Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2023 Volume 29 Issue 3: 202–222
https://doi.org/10.3846/jcem.2023.18076

THE APPLICATION OF BIM IN THE AECO INDUSTRY

Clyde Zhengdao LI[1], Yu ZHEN[1], Hengqin WU[1*], Zhe CHEN[1],
Bing XIAO[2], Vivian W. Y. TAM[2]

[1]*College of Civil Engineering, Shenzhen University, China*
[2]*School of Engineering, Design and Built Environment, Western Sydney University, Australia*

Received 6 March 2022; accepted 7 July 2022

Abstract. Building information Modeling (BIM) has been applied to the whole life cycle planning of construction projects, becoming the latest "engineering brain". Currently, researches on BIM involve various stages, but most of the review fields are relatively single and lack of systematic review and analysis. In order to comprehensively analyze the research trend of BIM in the field of engineering management, this paper takes the holistic analysis method as the framework. In the first stage, 2066 research projects were quantitatively analyzed by bibliometrics to clarify their research environment. In the second stage, scientometric analysis method is adopted to identify scholars, countries, key words and journal sources that have achieved fruitful results and influence in BIM research, and to clarify the research environment. In the last stage, in-depth qualitative discussion is carried out to achieve three objectives: (1) to divide the whole life cycle of the article and summarize the research hotspots in each stage; (2) identify BIM application problems; (3) determine the future research direction. This work is helpful for researchers and practitioners in this field to quickly find influential and fruitful research or journals, and to understand the current research hot spots and trends for the next research planning.

Keywords: building information modeling, life cycle management, categorisation, research trend, visualization.

Introduction

With its continuous deepening and increased application value, the scope of BIM has gradually included the life cycle of construction engineering, thereby making this technology the latest "engineering brain" in the Architecture, Engineering, Construction, and Operation (AECO) industry (Ghaffarianhoseini et al., 2017). BIM can be defined as a digital management tool that is applied to the life cycle of a building. This technology provides a technical platform for the creation, sharing, and management of information across various stages of design, construction, operation, maintenance, and demolition to meet the functional requirements of each stage and improve collaboration efficiency (Doumbouya et al., 2017).

Over the past decade, global theoretical research on BIM has reached new heights as the number of relevant documents continues to increase and as studies continue to investigate each dimension of BIM in depth. Some researchers have focused on the use of conceptual process models and BIM System-of-System (Cerovsek, 2011) models in examining framework-related functions and analyzed the development, implementation, and use of the BIM Schema from the standardization perspective, whereas others have focused on issues related to BIM+ and proposed Green BIM, Historical Building Information Modeling (HBIM), nD BIM, BIM+ Geographical Information Systems (GIS), BIM+ Internet of Things (IoT), BIM+ Building Energy Performance, BIM+Life Cycle Assessment), and other integrated technologies or platforms to facilitate the integration of data across all stages of the building life cycle and promote the digital transformation and upgrading of the engineering field (Miettinen & Paavola, 2014).

More than 100 reviews of BIM have been published over the past decade, among which 60% have been published within the past 2 years. However, most of these review articles mainly focus on a single stage or technical field in their summary analysis (Li et al., 2020; Vigneault et al., 2020; Sidani et al., 2021). For example, Boje et al. (2020) analyzed the use of nD BIM and the latest technologies in the construction process and then proposed the conceptual framework of digital twins. Although these articles can promote the research in a certain field

*Corresponding author. E-mail: *hengqin.wu@connect.polyu.hk*

or stage, they can show the research and application status and development trend of BIM in the whole AECO industry. There are also a few articles summarizing global BIN research and application. For example, Ghaffarianhoseini et al. (2017) reviewed the use of building information models, highlighted their benefits, explained their implementation, risks, and challenges, and proposed some suggestions for encouraging the future adoption of BIM. In a review of global BIM research between 2005 and 2006, Zhao (2017) identified and visualized some hot topics and trends in this research area. However, this review article was merely quantitative in nature and ignored the existing issues and future development of this research area. Santos et al. (2017) quantitatively analyzed and reviewed BIM studies published between 2005 and 2015. In their content analysis and general discussion, they proposed a sub-category structure according to the BIM method. However, Santos et al. (2017) only selected 381 articles with an impact factor of greater than 1.0 for the analysis, which may introduce limitations. Moreover, given that most of these articles were published in 2017, the results are not fully representative of the current status of BIM research.

The advantage of this paper is: (i) This study applies bibliometric and scientometric analysis, excavates the deep information of each study to the maximum extent, and reduces the subjectivity and deviation of development trend prediction. (ii) Currently, most of the review fields are relatively single and lack systematic review and analysis. This study conducts a comprehensive analysis on the whole life cycle of BIM. (iii) A more systematic summary and analysis of BIM research published from 2011 to 2021 is carried out, which not only identifies and visualizes key scholars or institutions and research hot spots at each stage through quantitative analysis, but also discusses the development trend of the whole life cycle of BIM through qualitative analysis. The specific objectives of this study are as follows: (i) use scientific cartography to analyze relevant research, identify key scholars or institutions related to BIM research, and clarify their research environment; (ii) according to the whole life cycle of building management, the research hotspots of each stage are divided and the research trends of each stage are compared; (iii) review the problems existing in the application of BIM technology in various stages, and predict the future research trend of BIM related fields by stages.

1. Methodologies

In view of the research objectives, this study adopts the holistic evaluation method combining quantitative evaluation with qualitative evaluation to eliminate biased conclusions and subjective interpretation. A three-stage model was used to evaluate published research in the field of BIM in the last decade. The overall pattern framework is shown in Figure 1, showing the workflow of this study.

1.1. Stage 1: bibliometric retrieval

(1) Database selection: WOS core database was selected for literature retrieval in this study. Compared with Scopus and PUBMED, WOS covers a wider range of disciplines and journals. It provides high quality bibliography, which has been widely used in bibliometrics research.

(2) Time span: This study selects literatures from 2011 to 2021 for analysis based on the following two considerations: 1) The number of research results before 2010 is small, which has little impact on quantitative analysis. After 2010, BIM research entered the high-speed development stage. 2) The technology related research has the ability of upgrading and optimization. The early research is relatively basic, and most of its achievements are reflected in the research in recent years. 3) Review research is time-sensitive, and the review in recent ten years is not sufficient.

(3) Literature search: A total of 1957 articles were initially retrieved from WOS using the search code TS= (BIM* AND building information model*), where * represents a fuzzy search and TS represents the topic of the article. To obtain he most comprehensive articles, several related topics were included in the search, such as “BIM and construction management”, “BIM and construction technology”, “BIM and engineering construction”, “BIM and operation and maintenance management”, and “BIM and point cloud”. The search results were refined, and only those journal articles written in English were retained for the analysis. As with most reviews, a total of 3386 journal articles were retrieved.

(4) Identify screening: After retrieving the relevant papers, their titles and abstracts were screened to determine whether they fit the research scope. A total of 2066 papers published between 2011 and 2021 passed the screening. Figure 2 shows the global research trend in the application of BIM in the life cycle of buildings over the past decade. Among these papers, 1926 were articles and 140 were reviews. Because reviews do not have stage characteristic. In the follow-up study, it is not clear which stage it belongs to. Therefore, the fourth and fifth sections are classified and analyzed with 1926 articles. While the number of related articles generally shows an increasing trend during this time range, slight declines were observed in 2016 and 2020. Further analysis shows that BIM research has stages. When the number of articles is flat or decreased in the alternating years of a development stage, then it increases steadily. Prior to 2016, most articles were written in the United States and some Nordic countries, and 2015 was

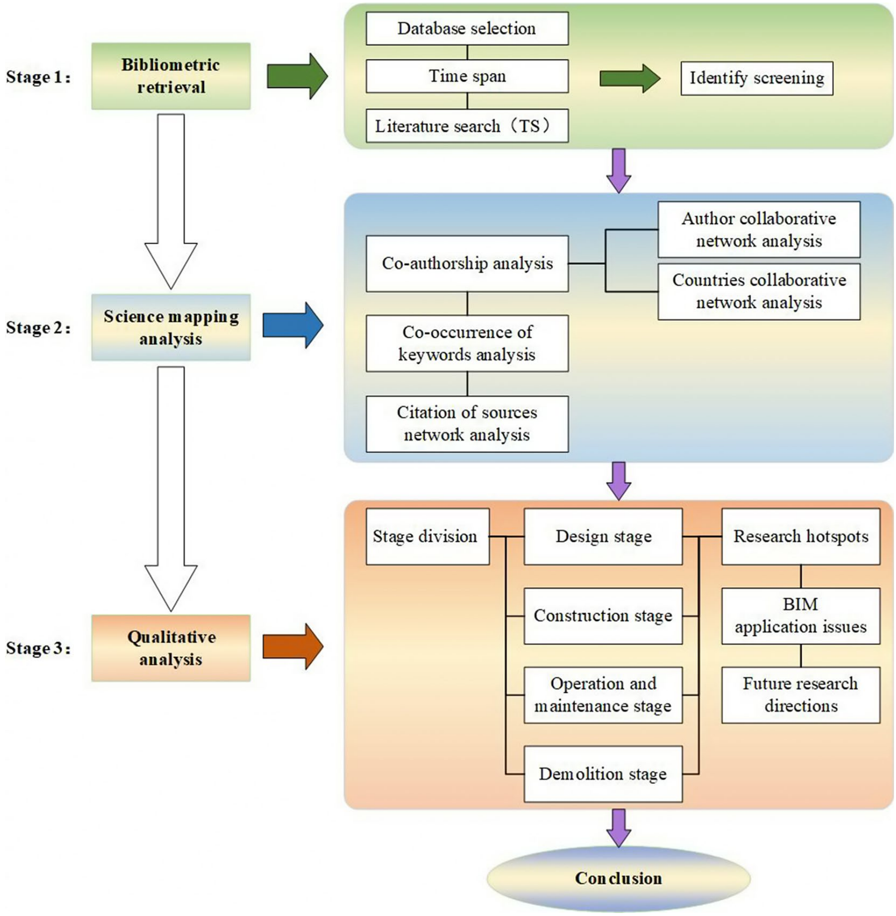


Figure 1. Research framework of this study

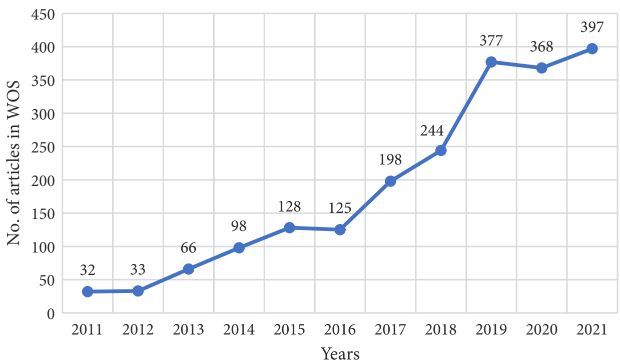


Figure 2. Number of BIM articles published between 2011 and 2021 and retrieved from the WOS core collection database

defined by these countries as the end of a development phase. In 2016, as the beginning of a new stage, its research entered a process, so there was a slight decline in the number of articles, followed by a steady increase from 2016 to 2019. The slight decline in the number of articles in 2020 is partly due to the use of it as the end of a development phase in countries such as Asia and the global impact of COVID-19.

1.2. Stage 2: science mapping analysis

The VOSviewer text mining tool was used to analyze the bibliometric network relationships of the selected articles. Three key processes were involved, namely, co-authorship analysis (including an analysis of collaborative networks of authors and countries), co-occurrence of keywords analysis, and citation source network analyses.

