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STATUS QUO AND FUTURE TRENDS OF BIM-BASED COORDINATION RESEARCH: A CRITICAL REVIEW

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Abstract. Enhancing coordination between stakeholders is a critical function of Building Information Modeling (BIM). Recently, there have been numerous studies investigating BIM-based coordination; however, no explicit attempt has been made to investigate the current status of relevant research and determine the future directions. Hence, this study examines the BIM-based coordination literature published from 2006 to 2020 through bibliometric literature searching, scientific mapping, and in-depth critical analysis to fill the research gap. After a comprehensive filtering process, 656 pieces of literature were collected from Scopus. To map the representative information in the BIM-based coordination research, the determination and visualization of the most influential scholars, journals, countries/regions, and articles, as well as their importance and relationships, were performed through VOSviewer. Four emerging research topics were further discussed according to the determined scientific map. Moreover, a framework that presents the existing research gaps and future research directions was proposed. This research provides a clear picture of the leading information and future research trends of the BIM-based coordination, contributing to the body of knowledge theoretically and offering references for related stakeholders practically.

Keywords: Building Information Modeling (BIM), construction management, coordination, network analysis, knowledge map.

Introduction

Building Information Modeling (BIM) is a developing technology that has received widespread attention in the Architecture, Engineering, and Construction (AEC) industry. Through integrated technology with "parameter intelligence", BIM can alter the representation process of digital buildings throughout their life cycles (Eastman et al., 2011). BIM is an innovative technology that forms, organizes, and manages information throughout construction processes (Boton et al., 2021). It enables different project stakeholders (owners, contractors, subcontractors, suppliers, architects, and engineers) to share and exchange real-time information to achieve more efficient and smoother collaboration than traditional processes (Azhar et al., 2015; Wu et al., 2019). Thus, adopting BIM in the AEC industry can efficiently solve problems caused by traditional rough construction methods. For example, Li et al. (2017) produced a Radio Frequency Identification Device (RFID) supported BIM platform, offering various mechanisms, resources, and services to multiple parties, thus enhancing operations and managerial procedures of operations and managerial procedures off-site construction. Wang et al. (2014) suggested combining BIM and Geographic Information System (GIS) to optimize the site layout for successful traffic planning. Tan et al. (2019) designed a 4D BIM-integrated simulation method to alleviate the noise impact on construction-site workers.

There are five main features of BIM identified by Monteiro and Martins (2013), namely, coordination, visualization, optimization, simulation, and plotting. Santos et al. (2017) and Zhao (2017) conducted a bibliometric analysis and literature review of BIM research. They found that BIM-based coordination has gained the attention of scholars and has thus become a hot topic in recent years. Raouf and Al-Ghamdi (2019) found that during the construc-

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tion of the project, various stakeholders often have asymmetric information, which may delay the construction period, affect the quality of the project, and result in conflicts. However, BIM's real-time information sharing and storage functions could effectively avoid these issues and achieve smooth cooperation (Oraee et al., 2017). Akponeware and Adamu (2017) and Hu et al. (2019) explored that BIM can be combined with supervised machine learning algorithms for clash detection. By improving the accuracy and quality of clash detection, this integrated technology enhances the coordination efficiency among different disciplines in projects. Moreover, through theoretically reviewing 73 journal articles, Oraee et al. (2019) established a theoretical system to discover the critical obstacles to achieving cooperation in BIM-supported networks. Although the significance of BIM-based coordination has received much attention, no studies have been conducted to investigate its current research status. Therefore, this study aims to fill this gap to determine the main research areas of BIM-based coordination, define the existing research gaps, and suggest future research directions through performing a combination of bibliometric searching, scientific mapping, and in-depth qualitative analysis of relevant literature published in 2006–2020.

