. Since there are few existing studies about the blockchain potential applications in the construction domain, the future interest in combination of BIM and blockchain is bound to keep growing to boost mutual confidence and reach meaningful information exchange especially in large and long-term engineering projects.

6 Conclusions

This paper provides a comprehensive review of the current development and future directions regarding the BIM-AI integration in the construction field. For one thing, BIM is envisioned as a novel digital paradigm to bring a remarkable shift in AEC industries for higher productivity and quality. It drives the construction industry into a data-intensive field. It provides a platform for not only collecting large volumes of data about all aspects of the project, but also sharing, exchanging, and analyzing data in real-time to achieve in-time communication and collaboration among various participants. For another, AI is a growing trend to drive digital transformation in many industries over the last few decades. The nature of AI is to invent computer programs to automatically learn and think on its own, enabling complex problem solving and smart decision making with fewer errors and higher efficiency. Due to the distinct advantages of BIM and AI, it is believed that the topic of BIM-AI integration is well worth exploring, where BIM can be reasonably considered as a digital backbone to work with AI to further boost intelligence in construction project management throughout the full project lifecycle, including planning and design, construction, and O&M phases.

According to the mixed review of bibliometric analysis and information analysis, it has been found that the United States, China, and the United Kingdom are the top three countries focusing more on the targeted topic for transforming the traditional project delivery and management towards a higher degree of automation, intelligence, and reliability. The timezone map of keywords shows that current researchers turn their interests to deep learning and digital twin in the context of Industry 4.0, indicating that digitalization in construction is bound to be increasingly important in the future. Remarkably, the advanced research interests on BIM-AI integration for construction projects are different from one another, including automated design and rule checking, 3D reconstruction, event log mining, VR/AR, and digital twin, aiming to deliver efficient information sharing and exploring to keep continuous updating and improvement of the ongoing project. Based on the in-depth analysis in a range of ways (i.e., simulation, prediction, and optimization), strategic decisions that are suitable for a certain project will be informed without human intervention under complicated and uncertain environments, which is expected to generate immediate reactions to streamline the complicated workflow, shorten operation time, cut costs, reduce risk, optimize staff arrangement, and others. As reviewed, the current status of the BIM and AI integration is still at an early stage. Herein, three potential research directions along with their practical applications, including the synthesis of human–machine intelligence, city-level digital twin, and blockchain, have been summarized, which can address the remaining challenges in civil engineering.

To further facilitate information digitalization in intelligent construction project management, BIM can be reasonably considered as a digital backbone to work with AI. In the immediate future, the integration of BIM and AI can move the paper-based work toward online management, which assists the traditional construction industry to catch up with the fast pace of automation and digitalization. As expected, it can deliver the most efficient and effective information to keep continuous updating of the ongoing project. The solutions for construction projects are different from one another. Based on the in-depth analysis in a range of ways (i.e., simulation, prediction, and optimization), strategic decisions that are suitable for a certain project will be informed without human intervention under complicated and uncertain environments, which is expected to generate immediate reactions to streamline the complicated workflow, shorten operation time, cut costs, reduce risk, optimize staff arrangement, and others. Meanwhile. this kind of tactical decision-making can possibly be adapted to the changeable conditions to optimize the project operation continuously for delivering smarter construction management throughout the full project lifecycle. Hence, it can be reasonably considered that the practical value of the hybrid framework based on BIM and AI lies in addressing challenges arising from characteristics of construction project management, including uniqueness, labor-intensive, dynamics, complexity, and uncertainty. This topic of BIM and AI integration deserves more attention.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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