VOSviewer creates and explores maps based on network data. Researchers have often adopted this tool to visualize and analyze scientific literature to capture a logically and cohesively organized knowledge system.

1.3. Stage 3: qualitative analysis

Qualitative analysis is a rational process. A multi-person group decision-making method based on article keywords, topics, and content was adopted to classify 1926 articles according to their applications at each stage of the building management life cycle, including the design stage, design-construction stage, construction stage, construction operation and maintenance stage, operation and maintenance stage, demolition stage, and full life cycle management stage (Rehman et al., 2019).

A multi-person group decision making involving three researchers was performed. In this process, each researcher divides an article based on its research stages. When two or three researchers agree on their division, the stage of the article can be determined. However, when no agreement is reached, the stage of the article was determined via discussions of its contents.

2. Bibliometric analysis outcomes

2.1. Co-authorship analysis

Collaboration among researchers in institutions around the world can promote the exchange and development of disciplinary research. In this study, author information was obtained from the selected articles to study their co-authorship and to analyze the cooperation between selected countries/regions and institutions.

2.1.1. Author collaborative network analysis

Given the excessive number of articles analyzed in this work, the minimum number of authors published in VOSviewer was set to 5, and the minimum number of citations was set to 20. Afterward, 151 out of 3869 authors were selected to analyze cooperation relationship. Table 1 lists those authors who have published more than 13 articles along with the 4 main quantitative measurement indicators, namely, number of papers, number of citations in the WOS, average publication year, and average number of citations in the WOS, all of which indicate the influence of an author in his/her respective research field. As shown in Table 1, Xiangyu Wang, Jack C. P. Cheng, and Heng Li were identified as those authors with the greatest influence in the field, with the article of Xiangyu Wang receiving 1336 citations, making him the most influential scholar in this area. Other researchers worthy of attention are Sijie Zhang and Jochen Teizer, whose articles have received an average of 110 and 81 citations, respectively, thereby offering significant contributions to BIM research.

Figure 3 shows the collaboration relationship analysis network of the authors, where each node represents an author, the node size represents the number of publications, the node color represents the grouping of clusters, and the link between the two nodes represents a collaborative relationship between the two authors. As shown in Figure 3, the authors can be divided into 13 clusters, with each cluster representing a research community. Many of these authors collaborated or are collaborating with one or two highly productive authors. For instance, the pink node group represents a research community dominated by Li Heng and includes Cao Dongping, Sepasgozar Samad M.E, and Tang Pingbo. Figure 3 also highlights dense connections among the 13 identified clusters, which indicates that collaboration and communication in this field have developed well and that a related research system has been formed. Wang Xiangyu obtained the largest number of links (up to 17) and ranked first in terms of total contact strength, making his research an important hub for multi-party research communities.

Table 1. Quantitative measurement of authors

Author	Organization	Country	Number of articles	Number of citations	Avg. pub. Year	Avg. citations
Xiangyu Wang	Curtin University	Australia	31	1336	2016	43
Jack C. P. Cheng	Hong Kong University of Science and Technology	People's Republic of China	26	892	2018	34
Heng Li	The Hong Kong Polytechnic University	People's Republic of China	19	463	2018	24
Weisheng Lu	University of Hong Kong	People's Republic of China	18	360	2018	20
Peter E. D. Love	Curtin University	Australia	17	616	2016	36
Heap-Yih Chong	Curtin University	Australia	16	278	2018	17
Yacine Rezgui	Cardiff University	Wales	14	358	2016	26
Qian Wang	National University of Singapore	Singapore	14	221	2019	16
Fan Xue	University of Hong Kong	People's Republic of China	14	401	2018	29
Al-Hussein Mohamed	University of Alberta	Canada	13	210	2018	16
Borrmann Andre	Technical University of Munich	Germany	13	134	2018	10
Chen Ke	Huazhong University of Science and Technology	People's Republic of China	13	250	2018	19
Charles M. Eastman	Georgia Institute of Technology	USA	13	812	2017	62
Inhan Kim	Kyung Hee University	South Korea	13	193	2017	15
Ghang Lee	Yonsei University	South Korea	13	281	2016	22
Jun Wang	Deakin University	Australia	13	389	2016	30

2.1.2. Countries collaborative network analysis

VOSviewer builds a network of partnerships based on their contributions to BIM-related research. The minimum number of publications in each country was set to 11, whereas the minimum number of citations was set to 50. A total of 32 out of 69 countries were selected for the analysis. Table 2 shows the top 10 countries by number of journal publications, and provides additional information, such as number of publications, number of citations, average year of publication, and average number of citations. As a newcomer developing country, China ranked first among these countries with 526 articles published. The explosive growth of studies in this country was prompted by the strong support and promotion of Chinese policies. In June 2015, the Ministry of Housing and Urban-Rural Development of China issued the "Guiding Opinions on Promoting the Application of Building Information Models", whose development goal was for the number of projects that integrate BIM in the survey, design, construction, and operation and maintenance stages of newly established projects to reach 90% by the end of 2020. With support from this policy, the development of China's BIM technology entered a peak period of rapid human development. As the country of origin of BIM technology, the US has been cited 17 times on average, which is the highest average citation among the selected countries. In sum, BIM is an area of common concern for both developed and developing countries.

Figure 4 shows the national relationship analysis network, which includes 32 nodes and 344 links, including the US (27), England (24), and China (22). All of these countries have made important contributions to BIM research. As shown in Figure 4, these countries can be divided into 5 clusters, among which the purple node cluster comprises China, US, South Korea, Australia, and Singapore, the 5 countries with the top 10 publications. The research exchanges among these countries are very close, and it can be regarded as a central cluster of global BIM research.

2.2. Co-occurrence of keywords analysis

Key words indicate the focus and direction of a study. The minimum keyword frequency was set to 30, and 48 out of 5224 keywords satisfied the requirements. Some com-

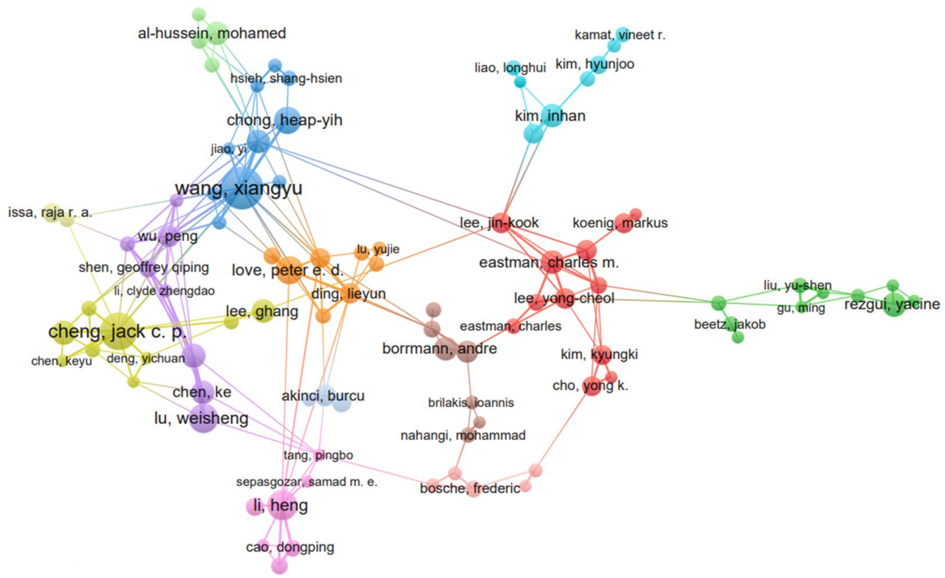


Figure 3. Collaboration relationship analysis network of authors

Table 2. Top 10 countries with the greatest number of published articles

Label	Number of articles	Number of citations	Avg. pub. Year	Avg. citations
Peoples Republic of China	526	7673	2018	15
United States of America	345	9487	2017	27
South Korea	207	4787	2017	23
Australia	190	4252	2018	22
England	174	3899	2018	22
Canada	102	2130	2017	21
Germany	91	2446	2017	27
Spain	69	1003	2018	15
Italy	53	629	2018	12
Singapore	51	712	2019	14

mon words, such as "building", "system", "realization", and "optimization", were removed. Keywords with the same meaning were also merged. For example, "building information modeling" and "building information model" were merged into "BIM", "industry foundation classes" was merged into "IFC", and "life cycle assessment" was merged into LCA". A total of 32 keywords remained after the filtering process.

Table 3 lists the 20 keywords with the highest number of occurrences and presents other information, such as number of connections, strength of keyword links, number of occurrences, and average year of occurrence. The average year shows that BIM-related research has been concentrated over the past five years and that the research hotspots have changed from IFC and Construction Safety in 2017 to Building Performance, Sustainability, and Point Cloud in 2018 and to LCA in 2019. These trends gradually cover the entire life cycle management research.

Figure 5 shows the co-occurring keyword network, which has 32 nodes and 716 links. The size of nodes indicates the frequency of occurrence of each keyword, the thickness of wirings represents the close relationship between two keywords, and the colors represent the cluster of each node. As can be seen from this figure, the key-

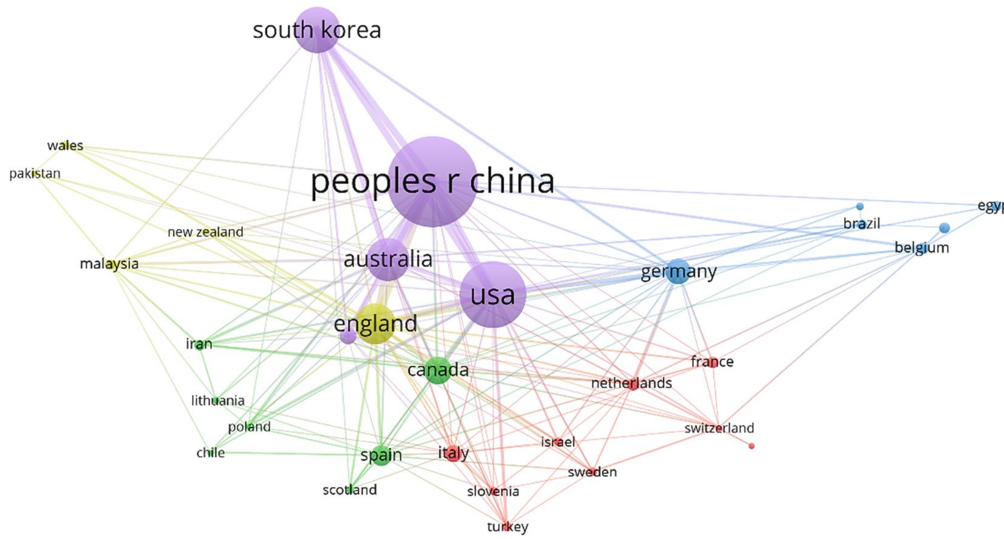


Figure 4. Analysis network of cooperation relations among countries

Table 3. Top 20 keywords used in BIM research from 2011 to 2020

Keywords	Number of links	Keywords link strength	Occurrences	Avg. pub. Year
BIM	30	2216	1352	2017
Design	28	693	272	2018
Construction	30	697	266	2017
Management	30	627	256	2018
Building Performance	28	414	154	2018
IFC	29	306	143	2017
Building Information	29	300	115	2018
Simulation	23	240	106	2017
Visualization	28	242	80	2017
Sustainability	20	223	76	2018
Interoperability	28	187	72	2017
Ontology	23	184	69	2017
Construction Safety	19	178	68	2017
Cost Estimate	27	175	67	2017
LCA	16	195	67	2019
Point Cloud	16	127	67	2018
Facilities Management	26	160	65	2018
Construction Management	23	153	61	2016
Laser Scanning	18	127	59	2017
Reconstruction	19	120	55	2018

words are closely related, and the technologies are based on BIM collaboration and intercommunication. Therefore, BIM can support the digital management of the entire life cycle of a building. The green node group comprises keywords such as design, building performance, LCA, simulation, sustainability, and energy, all of which are related to one another and created research hotspots over the past two years, including environmental impact assessment in the design and construction phase, energy management, and sustainability assessment.