In the following section, the research methodologies utilized in this study are introduced, including bibliometric analysis, database selection, and specific information collection and analysis process. Then, the result analysis of the collected literature based on networks is provided to deliver the leading information, principle, hotspots, and development trends of the BIM-based coordination research. Further in-depth discussions of dominant research topics in the BIM-based coordination field and future research tendencies are presented in the fourth section. Finally, the main findings, implications of this study, and limitations are concluded in the last section.

1. Research methodology

Regarding the research objective, the procedure of this research was designed as shown in Figure 1. Specifically, the bibliometric literature search was first conducted to filter and collect needed literature, followed by the scientific mapping through VOSviewer. Then, an in-depth discussion was undertaken to further analyze the research foci and the potential research directions.

1.1. Bibliometric literature search

Bibliometrics is a quantitative analysis method that combines statistical and mathematical methods to explore the representative framework from a large number of bibliographic documents (Baker et al., 2020). Since the bibliometric analysis indicates its advance in visualizing the structural relationship and scientific development process of a particular research theme (Bornmann, 2015; Hood & Wilson, 2001), it has been adopted in various fields and proved reliable.

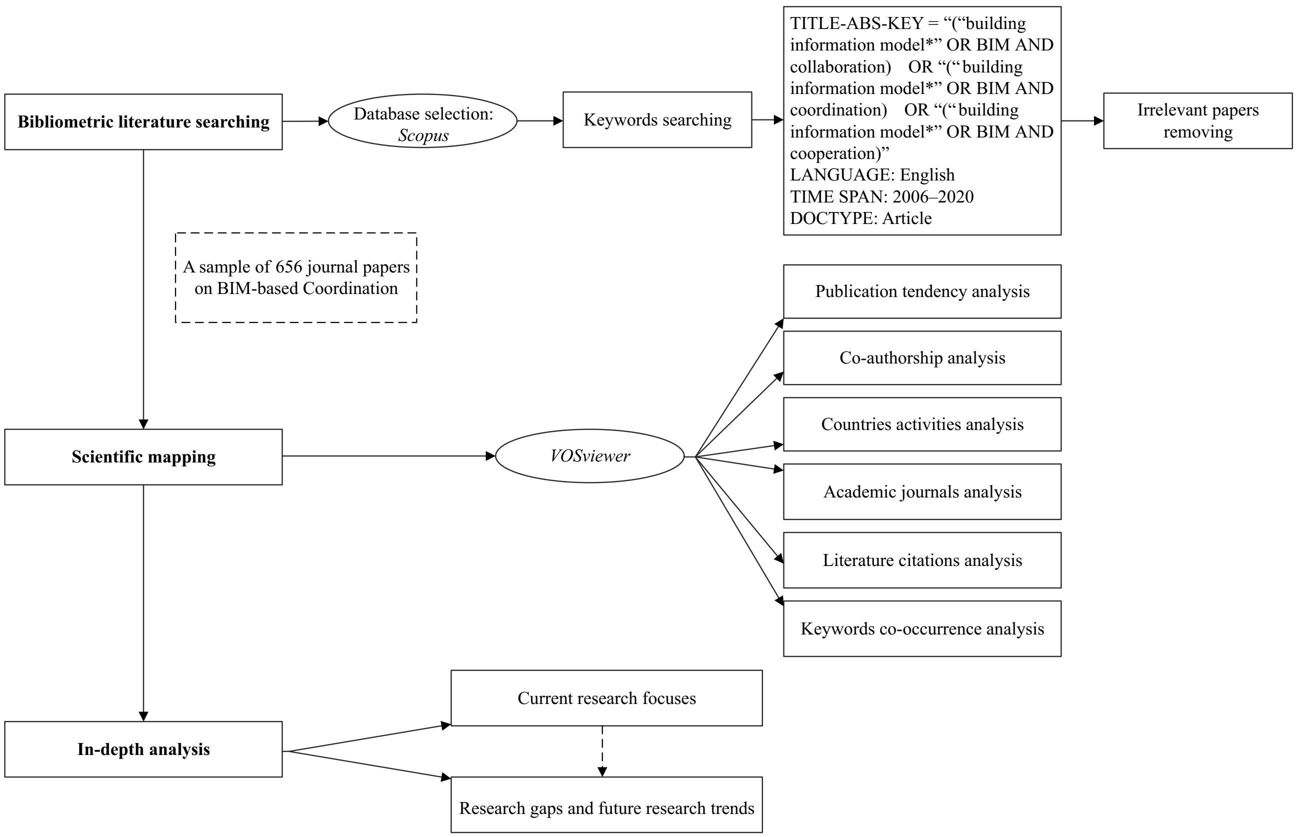

Figure 1. The workflow of the study

To perform the bibliometric literature search, the database was first selected. Scopus, Web of Science, and Google Scholar are three renowned, highly recognized, and powerful scholarly search engines (Shan & Hwang, 2018) that could help researchers track research progress in a specific field. Meho and Rogers (2008) conducted a comparative exploration of the performance of Scopus and Web of Science on different functions and concluded that a broader range of human-computer interaction studies was collected in Scopus. Similarly, Zhao et al. (2019) asserted that Scopus contains an enormous amount of scientific publications with a relatively more efficient indexing process. Their opinion was echoed by many other researchers (Darko et al., 2019; Hosseini et al., 2018b). Also, it has been proved that in the field of construction research, Scopus has a relatively more extensive coverage than other sources, like Google Scholar and Web of Science (Hosseini et al., 2018a; Mongeon & Paul-Hus, 2016; van Eck & Waltman, 2014; Yin et al., 2019). Therefore, this study selected Scopus to collect the BIM-based coordination articles for further research.