2.3. Citation of sources network analysis

In the network analysis of citation journals, the minimum value of articles in the source journal was set to 10, and the minimum value of citations was set to 10. A total of 28 out of 193 journals were selected. Figure 6 presents a network of journal citations and citation clusters with 28 nodes and 566 links, where each node represents a journal and the lines between nodes represent the citation relationship between journals. The fields involved in the 28 selected journals were highly diversified. In addition to civil engineering journals, scientific and technological journals, such as *Remote Sensing*, *Sensors*, *Computers in Industry and Energies*, were also added, thereby highlighting the diversification of BIM research and the current trend of interdisciplinary research.

Table 4 lists the top 10 journals in the area of BIM research from the WOS Core Collection database. *Automation in Construction* published the greatest number of BIM articles (446, 26.72% of the total), *Advanced Engineering Informatics* (87 articles) and *Journal of Computing in Civil Engineering* (80 articles). These three journals also had the largest number of links and greatest link strength, hence reflecting their importance in the BIM research field. The *Journal of Construction Engineering and Management* and the *Journal of Cleaner Production* also obtained an average citation volume of as high as 23, thereby reflecting their significant contributions to BIM research.

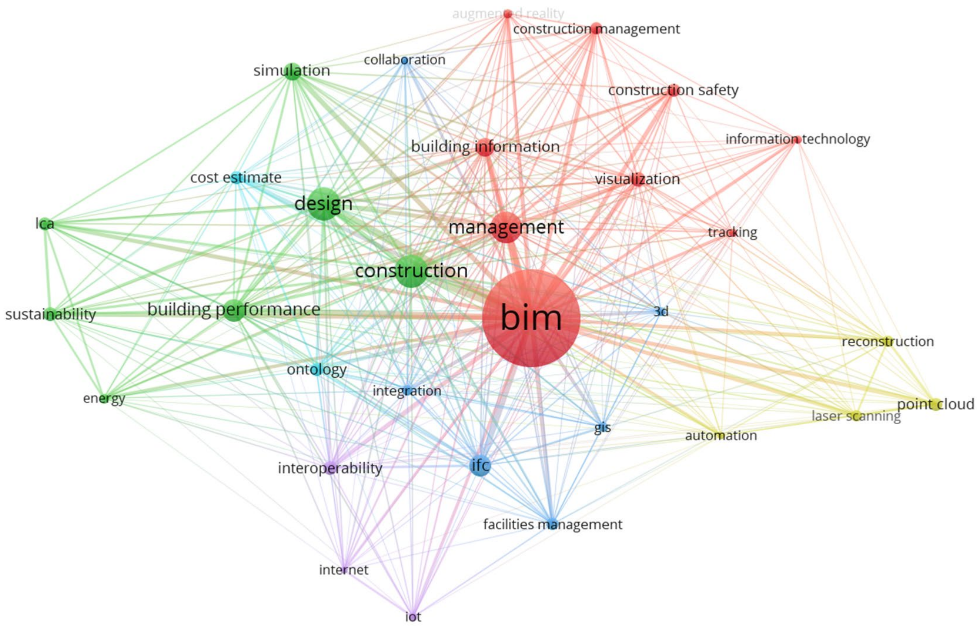


Figure 5. Co-occurring keywords network

Table 4. Citations analysis of highly influential journals in BIM research

Journal	Number of links	Total link strength	Documents	Number of citations	Avg. pub. Year	Avg. citations
Automation in Construction	27	3827	446	15177	2017	34
Advanced Engineering Informatics	27	911	87	2157	2016	25
Journal of Computing in Civil Engineering	27	728	80	1351	2016	17
Sustainability	23	496	71	293	2019	4
Journal of Construction Engineering and Management	25	638	70	1612	2017	23
Engineering Construction and Architectural Management	24	601	67	592	2018	9
Applied Sciences	25	354	54	242	2019	4
Journal of Civil Engineering and Management	24	519	45	510	2017	11
Journal of Cleaner Production	23	312	43	970	2019	23
Journal of Management in Engineering	22	362	35	758	2017	22

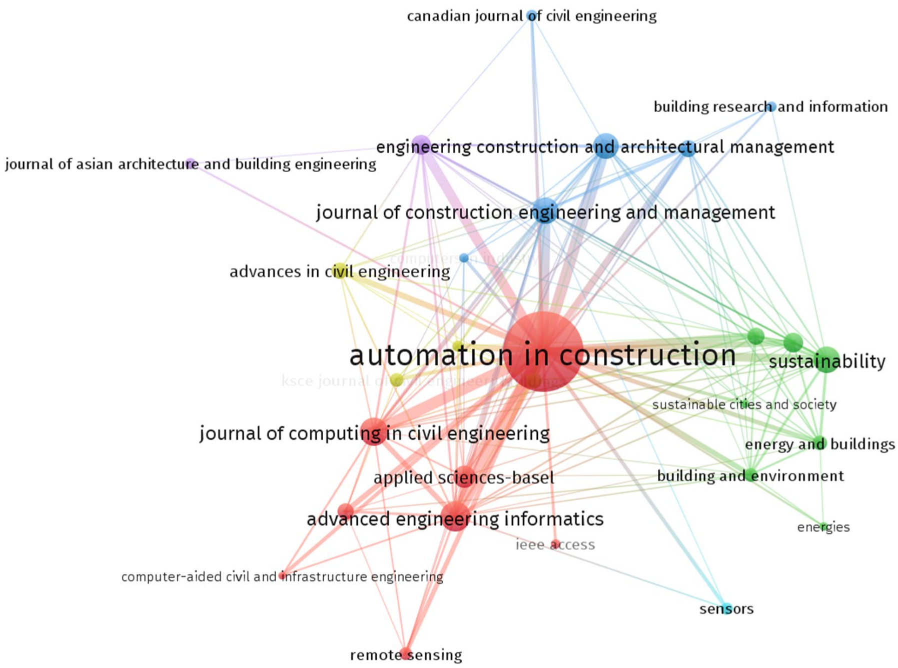


Figure 6. Mapping of the citation of sources network

In 2017, the top 10 journals with BIM research included 4 new journals, namely, *Sustainability*, *Engineering Construction and Architectural Management*, *Applied Sciences*, and *Journal of Cleaner Production*. The number of posts also sharply increases, indicating that BIM has become a hot research topic in engineering-related fields (Zhao, 2017).

3. Findings of the qualitative analysis

The scientometric review allows researchers to quickly identify key scholars, institutions, and hot topics in BIM research. Section 3.2 reveals that BIM-related research gradually covers life cycle management, but most articles continue to focus on the design and construction stages. To enhance the accuracy and objectiveness of the results, this research performs a scientometric analysis using the main content of the literature selected for the qualitative analysis. First, 1926 articles were further integrated and refined, and the life cycle stage of the project they were investigating was determined according to their themes, keywords, and content. Second, after an intensive reading of each article, the research hotspots for each stage of the article were summarized. Life cycle was divided into the design, design-construction, construction, construction operation and maintenance, operation and maintenance, and demolition stages in this study. The research trends for each stage were then compared to obtain a comprehensive view.

Figure 7 shows the number of articles in each stage of the life cycle. The design stage had 513 articles, the construction stage had 493 articles, the operation and maintenance stage had 358 articles, and the demolition stage had 24 articles. These results are consistent with those obtained in the third part of the quantitative analysis. The total number of publications in 2019, 2020 and 2021 accounted for 18.25%, 17.81% and 19.22% of all articles published over the past decade, respectively. Therefore, these two years marked a rise in BIM research and had a large research space.

3.1. Design stage

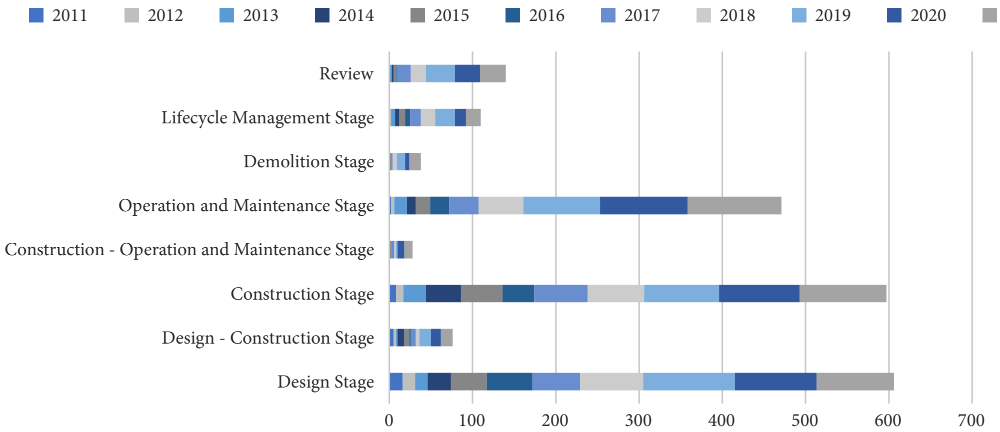
The contents of 606 articles at the design stage were combined with the keyword analysis results shown in Figure 5 to identify the main research hotspots at this stage as shown in Table 5. The design stage mainly involved five aspects, namely, design, data, life cycle assessment, building performance, and cost estimation.

3.1.1. Research hotspots: Design

Along with deepening research on this technology, BIM has also evolved from initial layout modeling and component design to structural design, seismic design, and design optimization over the past three years before moving on to automatic design verification, parametric design, and intelligent design, thereby highlighting automation and intelligence as research trends at the design stage. Khalili-Araghi and Kolarevic (2020) proposed an intelligent customization system for the residential industry based on the design method of mass customization. In this system, house size was mass-customized in order for customers to participate in the process of collaborative design and to meet their expectations regarding the uniqueness and individualization of residences. In terms of actual optimization, Eleftheriadis et al. (2018) proposed a calculation method that supports BIM and is used to automatically carry out reinforcement specifications to support the optimization of reinforced concrete slabs. Along with reduction in labor, increased costs, and enhanced global attention to environmental issues, prefabricated buildings and construction waste have also become issues of concern for researchers. Regarding the design of prefabricated components, Yuan et al. (2018) combined Design for Manufacture and Assembly-oriented parametric design concepts and processes with BIM to improve the manufacturability and assembly of the prefabricated building model, thereby improving the efficiency of post-production and assembly. The number of studies on construction waste at the design stage has also gradually increased. Banihashemi et al. (2018) proposed integrating the parametric design into modular coordination. Years of practice have proven that this technology reduces the amount of panel waste to at least 2% and accelerates the entry of waste reduction into the design stage. Other technologies, such as the deconstruction design proposed by Akinade et al. (2015) and the building dismantling analysis system proposed by Akanbi et al. (2019), were also proposed to provide evaluate the end-of-life performance of buildings starting from the design stage.

3.1.2. Research hotspots: Data

Research in the field of data serves as the basis for the development of BIM. Accordingly, this research hotspot also had the largest number of articles and technologies employed at the design stage, and many researchers have



	Design Stage	Design-Construction Stage	Construction Stage	Construction-Operation and Maintenance Stage	Operation and Maintenance Stage	Demolition Stage	Lifecycle Management Stage	Review
2011	16	5	8	0	2	0	0	1
2012	15	3	9	0	4	0	2	0
2013	15	2	27	0	15	0	5	2
2014	28	8	42	1	11	1	5	2
2015	43	6	50	1	17	1	7	3
2016	55	2	38	0	23	0	6	1
2017	57	6	64	4	35	2	13	17
2018	76	4	68	2	54	5	17	18
2019	110	14	90	2	92	10	24	35
2020	98	12	97	8	105	5	13	30
2021	93	14	104	10	113	14	18	31

Figure 7. Number of articles at each stage of the life cycle from 2011 to 2020

Table 5. Main research focus at the design stage

Research hotspots	Sub-categories
Design	Design verification, parametric design, structural design, seismic design, steel bar design, design optimization, etc.
Data	Interoperability, industry foundation classes (IFC), log data mining, data storage, integration optimization, programming development, etc.
Life Cycle Assessment (LCA)	Environmental assessment, sustainable design, green design, low carbon design, greenhouse gas emissions, etc.
Building performance	Daylighting simulation, energy performance optimization, energy efficiency simulation, building thermal simulation, carbon emissions, etc.
Cost estimate	Cost analysis, cost estimation, life cycle cost assessment (LCC), etc.

focused on this problem over the past decade. Despite not being a new trend, this research hotspot shows great potential. Table 5 shows that the data hot spot includes many sub-categories, such as interoperability, IFC, log data mining, data storage, integration optimization, and programming development, of which the most studied are interoperability and IFC. Many researchers have studied the interoperability of BIM tools across different applications. For instance, Sibenik and Kovacic (2020) argued that IFC-based data exchange is widely applied in research and software tools that support the construction and engineering industries. They also proposed a data exchange between architectural design and structural analysis and formulated the priority of improvement strategy.

Along the continuous advancement of smart city research, the integration of BIM and GIS has attracted much research attention in the AEC and geospatial fields. Zhu et al. (2019) enhanced the previously developed open source by proposing an enhanced automatic polyhedron generation algorithm that converts IFC geometry into shapefiles. Zhou et al. (2019) proposed the OutDet algorithm for contour detection. Lee et al. (2019) developed the MVD-based rule checking function in the IfcDoc tool to accelerate the standardization of data exchange specifications and to standardize the development of MVD guidelines, thereby ensuring the consistency and reliability of MVD and ultimately speeding up the use of BIM across disciplines.

3.1.3. Research hotspots: Life cycle assessment

In response to the call of the World Meteorological Organization, reducing greenhouse gas emissions and mitigating the impact of climate change have become research directions of various related industries. To achieve these goals, the construction industry proposed LCA. Azhar et al. (2011) built several models for analyzing the sustainable design and the energy and environmental design of buildings.

Many sub-categories of LCA have been further divided to include environmental assessment, sustainable design, green design, low-carbon design, and greenhouse gas emissions. LCA research has also reported one of the highest growth rates over the past few years. For research on the application of BIM and LCA at the design stage, Hollberg et al. (2020) introduced a BIM-LCA tool to evaluate the global warming potential embodied in the design process of actual buildings. By integrating BIM and LCA, Rezaei et al. (2019) proposed a novel technology for evaluating the environmental performance of buildings. From an environmental perspective, they calculated the impact of different construction stages and components on the environment to determine the best choice of building materials.

LCA interacts with building performance, life cycle cost assessment (LCC), and other fields, and multidisciplinary research on this topic has gradually become one of the goals of important buildings in the world. Santos et al. (2020) combined BIM technology with LCA and LCC and developed an economic assessment tool for the built environment.

3.1.4. Research hotspots: Building performance

Building performance research utilizes LCA as a theoretical basis and provides evaluation indicators for LCA research, hence starting a new research trend that shows great potential. Building performance research integrates daylighting simulation, energy efficiency optimization, energy efficiency simulation, building thermal simulation, and carbon emissions. To save energy and reduce emissions, Cang et al. (2020) proposed a BIM-based calculation method that considers the embodied carbon emissions (ECE) of buildings in the design optimization process. This method treats building elements (BE) as the basic unit, considers the carbon emission factor of BE as the basis for calculation, and combines the quantity extracted from the model list through the code to efficiently identify the potential hot spots of ECE and to provide design feedback for reducing carbon emissions. Jeon et al. (2019) analyzed the impact of the current building state of BIM design on the reliability of energy analysis. In addition to research on energy efficiency, some performance simulations have also been conducted to facilitate building design. For example, Akin et al. (2022) integrated BIM, daylighting simulations, and immersive environments in an interactive environment to study immersive high-performance architectural design tools.

3.1.5. Research hotspots: Cost estimate

At the early design stage of a construction project, an accurate and timely cost feedback is essential in making design decisions. The cost estimate hotspot includes several sub-categories, such as cost analysis, cost estimation, and LCC. Most scholars have adopted a rule-based approach to generate detailed component quantities based on BIM designs and to associate them with cost items in the cost estimation database. For instance, Ma et al. (2013) proposed a BIM-based design model for a semi-automatic and compliant construction project bidding cost estimation that minimizes the workload and risk of errors for the estimator. In response to the limitations of previous studies, Lawrence et al. (2014) used an estimator to encode the various relationships between design and estimation and then used flexible mapping between building models and cost estimates to create and maintain cost estimates. LCC has recently become a hotspot in this field. Marzouk et al. (2018) proposed a framework that combines BIM with genetic algorithm optimization and Monte Carlo simulation and uses the LCC model to select the best building materials for architectural design. In the material selection process, green building materials are used to replace traditional building materials to improve building performance and promote the development of sustainable buildings.

3.2. Construction stage

The application of BIM in the construction phase has also become a top priority in BIM research. A total of 597 articles were studied over the past decade. By summarizing the content of these articles at the construction stage, the distribution of research hotspots in BIM was obtained. Figure 8 shows the main research content and number of related articles in each field. Among them, construction schedule (81 papers), construction safety (78 papers), and construction quality (69 papers) had the largest number of articles.

3.2.1. Research hotspots: Construction schedule

A detailed progress monitoring can detect delays as early as possible and take the corresponding countermeasures to improve the efficiency of construction management. With the gradual deepening of BIM research, the construction industry has abandoned traditional manual detection and recording methods in favor of automated and visualized construction progress monitoring, which effectively improves process control. Many studies have also proposed Scan-to/vs-BIM methods to achieve an automatic construction progress monitoring. A point cloud with better quality corresponds to better monitoring results. Rebolj et al. (2017) defined a new metric to improve the effect of high point cloud on construction schedule management applications. Braun et al. (2020) studied the combination of point cloud and 4DBIM to achieve automatic progress monitoring. To further improve the reliability of their method, they proposed a machine-learning-based method combined with 4D building information model and inverse photogrammetry for automatically marking building images. However, given the occlusion of elements and inaccurate reconstruction, the construction progress detection has poor accuracy or completeness. To address these limitations, Braun and Borrmann (2019) improved monitoring of construction progress by integrating point clouds, semantic data, and computer vision.

3.2.2. Research hotspots: Construction safety

Adopting and implementing innovative solutions effectively improve the safety performance of buildings. Construction safety has received much attention over the past decade. This area has been divided into two sub-categories, namely, risk management and worker safety.

In risk management, Ahmad et al. (2018) developed a risk-integrated BIM plug-in theoretical model for automating the risk management process and improving overall project management. Choe and Leite (2017) proposed a formal 4D construction safety planning process that integrates the safety, time, and space information of a specific location to facilitate construction safety communication.

Compared with other work departments, construction workers are highly exposed to harsh environments with high safety risks. Therefore, worker safety has also received much attention from scholars. Arslan et al. (2019a) identified unsafe worker movement behavior as one of the main causes of worker casualties. To understand the movement trajectory of workers during the construction process, they proposed the Worker Trajectory Analysis System, which utilizes BIM to identify unsafe building locations and subsequently applies the Hidden Markov Model on semantic trajectories to extract worker mobility insights and improve worker safety. In another study, Arslan et al. (2019b) combined Bluetooth low energy beacons with BIM to visualize the intrusions in a dynamic building environment and ensure worker safety. Marzouk and Al Daour (2018) used BIM, computer simulation, and alternative construction methods to help contractors and safety managers plan the evacuation of construction sites.

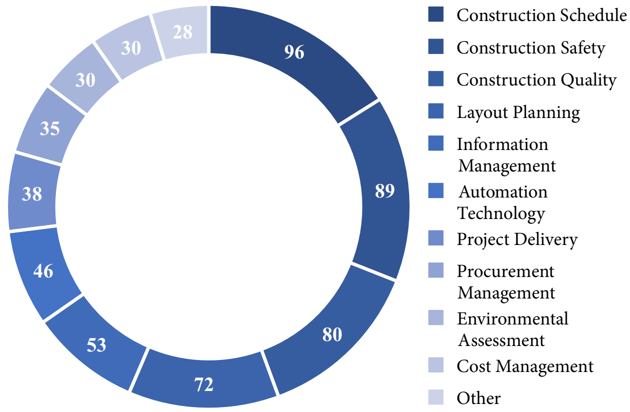


Figure 8. Distribution of BIM use at the construction stage

3.2.3. Research hotspots: Construction quality

Construction quality has an important role in the lives and safety of the public. Therefore, research on construction quality has also developed over the years. Ma et al. (2018) proposed a collaborative system for building quality management that integrates BIM and indoor positioning technology to reduce the workload of inspectors and to prevent errors in inspection, thereby greatly improving the effectiveness of quality management.

With the prevalent construction of prefabricated buildings, most of the construction work is completed in factories, thereby reducing on-site work. Therefore, inspecting the quality of prefabricated components has also become a new research trend. To ensure a smooth assembly of the construction site, geometric quality inspections need to be performed in prefabricated factories to ensure that the prefabricated components have the correct dimensions. Guo et al. (2020) proposed an automatic geometric quality inspection technology that uses 3D laser scanning to estimate the geometric characteristics of prefabricated mechanical, electrical, and sanitary (MEP) modules. The scanned data are then registered into the BIM model, and the MEP elements in the scanned data are detected by using a fitting algorithm. Then calculate the inspection items of geometric quality inspection.

3.2.4. Research hotspots: Layout planning

The effective layout planning of a construction site plays a vital role in the scheduling of construction activities. This hotspot covers equipment layout planning, building material layout, site logistics planning, and workspace planning. Planning the workspace of a construction site is part of a construction preparation. Getuli et al. (2020) used immersive virtual reality and BIM to simulate construction activities by facilitating the sharing of safety-related information among partners, thereby improving the manual workspace planning process. Hosny et al. (2020) measured the sensitivity of the workspace planning model to actual uncertainties in a construction project by analyzing workspace management during the construction process. In this process, operating the crane greatly affects the execution and preparation costs. Therefore, tower cranes should be used to achieve a smooth construction process with minimal cost. Dutta et al. (2020) introduced a new module comprising a decision support system and a path re-planner for automatically replanning the lifting path of robotic tower cranes in a dynamic BIM environment. Given the large number of building materials or prefabricated components, storage areas need to be designed when planning a construction site. Therefore, the logistics planning of the construction sites and the transportation routes between regions produces a great impact. Cheng and Chang (2019) proposed an optimization model for dynamic building material layout planning and studied the optimization of material layout from the perspective of dynamic task scheduling. Bortolini et al. (2019) proposed the on-site logistics planning and control of prefabricated buildings based on BIM 4D by studying the collaboration between BIM and lean construction.