After the selection of the database, the study performed the bibliometric information collection. The retrieval code that was conducted in Scopus was as follows: TITLE-ABS-KEY = "("building information model*" OR BIM AND collaboration)" OR "("building information model*" OR BIM AND coordination)" OR "("building information model*" OR BIM AND cooperation)". Here, "*" represents a fuzzy search. According to the search records, BIM research started to emerge in 2006, so the literature collection period was defined as 2006–2020. Since journal articles indicate higher quality research results with a convincing reputation, only journal articles were taken in this study, while conference papers, book chapters, and reviews were ignored (Yi & Chan, 2014; Zheng et al., 2016). Under this filter, 656 pieces of literature were gathered.

1.2. Scientific mapping

The scientific knowledge map is a cross-field of computer science, information science, and applied mathematics, which can visualize complex relationships, such as evolutions and networks (Hosseini et al., 2018b; Olawumi & Chan, 2018). Existing research indicated that scientific mapping could mitigate the dispute produced by human subjective judgment when conducting the research field exploration study (van Eck & Waltman, 2017). Combining the bibliometric method and the information visualization tool to create the scientific knowledge map could provide researchers and practitioners with a shortcut of the leading information, principle, hotspots, and development trends of the particular field (Kaffash et al., 2021) hence benefiting the academic research and industry applications.

After collecting the required literature, the VOSviewer program was employed to create the scientific knowledge map of the BIM-based coordination research field. The VOSviewer could present comprehensive bibliometric maps and serve a convenient access approach to users (Adegoriola et al., 2021). In the VOSviewer, a circle and a text label form an element, and its color indicates its belonging cluster. While different colors indicate different clusters, the distance and connection between elements reflect the network relationship between them.

This paper investigated the collected 656 journal articles related to BIM-based coordination from six perspectives: publication tendency, co-authorship, countries/regions activities, academic journals, literature citations, and keywords co-occurring. Besides the overview of the literature collected that formed the first perspective, the other five were selected because through the analysis of these aspects, the overall status of the research can be presented (Jin et al., 2019). The defined comparative dimensions were publications, citations, average (/normalized) citations, and average publication year. The former three ones generally have a strong correlation. The calculation approach of average citations is defined as separating the overall citations of publications, which is why normalization is needed to fix the misinterpretation that age-old articles take longer to cite than more recent documents. The average normalized citations are adopted as the measurement of the influence, which means the larger its value, the more significant the impact. Moreover, the research foci for a period of time are represented by the average publication year.