3.2.5. Research hotspots: Automation technology

Global scientific and technological innovation capabilities have been significantly enhanced over the past years. To address many problems including labor shortage and safety risks, building automation construction has become a new research trend. This research hotspot involves automated construction site layout planning, crane automation planning, automatic construction progress monitoring, and automatic inspection of the geometric quality of prefabricated components, among which the application of robotics in building construction has received the most attention. Robotics is an advanced form of automation technology. Although previous studies have laid a solid foundation for applying construction robots, the construction industry still lags far behind the manufacturing industry in terms of the application of these robots. The limitations of previous objective studies also hinder the widespread adoption of their proposed methods. Nevertheless, the high efficiency and high quality of intelligent robot construction have always attracted much research attention. For example, Ding et al. (2020a) proposed a BIM-based robot assembly model that contains all the information required for the planning and allows robots to lay bricks in the specified position. Lundeen et al. (2017, 2019) studied the method of autonomous perception building model. The prefabricated component model fitting technology is proposed to help the construction robot adapt to the emergency situation and ensure the working efficiency. In response to deepening research in this area, researchers have proposed a construction robot that uses its sensors and BIM to perceive and model the actual geometry of its workpieces and to adjust its work plan (Ma et al., 2020).

3.3. Operation and maintenance stage

BIM has been comprehensively applied at the design and construction stages, but only few successful cases have been reported. As shown in Figure 7, a total of 471 articles were collected at the operation and maintenance stage. The explosive growth of studies on BIM over the past two years has highlighted the feasibility of applying BIM at the operation and maintenance stage. The smart building concept was also introduced in recent years given its huge potential for informatization at the operation and maintenance stage. Figure 9 shows the content and number of related articles in each field at this stage. Among them, facility management (83 papers), safety management (71 papers), energy, environmental management (57 papers), and indoor positioning/navigation (41 papers) had the largest number of papers.

3.3.1. Research hotspots: Facility management

The application of BIM technology in facility management is a relatively new and growing field of research that aims to meet the information needs at the operational stage

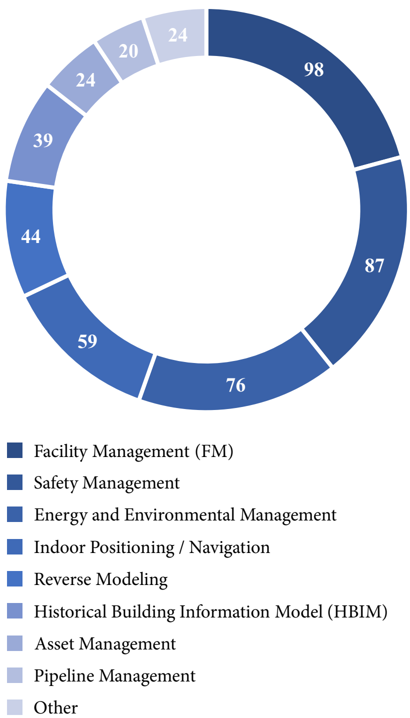


Figure 9. Distribution of BIM use at the operation and maintenance stage

of a digital project. Many scholars have examined this field and proposed many valuable implementation plans. For example, Ma et al. (2020) established a maintenance management system by integrating the reliability centered maintenance, BIM, and GIS technologies. This method reduces labor costs and the difficulty of making equipment maintenance decisions. El Ammari and Hammad (2019) proposed a BIM-based collaborative mixed reality method for a remote interactive collaboration in facility management. Wei and Akinci (2019) proposed a vision and learning-based indoor positioning and component association framework for facility operation and management. Kameli et al. (2021) improved maintenance performance by developing a computer system based on IFC BIM/RFID. Among many programs, BIM+FM research has become mainstream. Marmo et al. (2020) proposed a method based on the integration of BIM and FM systems that supports performance evaluation and maintenance management by using performance information models.

Cheng et al. (2020) found that the current equipment management methods suffer from delays given the inability of passive maintenance to prevent failures and the low predictability of equipment failures. To formulate better predictive maintenance strategies for building facilities, they developed a facility maintenance management data-driven predictive maintenance planning framework by integrating data from BIM, IoT networks, and FM systems. This framework can help FM personnel perform maintenance tasks efficiently. Patacas et al. (2020) established a BIM implementation requirement model for facility management and the Common Data Environment framework for information specification, production, and verification to address the gaps in the entire BIM+FM workflow and solve the problems related to information standardization, verification, and use.

3.3.2. Research hotspots: Safety management

The application of safety management at the re-construction stage of BIM has been introduced in Section 4.2.2. Safety management research is also the top priority at the operation and maintenance stage. Therefore, to improve the management of the construction operation and maintenance stage, construction safety management warrants further research. By analyzing and summarizing 71 articles in this field, the current safety management research mainly includes the structural health detection (SHM) of the building itself and disaster safety management. Given that the health of buildings is directly related to the safety and health of their users, testing the health of buildings has recently become a concern for both engineers and scholars. The abnormal symptoms of a structure are initially tracked and evaluated through SHM, and then a response plan is designed in advance to avoid the catastrophic consequences of a building system failure. Ma and Du (2020) proposed a structure intelligent monitoring system by combining acoustic emission and data mining technology. This system greatly improves the data application ability and computing ability of fog calculation. Ding et al. (2020c) proposed a new building health assessment model that integrates analytic hierarchy process, BIM, and GIS. This model considers five aspects, namely, comfort performance (weight 5.15%), safety performance (51.88%), environmental performance (24.92%), operation management (12.56%), and economic performance (6.49%). Through practical analysis, this model successfully optimizes the evaluation of building health performance.

Meanwhile, management research on disaster safety mostly focuses on simulation drills, such as fires and earthquakes, and emergency management. Lei et al. (2020) proposed a network physical system for intelligent disaster prevention by integrating BIM and Internet of Things technology. Based on the BIM platform, Ma and Wu (2020) built a fire emergency management system that incorporates four modules, namely, fire intelligent monitoring, fire warning, fire response, and fire treatment. Based on virtual reality and BIM, Lu et al. (2020) proposed a simulation framework for indoor fire rescue scenes that combines volume rendering with a particle system to visualize smoke. A variety of dangerous combinations has also been considered in designing fire protection plans. Xu et al. (2018) proposed a post-earthquake fire simulation method that considers the earthquake damage of the sprinkler system to quantitatively evaluate the impact of fire spread caused by earthquake damage.

3.3.3. Research hotspots: Indoor positioning/navigation

Indoor positioning/navigation technology has become a hotspot in operation and maintenance management research over the past two years. This technology is mainly investigated by combining BIM with point cloud, IoT, deep learning, and network topology maps to achieve various functional requirements for research on intelligent exit navigation, indoor wayfinding, facility status, and fire escape.

Fu et al. (2020) proposed a straight skeleton-based navigation network that generates a complete 3D indoor navigation network for indoor wayfinding. Won et al. (2020) used deep learning to semantically segment the synthetic point cloud inside a BIM-based building. Experiments have proven the feasibility of combining the synthetic point cloud generated by BIM with the small dataset of a real point cloud. Zhang et al. (2020) proposed an indoor barrier-free plane intelligent lofting system based on a combination of BIM and multi-sensor. They also designed a micro-electromechanical system inertial measurement unit on a highly flexible, low-cost autonomous mobile robot platform based on a single-chip microcomputer. Through practice, the system can significantly improve the efficiency of stakeout and reduce the amount of required manpower. Zhou et al. (2020) designed a BIM based indoor pathfinding scheme by optimizing the grid topology structure, then analyzed the feasibility and accuracy of the scheme through examples. Fu and Liu (2020) proposed a method to automatically determine the direction of export signs based on BIM technology. This can represent the danger area and automatically generate the shortest path.

3.4. Demolition stage

On a global scale, the large-scale construction of infrastructure and rapid development of urbanization over the past few years have led to an increasing number of construction waste (CW). Most of these wastes are neither reused nor recycled and are sent to landfills. The environmental impact of these wastes and the shortage of land resources for creating new landfills have increased the need for innovative CW management practices. Many scholars have attempted to address this problem by proposing certain designs, such as deconstruction and sustainable designs at the design stage. Applying off-site construction at the construction stage is an extremely effective solution for reducing CW. However, with the development of urban renewal, many old and dangerous buildings are facing the threat of demolition. While 24 articles have examined the application of BIM at the demolition stage, research in this area is still in its infancy. Most of these articles focus on CW estimation and CW management (CWM).

Bakchan and Faust (2019) analyzed 535 items of CW data to quantify the CW produced from non-resident institutional construction projects. Advancing CWM to improve the sustainability of the construction industry requires an improved reporting of CW estimates for non-residential buildings. Guerra et al. (2019) addressed the limitations of existing CW estimation methods by proposing a BIM-based automated CW estimation algorithm, which minimizes the errors in manual estimation and facilitates the formulation of effective CWM decisions. Xu et al. (2019) proposed a BIM-based construction and demolition waste information management system that helps in accurately estimating CW information and in quantifying and reducing greenhouse gases.

4. Discussions and future needs

With the implementation of policies around the world, the establishment of standards, the in-depth exploration of research institutions, and the continuous practice of enterprises over the past decade, the AECO industry has gradually formed a cognitive consensus regarding the value of BIM applications and confirmed its "engineering brain" status. Based on the previous re-clustering of the keywords from the selected 2066 articles and the results of the qualitative analysis of relevant research at each stage of the building management life cycle, this paper summarizes the problems encountered in the application of BIM. From the identified problems and literature, some research trends were inferred and directions for future BIM research were proposed.

4.1. BIM application issues

4.1.1. Issues in BIM software and application standards

Figure 8 shows that the software types, business application scope, and application points of BIM have expanded across the entire business management life cycle over the past few years. However, some problems have inevitably emerged during the development of BIM software and application standards as enumerated below.

(1) Availability of many types of BIM software and the ease of use of related software. Many types of BIM software with fast update iterations are currently available in the market. However, using different BIM software may contribute to the failure to produce a centralized and comprehensive product. Most of this software also have high hardware requirements and have demonstrated some stability issues, making them far from the ideal in terms of operating convenience.

(2) Uniformity of data standards for BIM-related software. As mentioned in Section 4.1.2, data remain a research hotspot in the BIM literature. Given the inconsistency among data models, information structures, and data exchange standards, each BIM software manufacturer follows a custom file format expression to store data, thereby introducing problems in data compatibility among various types of BIM software (Costa & Sicilia, 2020). In the data exchange process, information loss or data errors may occur, which may easily lead to the formation of data islands and make the software lose the effect of data coordination. For example, parts are often lost when using Revit to export IFC files (Gui et al., 2019).

(3) Insufficient matching between BIM application standards and business requirements. The fineness of models is continuously improved along with the development of the entire construction process. Therefore, the required model fineness also differs across each stage of the building life cycle (Olawumi & Chan, 2019). For example, construction drawing design models, detailed design models, construction process models, and as-built models each have unique accuracy requirements, hence reducing the accuracy of general models.

4.1.2. Islanding of BIM applications across all stages of the building life cycle

The implementation of BIM application requires the coordinated management of units responsible for each stage of the project cycle. As shown in Figure 7, isolated research on each phase of BIM is relatively prominent, whereas correlation research among multiple phases is relatively few. As a result, managing BIM applications across various stages of a project is out of touch and forms phased islands, which are among the main problems encountered when applying BIM in the construction industry.

(1) Discontinuity of project information in BIM applications. BIM has broken through simple applications, such as initial key point simulation, collision checking, and visualization, and has grown into a carrier of information that ensures efficient management throughout the entire building life cycle

(Zhang & Dong, 2019). Generating value from data requires a timely, accurate, and complete collection of source data, which in turn require a collaborative use of information technology among various departments. However, during the phased delivery of a project, data discontinuities, missing data, and data mismatch are often observed and greatly influence data value.

(2) The application value of BIM in project management is not obvious. The insignificance of BIM in project management is mainly ascribed to two reasons. First, improvements at the project management level and in management efficiency are not easy to quantify and are not specific. Second, the input-output ratio is difficult to measure (Ahmed & Kassem, 2018). BIM also lacks a unified measurement standard for improving management level and management effectiveness. Effect and effectiveness are often observed by managers and cannot be quantified and described in detail.

4.1.3. BIM talent problems

(1) Lack of overall BIM talents. In the entire life cycle of an engineering project design, practitioners need to combine different engineering disciplines with BIM. For example, in the construction phase, BIM practitioners should be compound talents with BIM software operating capabilities, BIM application capabilities, construction engineering business experience, and management capabilities for the integration of various business lines of engineering projects.

(2) The ability of BIM personnel does not match the job requirements. Most talents who have recently graduated from colleges and universities usually lack engineering project experience and are unable to integrate themselves in the operation and application of BIM. Internally trained technicians with one to two years of experience are usually part-time employees, and the staff often lacks energy. In addition, people who have worked for a long time in engineering projects face difficulties in accepting new technologies and breaking through their comfort zones. If BIM cannot produce benefits to these personnel, then they lack a strong driving force.

(3) Lack of BIM talent training methods. The training of BIM talents takes enterprises as the core, and colleges, enterprises, and industries form a training chain. However, few training methods are designed for each link, and the connection among these links is generally weak.

4.2. Future research directions

After summarizing the problems in the application of BIM in the AECO industry, combining the current research hotspots, and analyzing the work that needs to be carried out, several future research directions are proposed to be further explored in stages. Figure 10 presents some of these directions.

4.2.1. Future research directions: Design stage

(1) In the selection and development of design software, ease of use should be considered to reduce the number of professional software applications and develop products with concentrated, comprehensive, and efficient functions that facilitate collaborative design among professionals at the design stage.

(2) The lack of a standard data interface easily leads to the formation of data islands and reduce the data synergy capabilities of the software (Costa & Sicilia, 2020). The BIM technologies currently applied in China mainly include interoperability, IFC, BIM semantics, ontology, and engineering-practice-based BIM.

(3) In the design process, automatic design, automatic detection, intelligent structure design, intelligent deconstruction design, and modular design are expected to become research hotspots (Hamidavi et al., 2020).

(4) Performance simulation and LCA have become research hotspots in recent years. As this technology matures, optimizing LCA/LCC based on building performance simulations will greatly improve the reliability of evaluation and promote sustainable development (Lu et al., 2017).

(5) BIM minimizes waste at the design stage and subsequently reduce CW. While many research teams have taken CW into consideration, very few studies have concentrated on this topic (Bilal et al., 2016).

(6) Collaborative design with customer participation is an interesting topic for future research. A continuous economic development corresponds to an increasing demand for better and comfortable living conditions. The participation of clients in the design can also reduce the impact of later decorations on the building structure (Khalili-Araghi & Kolarevic, 2016).

4.2.2. Future research directions: Construction stage

(1) Endless levels of management technology are being implemented in all aspects of the construction stage. A comprehensive construction management system should be established to control the safety, quality, schedule, cost, and materials of the entire construction process.

(2) Building quality has always been the main concern of owners. Research on structural health detection based on Information technology such as BIM will gradually become popular. The structural health inspection mainly includes four aspects: (i) Quality inspection in the production stage of

prefabricated components. (ii) Quality inspection of precast components entering the site. (iii) Quality inspection of the main structure and installation components on the construction site. (iv) Structural health detection in operation and maintenance stage.

(3) In order to ensure the quality, safety and economy of the prefabricated components transported from the production workshop to the construction site, the whole storage, assembly and transportation of the prefabricated components are realized. And improve the transportation scheduling of prefabricated components in the construction site to achieve the target of low stacking rate. BIM based prefabricated component transportation route selection and field layout planning research arises spontaneously.

(4) Waste management and carbon emission measurement/reduction based on BIM at the physical and chemical stages have recently become research trends. With the increasing construction of prefabricated buildings, many scholars believe that off-site construction is an important strategy for reducing the carbon emissions of buildings (Ding et al., 2020b).

(5) Automated construction, including construction robots, aerial building machines, and programmable machines, can effectively improve the productivity and product quality of construction projects, solve many associated problems such as labor shortage and safety risks, and holds significant research and social value (Ding et al., 2020a).

(6) Information technology has become a very important tool for the industrialization of construction. The rapid development of information technology as represented by cloud computing, BIM, internet, IoT, and big data provides the technical foundation for the development of a lean, modern, and smart construction.

(7) To manage the full BIM cycle, information must be collected at each stage of the construction project. Therefore, a method for automatically updat-

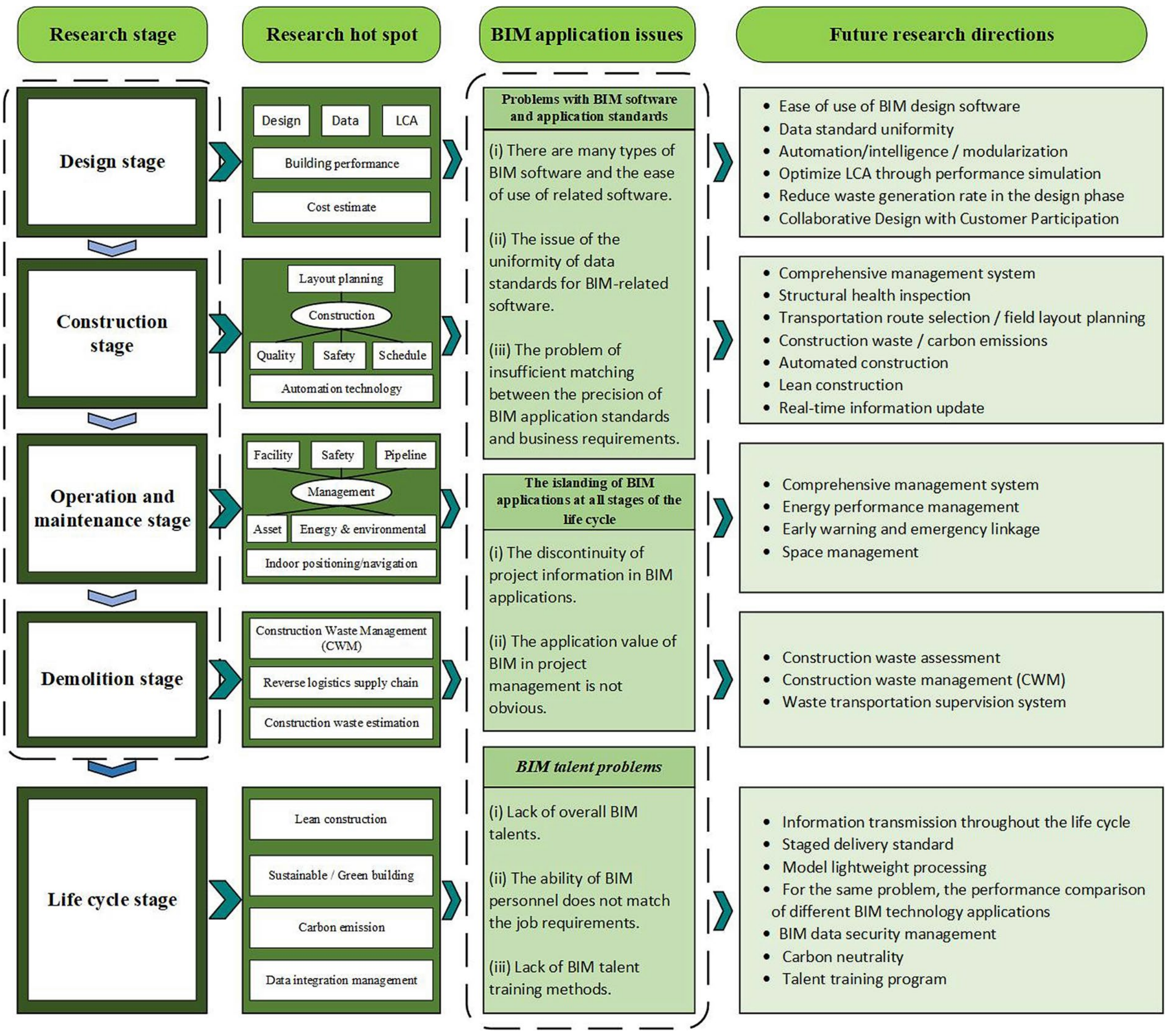


Figure 10. Research status and future development direction of BIM

ing construction schedule, component, scheduling cost, worker safety, and other types of information must be designed to visualize such information and lay a solid foundation for the entire information transmission cycle.

4.2.3. Future research directions: Operation and maintenance stages

(1) Similar to the construction phase, a comprehensive operation and maintenance management system should be established at the operation and maintenance stage to control the entire operation and maintenance process across all areas, including safety, structural health, space, assets, and energy consumption.
(2) The current research on the energy management of BIM-based building operation and maintenance remains in its infancy and still has huge room for development (Kang, 2020).
(3) The current research on safety management mainly covers disaster safety simulation, escape simulation, and SHM. Moreover, disaster warning and emergency response based on BIM have attracted limited research attention (Chen et al., 2018).
(4) The current research on the operation and maintenance phase is relatively comprehensive, but space management, including space allocation, space planning, lease management, and statistical analysis, warrants further investigation.

4.2.4. Future research directions: Demolition stage

(1) The impact of CW on the environment and society has received limited research attention. BIM can be used to evaluate the impact of wastes on the society, environment, and economy. Social and environmental impacts are two intangible benefits that cannot be used for quantitative analysis.
(2) A BIM-based CW management system should be developed to control the calculation, evaluation, recycling, transportation, and data mining processes throughout the course of demolition to achieve a sustainable waste management.
(3) BIM should be combined with GIS to develop a waste transportation supervision system. Transportation vehicles need to be tracked to effectively manage CW in real time.

4.2.5. Future research directions: Life cycle stage

(1) To manage the full life cycle of BIM, the collection and transmission of information at each stage should be examined to improve the comprehensiveness, authenticity, and effectiveness of such information.
(2) Given that each stage of the building life cycle imposes different requirements for building and project information models, phased delivery standards used should be formulated for the application of BIM (Succar & Poirier, 2020).
(3) In project delivery, how to automatically lighten the building information model according to relevant standards needs to be investigated (Xue & Lu, 2020).
(4) With the continuous deepening of research, different studies, technologies, and methods for solving the same problem may be formulated. However, the various application scenarios of BIM lack comprehensive research.
(5) Data security should be achieved for BIM to realize a full-cycle digital management. Only a safe and reliable digital system allows users to safely transfer their decision-making and control powers to the digital system for an automatic or semi-automatic operation.
(6) Environmental issues have always been a concern in all walks of life. In 2020, China proposed its goal of achieving carbon peak/neutrality. As a pillar sector, the construction industry should also consider the benefits of carbon neutrality in the process of full life cycle management.
(7) The lack of BIM talents, the mismatch between BIM personnel's abilities and job requirements, and the lack of BIM talent training methods pose other major problems that limit the development of BIM. However, relevant studies have not yet proposed a practical and effective solution to these problems.

Conclusions

Research on BIM has continued to grow in recent years, thereby attracting the attention of a large number of researchers and practitioners. As shown in Figure 2, the number of BIM publications over the past four years accounts for about 70% of all publications on this topic. In the AECO industry, BIM is considered its "engineering brain" and has been applied across all stages of life cycle management. To understand the current status and trends of global BIM research at various stages of life cycle management over the past decade, this study collected 1699 articles from the WOS core collection database, used VOSviewer to carry out a scientometric analysis, and carried out qualitative analysis according to stage classification.