1.3. Qualitative analysis

The in-depth qualitative critical analysis was the last procedure of this research. There are two objectives involved in this part. The first is to determine the current study foci, and the other is to propose the research gaps and their leaded future research trends in the BIM-based coordination field.

Specifically, the identified research foci were further discussed on a cluster basis by conducting an in-depth literature content review. Through the content analysis and discussion, research gaps in the explored domain were identified. The future research trends were then proposed based on the discovered research gap and prospects from the existing literature.

2. Analysis of results

2.1. Publication tendency analysis

The distribution of BIM-based coordination-related publications is presented in the following Figure 2.

Since 2006, research in the BIM-based coordination field has continued to rise. In the two time periods of 2012–2014 and 2016–2018, BIM-based coordination-related publications have seen two substantial increases. This phenomenon is coincidental with the global promotion and application trend of BIM. Between 2012 and 2014, many countries have officially planned or started to commence their BIM adoption in the AEC sector. For example, the US Army Corps of Engineers has introduced

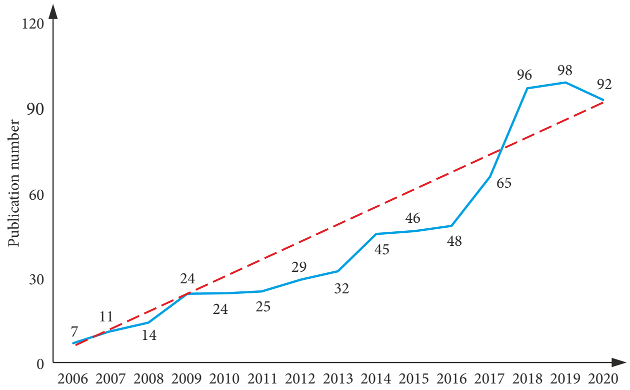

Figure 2. The BIM-based coordination publication tendency in Scopus in 2006–2020

a detailed BIM roadmap, application template, and contract requirements for BIM tools in 2012 (USACE, 2012). Finland released a complete set of BIM implementation guidelines, including application experience, in 2012 (buildingSMART. Finland, 2012). Likewise, 2016–2018 is also a period when BIM has received much attention. The Ministry of Housing and Urban-Rural Development of China published the "Outline of Development of Construction Industry Informatization (2016–2020)" to highlight the integrative application of BIM and other information technologies in 2016 (Lee & Borrmann, 2020). In 2016, the Ministry of Land, Infrastructure, Transport, and Tourism of Japan (MLIT) proclaimed promoting information technologies, such as BIM, in construction practice in 2016 (Tateyama, 2017).

2.2. Co-authorship analysis

The authors of these articles can be captured from bibliographic records, which identified scholars who have had an academic collaboration in the BIM-based coordination field. The minimum numbers of publications and citations of one author were determined as 5 and 24. Since there are no clear regulations and uniform habits for setting numerical boundaries, the numerical threshold settings in this article are based on both referring to other similar studies (Hosseini et al., 2018b; Khudhair et al., 2021; Oraee et al., 2017; Yin et al., 2019) and repeated tests. The numerical values that can achieve the ideal classification effect were selected. Overall, 22 of 1817 authors satisfied the filtering criteria. Excluding the unrelated authors, the co-authorship of 12 authors was shown in Figure 3. In the created networks, the sizes of the nodes illustrate the occurrence frequencies or prominent levels of the representing elements; the links between the nodes indicate the relationships between the elements with the principle that the more significant the link, the stronger the relationship; the various colors illustrate the different clusters of elements grouped by the VOSviewer.