The scientometric analysis covers co-author analysis, keyword co-occurrence analysis, and co-citation analysis. The contribution and influence of the main researchers are determined through a quantitative analysis. Xiangyu Wang, Jack C. P. Cheng, and Heng Li were identified as the three scholars who have published the greatest number of articles in this field. With regard to the distribution of BIM journal articles, China holds the record for publishing the greatest number of articles, whereas the US has the largest average number of citations. In terms of keywords, "BIM", "design", "construction", "management", and "building performance" were used most frequently and received an extremely high number of citations. Among the subjects explored in BIM research, engineering construction, civil engineering, construction, and construction technology have the greatest number of publication records, such as in *Automation in Construction*, *Advanced Engineering Informatics*, and *Journal of Computing in Civil Engineering*. These three journals have the greatest number of publications and highest relevance, thereby highlighting their important position in BIM research.

In the qualitative analysis, the collected articles were further integrated and refined, resulting in 1926 articles used in the analysis. These articles were systematically classified and summarized according to the stages of the project life cycle, namely, the design stage, design-construction stage, construction stage, construction operation and maintenance stage, operation and maintenance stage, and demolition stage. By combining the research hotspots of each stage, a comprehensive view is obtained. Existing studies have focused on the construction phase. In addition, the research focuses on the realization of BIM technology, while the research from the perspective of management is relatively weak, and shows a trend from technology research to management research. Based on the analysis results for the first two stages, this paper summarized the problems involved in the application of BIM. According to these problems and the existing literature, some possible research trends in each stage can be inferred and directions for future research directions can be proposed.

This work helps researchers and practitioners in the BIM field quickly locate influential and fruitful scholars or journals and understand the current research status, hotspots, and future research directions in this field across all stages of life cycle management. The literature samples selected for this study were limited to English journals and review articles in WOS. Therefore, future studies should further identify the uncertainties and differences between the latest academic research and industry practices.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (NSFC) (Grant No. 52078302), the National Natural Science Foundation of Guangdong Province (Grant No. 2021A1515012204 and 2021A1515110474), the Department of Education of Guangdong Province (Grant No. 2021ZDZX1004), the Shenzhen Science and Technology Innovation Commission (Grant No. JCYJ20190808174409266, No. GJHZ20200731095806017 and No. SGDX20201103093600002) and the funding support from the Fellowship of China Post-doctoral Science Foundation (No. 2021M692169 and No. 2021M702236).

References

Ahmad, Z., Thaheem, M. J., & Maqsoom, A. (2018). Building information modeling as a risk transformer: An evolutionary insight into the project uncertainty. *Automation in Construction*, *92*, 103–119. https://doi.org/10.1016/j.autcon.2018.03.032

Ahmed, A. L., & Kassem, M. (2018). A unified BIM adoption taxonomy: Conceptual development, empirical validation and application. *Automation in Construction*, *96*, 103–127. http://doi.org/10.1016/j.autcon.2018.08.017

Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Delgado, J. M. D., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production*, *223*, 386–396. http://doi.org/10.1016/j.jclepro.2019.03.172

Akin, S., Ergun, O., Surer, E., & Dino, I. G. (2022). An immersive performative architectural design tool with daylighting simulations: A building information modeling-based approach. *Engineering, Construction and Architectural Management*, *28*(4), 1319–1344. http://doi.org/10.1108/ecam-07-2020-0562

Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources Conservation and Recycling*, *105*(A), 167–176. http://doi.org/10.1016/j.resconrec.2015.10.018

Arslan, M., Cruz, C., & Ginhac, D. (2019a). Semantic trajectory insights for worker safety in dynamic environments. *Automation in Construction*, *106*, 102854. http://doi.org/10.1016/j.autcon.2019.102854

Arslan, M., Cruz, C., & Ginhac, D. (2019b). Visualizing intrusions in dynamic building environments for worker safety. *Safety Science*, *120*, 428–446. http://doi.org/10.1016/j.ssci.2019.07.020

Azhar, S., Carlton, W. A., Olsen, D. & Ahmad, I. (2011). Building information modeling for sustainable design and LEED$^{(R)}$ rating analysis. *Automation in Construction*, *20*(2SI), 217–224. http://doi.org/10.1016/j.autcon.2010.09.019

Bakchan, A., & Faust, K. M. (2019). Construction waste generation estimates of institutional building projects: Leveraging waste hauling tickets. *Waste Management*, *87*, 301–312. http://doi.org/10.1016/j.wasman.2019.02.024

Banihashemi, S., Tabadkani, A., & Hosseini, M. R. (2018). Integration of parametric design into modular coordination: A construction waste reduction workflow. *Automation in Construction*, *88*, 1–12. http://doi.org/10.1016/j.autcon.2017.12.026

Bilal, M., Oyedele, L. O., Akinade, O. O., Ajayi, S. O., Alaka, H. A., Owolabi, H. A., Qadir, J., Pasha, M., & Bello, S. A. (2016). Big data architecture for construction waste analytics (CWA): A conceptual framework. *Journal of Building Engineering*, *6*, 144–156. http://doi.org/10.1016/j.jobe.2016.03.002

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, *114*, 103179. http://doi.org/10.1016/j.autcon.2020.103179

Bortolini, R., Formoso, C. T., & Viana, D. D. (2019). Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. *Automation in Construction*, *98*, 248–264. http://doi.org/10.1016/j.autcon.2018.11.031

Braun, A., & Borrmann, A. (2019). Combining inverse photogrammetry and BIM for automated labeling of construction site images for machine learning. *Automation in Construction*, *106*, 102879. http://doi.org/10.1016/j.autcon.2019.102879

Braun, A., Tuttas, S., Borrmann, A., & Stilla, U. (2020). Improving progress monitoring by fusing point clouds, semantic data and computer vision. *Automation in Construction*, *116*, 103210. http://doi.org/10.1016/j.autcon.2020.103210

Cang, Y., Luo, Z. X., Yang, L., & Han, B. (2020). A new method for calculating the embodied carbon emissions from buildings in schematic design: Taking "building element" as basic unit. *Building and Environment*, *185*, 107306. http://doi.org/10.1016/j.buildenv.2020.107306

Cerovsek, T. (2011). A review and outlook for a "Building Information Model" (BIM): A multi-standpoint framework for technological development. *Advanced Engineering Informatics*, *25*(2), 224–244. http://doi.org/10.1016/j.aei.2010.06.003

Chen, X., Liu, C., & Wu, I. (2018). A BIM-based visualization and warning system for fire rescue. *Advanced Engineering Informatics*, *37*, 42–53. http://doi.org/10.1016/j.aei.2018.04.015

Cheng, M., & Chang, N. (2019). Dynamic construction material layout planning optimization model by integrating 4D BIM. *Engineering with Computers*, *35*(2), 703–720. http://doi.org/10.1007/s00366-018-0628-0

Cheng, J. C. P., Chen, W. W., Chen, K. Y., & Wang, Q. (2020). Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Automation in Construction*, *112*, 103087. http://doi.org/10.1016/j.autcon.2020.103087

Choe, S., & Leite, F. (2017). Construction safety planning: Site-specific temporal and spatial information integration. *Automation in Construction*, *84*, 335–344. http://doi.org/10.1016/j.autcon.2017.09.007

Costa, G., & Sicilia, A. (2020). Alternatives for facilitating automatic transformation of BIM data using semantic query languages. *Automation in Construction*, *120*, 103384. http://doi.org/10.1016/j.autcon.2020.103384

Ding, L., Jiang, W. G., Zhou, Y., Zhou, C., & Liu, S. (2020a). BIM-based task-level planning for robotic brick assembly through image-based 3D modeling. *Advanced Engineering Informatics*, *43*, 100993. http://doi.org/10.1016/j.aei.2019.100993

Ding, Z., Liu, S., Luo, L. W., & Liao, L. H. (2020b). A building information modeling-based carbon emission measurement system for prefabricated residential buildings during the materialization phase. *Journal of Cleaner Production*, *264*, 121728. http://doi.org/10.1016/j.jclepro.2020.121728

Ding, Z., Niu, J. D., Liu, S., Wu, H. Y., & Zuo, J. (2020c). An approach integrating geographic information system and building information modelling to assess the building health of commercial buildings. *Journal of Cleaner Production*, *257*, 120532. http://doi.org/10.1016/j.jclepro.2020.120532

Doumbouya, L., Guan, C. S., Gao, G., & Pan, Y. (2017). Application of BIM technology in design and construction: A case study of pharmaceutical industrial base of amino acid building project. In L. Malinovska, & V. Osadcuks (Eds.), *16th International Scientific Conference on Engineering for Rural Development* (pp. 1495–1502). Latvia University of Agriculture, Faculty of Engineering, Jelgava, Latvia. http://doi.org/10.22616/ERDev2017.16.N338

Dutta, S., Cai, Y. Y., Huang, L. H., & Zheng, J. M. (2020). Automatic re-planning of lifting paths for robotized tower cranes in dynamic BIM environments. *Automation in Construction*, *110*, 102998. http://doi.org/10.1016/j.autcon.2019.102998

El Ammari, K., & Hammad, A. (2019). Remote interactive collaboration in facilities management using BIM-based mixed reality. *Automation in Construction*, *107*, 102940. http://doi.org/10.1016/j.autcon.2019.102940

Eleftheriadis, S., Duffour, P., Stephenson, B., & Mumovic, D. (2018). Automated specification of steel reinforcement to support the optimisation of RC floors. *Automation in Construction*, *96*, 366–377. http://doi.org/10.1016/j.autcon.2018.10.005

Fu, M., & Liu, R. (2020). BIM-based automated determination of exit sign direction for intelligent building sign systems. *Automation in Construction*, *120*, 103353. http://doi.org/10.1016/j.autcon.2020.103353

Fu, M., Liu, R., Qi, B., & Issa, R. R. (2020). Generating straight skeleton-based navigation networks with Industry Foundation Classes for indoor way-finding. *Automation in Construction*, *112*, 103057. http://doi.org/10.1016/j.autcon.2019.103057

Getuli, V., Capone, P., Bruttini, A., & Isaac, S. (2020). BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach. *Automation in Construction*, *114*, 103160. http://doi.org/10.1016/j.autcon.2020.103160

Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., & Raahemifar, K. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges. *Renewable & Sustainable Energy Reviews*, *75*, 1046–1053. http://doi.org/10.1016/j.rser.2016.11.083

Guerra, B. C., Bakchan, A., Leite, F., & Faust, K. M. (2019). BIM-based automated construction waste estimation algorithms: The case of concrete and drywall waste streams. *Waste Management*, *87*, 825–832. http://doi.org/10.1016/j.wasman.2019.03.010

Gui, N., Wang, C. H., Qiu, Z. F., Gui, W. H., & Deconinck, G. (2019). IFC-based partial data model retrieval for distributed collaborative design. *Journal of Computing in Civil Engineering*, *33*(3), 040190163. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000829

Guo, J., Wang, Q., & Park, J. (2020). Geometric quality inspection of prefabricated MEP modules with 3D laser scanning. *Automation in Construction*, *111*, 103053. http://doi.org/10.1016/j.autcon.2019.103053

Hamidavi, T., Abrishami, S., & Hosseini, M. R. (2020). Towards intelligent structural design of buildings: A BIM-based solution. *Journal of Building Engineering*, *32*, 101685. http://doi.org/10.1016/j.jobe.2020.101685