As shown in Figure 3, the authors are divided into four categories with different colors, indicating that the publications could be classified into four types referring to the collaboration level between the authors. The node represented X. Wang has the relatively largest size and is closely related to the node of other categories, illustrating that X. Wang has the greatest influence in the BIM-based coordination field. Besides, H. Li, M. R. Hosseini, and J. Wang have the most prominent nodes in their respective categories. According to Figure 3, the co-authoring networks of different categories are not independent. These networks have some interactive connections with each other. It means that cross-category cooperation among scholars, which helps develop a research field, has already existed. Also, the green network has interaction with all other clusters, representing that the research interest of H. Li, J. Zhang, and X. Li has been extensive. To further investigate the representative authors, a detailed co-authorship network has been summarized in Table 1.

As shown in Table 1, X. Wang ranks first with 678 citations, followed by M. R. Hosseini (328), H. Li (162), J. Zhang (129), and H.-Y. Chong (126). Considering the average citations, X. Wang obtained the highest score (56.50), followed by E. Papadonikolaki (43.00) and X. Li (40.40). Besides, in this field, two emerging scholars, S. Abrishami and W. Lu published most research works around 2019, demonstrating their potential. In addition, X. Li received the highest score in the measurement of average normalized citations. More detailed information is presented in Table 1. Among all selected authors, there were three authors from Curtin University and three scholars from universities in Hong Kong, revealing that these institutions play a significant part in this research field.

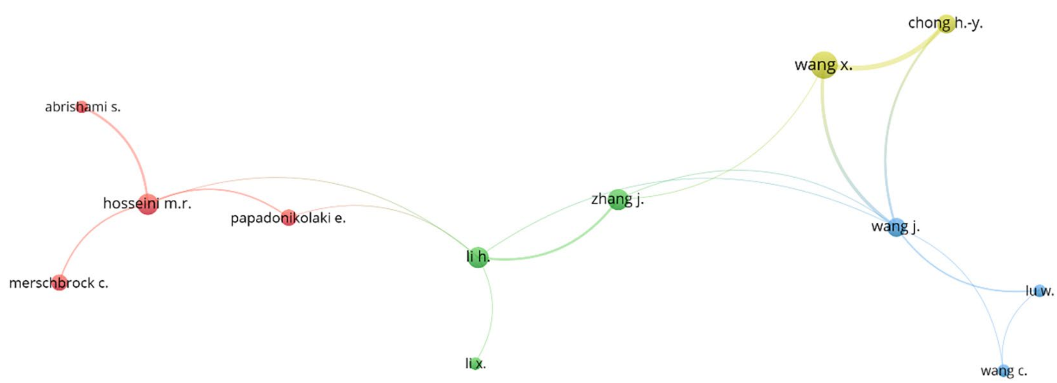

Figure 3. Co-authorship network

Table 1. Co-authorship network

Scholar	Affiliation	Documents	Citations	Avg. citations	Avg. norm. citations	Avg. pub. year
X. Wang	Curtin University	12	678	56.50	1.84	2016
M. R. Hosseini	Deakin University	9	328	36.44	2.13	2018
H. Li	Hong Kong Polytechnic University	9	162	18.00	1.28	2017
J. Zhang	Tsinghua University	9	129	14.33	0.63	2016
H.-Y. Chong	Curtin University	8	163	20.38	1.12	2017
C. Merschbrock	Oslo and Akershus University College	7	193	27.57	1.02	2015
E. Papadonikolaki	University College London	7	301	43.00	2.26	2018
J. Wang	Curtin University	7	142	17.75	1.86	2018
S. Abrishami	University of Portsmouth	5	41	8.20	0.94	2019
W. Lu	University of Hong Kong	5	87	17.40	1.77	2019
X. Li	Hong Kong Polytechnic University	5	202	40.40	2.80	2018
C. Wang	Chongqing University of Technology	5	42	8.40	0.72	2018

2.3. Countries/regions activities analysis

The countries/regions' activities were identified to explore the distribution of articles on BIM-based coordination. 10 and 135 were defined as the minimum numbers of publications and citations. Under this extraction criteria, 18 out of 75 areas were selected and visualized in Figure 4.