Hollberg, A., Genova, G., & Habert, G. (2020). Evaluation of BIM-based LCA results for building design. *Automation in Construction*, *109*, 102972. http://doi.org/10.1016/j.autcon.2019.102972

Hosny, A., Nik-Bakht, M., & Moselhi, O. (2020). Workspace planning in construction: Non-deterministic factors. *Automation in Construction*, *116*, 103222. http://doi.org/10.1016/j.autcon.2020.103222

Jeon, J., Lee, J., & Ham, Y. (2019). Quantifying the impact of building envelope condition on energy use. *Building Research and Information*, *47*(4), 404–420. http://doi.org/10.1080/09613218.2018.1448959

Kameli, M., Hosseinalipour, M., Sardroud, J. M., Ahmed, S. M., & Behruyan, M. (2021). Improving maintenance performance by developing an IFC BIM/RFID-based computer system. *Journal of Ambient Intelligence and Humanized Computing*, *12*(2), 3055–3074. http://doi.org/10.1007/s12652-020-02464-3

Kang, T. (2020). BIM-Based Human Machine Interface (HMI) framework for energy management. *Sustainability*, *12*(21), 886121. http://doi.org/10.3390/su12218861

Khalili-Araghi, S., & Kolarevic, B. (2016). Development of a framework for dimensional customization system: A novel method for customer participation. *Journal of Building Engineering*, *5*, 231–238. http://doi.org/10.1016/j.jobe.2016.01.001

Khalili-Araghi, S., & Kolarevic, B. (2020). Variability and validity: Flexibility of a dimensional customization system. *Automation in Construction*, *109*, 102970. http://doi.org/10.1016/j.autcon.2019.102970

Lawrence, M., Pottinger, R., Staub-French, S., & Nepal, M. P. (2014). Creating flexible mappings between Building Information Models and cost information. *Automation in Construction*, *45*, 107–118. http://doi.org/10.1016/j.autcon.2014.05.006

Lee, Y., Solihin, W., & Eastman, C. M. (2019). The mechanism and challenges of validating a building information model regarding data exchange standards. *Automation in Construction*, *100*, 118–128. http://doi.org/10.1016/j.autcon.2018.12.025

Lei, Y., Rao, Y. P., Wu, J. M., & Lin, C. S. (2020). BIM based cyber-physical systems for intelligent disaster prevention. *Journal of Industrial Information Integration*, *20*, 100171. http://doi.org/10.1016/j.jii.2020.100171

Li, C. T., Cheng, J. C. P., & Chen, K. (2020). Top 10 technologies for indoor positioning on construction sites. *Automation in Construction*, *118*, 103309. http://doi.org/10.1016/j.autcon.2020.103309

Lu, X., Yang, Z. B., Xu, Z., & Xiong, C. (2020). Scenario simulation of indoor post-earthquake fire rescue based on building information model and virtual reality. *Advances in Engineering Software*, *143*, 102792. http://doi.org/10.1016/j.advengsoft.2020.102792

Lu, Y., Le, V. H., & Song, X. (2017). Beyond boundaries: A global use of life cycle inventories for construction materials. *Journal of Cleaner Production*, *156*, 876–887. http://doi.org/10.1016/j.jclepro.2017.04.010

Lundeen, K. M., Kamat, V. R., Menassa, C. C., & McGee, W. (2017). Scene understanding for adaptive manipulation in robotized construction work. *Automation in Construction*, *82*, 16–30. http://doi.org/10.1016/j.autcon.2017.06.022

Lundeen, K. M., Kamat, V. R., Menassa, C. C., & McGee, W. (2019). Autonomous motion planning and task execution in geometrically adaptive robotized construction work. *Automation in Construction*, *100*, 24–45. http://doi.org/10.1016/j.autcon.2018.12.020

Ma, G., & Du, Q. (2020). Optimization on the intellectual monitoring system for structures based on acoustic emission and data mining. *Measurement*, *163*, 107937. http://doi.org/10.1016/j.measurement.2020.107937

Ma, G., & Wu, Z. (2020). BIM-based building fire emergency management: Combining building users' behavior decisions. *Automation in Construction*, *109*, 102975. http://doi.org/10.1016/j.autcon.2019.102975

Ma, Z., Cai, S. Y., Mao, N., Yang, Q. L., Feng, J. G., & Wang, P. Y. (2018). Construction quality management based on a collaborative system using BIM and indoor positioning. *Automation in Construction*, *92*, 35–45. http://doi.org/10.1016/j.autcon.2018.03.027

Ma, Z., Ren, Y., Xiang, X. L., & Turk, Z. (2020). Data-driven decision-making for equipment maintenance. *Automation in Construction*, *112*, 103103. http://doi.org/10.1016/j.autcon.2020.103103

Ma, Z., Wei, Z., & Zhang, X. (2013). Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model. *Automation in Construction*, *30*, 126–135. http://doi.org/10.1016/j.autcon.2012.11.020

Marmo, R., Polverino, F., Nicolella, M., & Tibaut, A. (2020). Building performance and maintenance information model based on IFC schema. *Automation in Construction*, *118*, 103275. http://doi.org/10.1016/j.autcon.2020.103275

Marzouk, M., & Al Daour, I. (2018). Planning labor evacuation for construction sites using BIM and agent-based simulation. *Safety Science*, *109*, 174–185. http://doi.org/10.1016/j.ssci.2018.04.023

Marzouk, M., Azab, S., & Metawie, M. (2018). BIM-based approach for optimizing life cycle costs of sustainable buildings. *Journal of Cleaner Production*, *188*, 217–226. http://doi.org/10.1016/j.jclepro.2018.03.280

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. *Automation in Construction*, *43*, 84–91. http://doi.org/10.1016/j.autcon.2014.03.009

Olawumi, T. O., & Chan, D. W. M. (2019). Building information modelling and project information management framework for construction projects. *Journal of Civil Engineering and Management*, *25*(1), 53–75. http://doi.org/10.3846/jcem.2019.7841

Patacas, J., Dawood, N., & Kassem, M. (2020). BIM for facilities management: A framework and a common data environment using open standards. *Automation in Construction*, *120*, 103366. http://doi.org/10.1016/j.autcon.2020.103366

Rebolj, D., Pucko, Z., Babic, N. C., Bizjak, M., & Mongus, D. (2017). Point cloud quality requirements for Scan-vs-SIM based automated construction progress monitoring. *Automation in Construction*, *84*, 323–334. http://doi.org/10.1016/j.autcon.2017.09.021

Rehman, A., Hussain, M, Farooq, A, & Akram, M. (2019). Consensus-based multi-person decision making with incomplete fuzzy preference relations using product transitivity. *Mathematics*, *7*(2), 185. https://doi.org/10.3390/math7020185

Rezaei, F., Bulle, C., & Lesage, P. (2019). Integrating building information modeling and life cycle assessment in the early and detailed building design stages. *Building and Environment*, *153*, 158–167. http://doi.org/10.1016/j.buildenv.2019.01.034

Santos, R., Costa, A. A., & Grilo, A. (2017). Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015. *Automation in Construction*, *80*, 118–136. http://doi.org/10.1016/j.autcon.2017.03.005

Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2020). Development of a BIM-based environmental and economic life cycle assessment tool. *Journal of Cleaner Production*, *265*, 121705. https://doi.org/10.1016/j.jclepro.2020.121705

Sibenik, G., & Kovacic, I. (2020). Assessment of model-based data exchange between architectural design and structural analysis. *Journal of Building Engineering*, *32*, 101589. http://doi.org/10.1016/j.jobe.2020.101589

Sidani, A., Dinis, F. M., Sanhudo, L., Duarte, J., Baptista, J. S., Martins, J. P., & Soeiro, A. (2021). Recent tools and techniques of BIM-based virtual reality: A systematic review. *Archives of Computational Methods in Engineering*, *28*(2), 449–462. http://doi.org/10.1007/s11831-019-09386-0

Succar, B., & Poirier, E. (2020). Lifecycle information transformation and exchange for delivering and managing digital and physical assets. *Automation in Construction*, *112*, 103090. http://doi.org/10.1016/j.autcon.2020.103090

Vigneault, M., Boton, C., Chong, H. Y., & Cooper-Cooke, B. (2020). An innovative framework of 5D BIM solutions for construction cost management: A systematic review. *Archives of Computational Methods in Engineering*, *27*(4), 1013–1030. http://doi.org/10.1007/s11831-019-09341-z

Wei, Y., & Akinci, B. (2019). A vision and learning-based indoor localization and semantic mapping framework for facility operations and management. *Automation in Construction*, *107*, 102915. http://doi.org/10.1016/j.autcon.2019.102915

Won, J., Czerniawski, T., & Leite, F. (2020). Semantic segmentation of point clouds of building interiors with deep learning: Augmenting training datasets with synthetic BIM-based point clouds. *Automation in Construction*, *113*, 103144. http://doi.org/10.1016/j.autcon.2020.103144

Xu, J., Shi, Y., Xie, Y. C., & Zhao, S. W. (2019). A BIM-based construction and demolition waste information management system for greenhouse gas quantification and reduction. *Journal of Cleaner Production*, *229*, 308–324. http://doi.org/10.1016/j.jclepro.2019.04.158

Xu, Z., Zhang, Z. C., Lu, X. Z., Zeng, X., & Guan, H. (2018). Post-earthquake fire simulation considering overall seismic damage of sprinkler systems based on BIM and FEMA P-58. *Automation in Construction*, *90*, 9–22. http://doi.org/10.1016/j.autcon.2018.02.015

Xue, F., & Lu, W. (2020). A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. *Automation in Construction*, *118*, 103270. http://doi.org/10.1016/j.autcon.2020.103270

Yuan, Z., Sun, C., & Wang, Y. (2018). Design for manufacture and assembly-oriented parametric design of prefabricated buildings. *Automation in Construction*, *88*, 13–22. http://doi.org/10.1016/j.autcon.2017.12.021

Zhang, L., & Dong, L. (2019). Application sudy on Building Information Model (BIM) standardization of Chinese engineering breakdown structure (EBS) coding in life cycle management processes. *Advances in Civil Engineering*, *2019*, 1581036. http://doi.org/10.1155/2019/1581036

Zhang, Z., Cheng, X. J., Yang, B. L., & Yang, D. (2020). Exploration of indoor barrier-free plane intelligent lofting system combining BIM and multi-sensors. *Remote Sensing*, *12*(20), 3306. http://doi.org/10.3390/rs12203306

Zhao, X. (2017). A scientometric review of global BIM research: Analysis and visualization. *Automation in Construction*, *80*, 37–47. https://doi.org/10.1016/j.autcon.2017.04.002

Zhou, X., Xie, Q. S., Guo, M. Z., Zhao, J. C., & Wang, J. (2020). Accurate and efficient indoor pathfinding based on building information modeling data. *IEEE Transactions on Industrial Informatics*, *16*(12), 7459–7468. https://doi.org/10.1109/TII.2020.2974252

Zhou, X., Zhao, J. C., Wang, J., Su, D. D., Zhang, H. Y., Guo, M., Guo, M. Z., & Li, Z. (2019). OutDet: An algorithm for extracting the outer surfaces of building information models for integration with geographic information systems. *International Journal of Geographical Information Science*, *33*(7), 1444–1470. http://doi.org/10.1080/13658816.2019.1572894

Zhu, J., Wang, X. Y., Chen, M. C., Wu, P., & Kim, M. J. (2019). Integration of BIM and GIS: IFC geometry transformation to shapefile using enhanced open-source approach. *Automation in Construction*, *106*, 102859. http://doi.org/10.1016/j.autcon.2019.102859