Figure 4 illustrates that the country/region is divided into six categories; with the largest node in the United States, United States scholars have the most outstanding contribution to this research field. The following Table 2 presents the performances of the countries/regions.

Table 2 illustrates that the following countries/regions have contributed significantly to BIM-based coordination research: the United States (132), China (125), the United Kingdom (92), Australia (57), Malaysia (34), South Korea (33), Germany (32), and Hong Kong (30). In terms of the average publication year, the rising countries/regions in BIM-based coordination were Hong Kong, Canada, and Singapore, whose publications are generally based around 2018. According to the average normalized citations measurement, Singapore received the highest value (2.14), indicating that their outcomes have had the most considerable influence on the development of BIM-based coordination research.

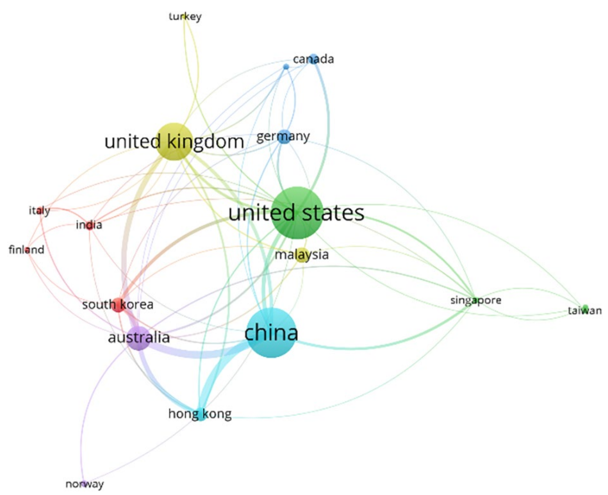

Figure 4. The network of countries/regions

2.4. Academic journals analysis

BIM-based coordination publications have appeared in 261 journals. The filtering numbers set for publications and citations were 5 and 100. After excluding the unconnected four journals, 18 of 261 academic journals that have been analyzed were presented in Figure 5.

Table 2. The network of countries/regions

Country/ Region	Documents	Citations	Avg. pub. year	Avg. citations	Avg. norm. citations
United States	132	4524	2015	34.27	1.16
China	125	2567	2016	20.54	1.11
United Kingdom	92	2900	2017	31.52	1.31
Australia	57	2569	2016	45.07	1.75
Malaysia	34	805	2017	23.68	0.84
South Korea	33	984	2017	29.82	0.96
Germany	32	977	2016	30.53	1.07
Hong Kong	30	827	2018	27.57	1.76
Canada	22	617	2018	28.05	1.28
India	20	212	2017	10.60	0.61
Italy	15	280	2013	18.67	0.88
Norway	14	257	2016	18.36	0.69
Netherlands	13	599	2016	46.07	1.49
Singapore	13	711	2018	54.69	2.14
Taiwan	13	209	2017	16.08	0.88
Finland	12	368	2017	30.67	1.15
Poland	11	140	2016	12.73	0.67
Turkey	11	332	2016	30.18	0.82

As shown in Figure 5, the journals are divided into five categories. The node of *Automation in Construction* is closely connected with all the other journals with the largest size. This phenomenon illustrates that *Automation in Construction* is of great importance in this research field. The following Table 3 provides more detailed information on the related academic journals.

Table 3 verifies that *Automation in Construction* could be considered as the leading journal that shows superiorities in the document number (55), citations (3974), average citations (72.25), and average normalized citations (2.64). The *International Journal of Project Management and Advanced Engineering Informatics* also received a greater number of citations. Considering the average normalized citations, the *International Journal of Project Management*, *Automation in Construction*, and *Applied Sciences* (Switzerland) should be ranked the top journals.

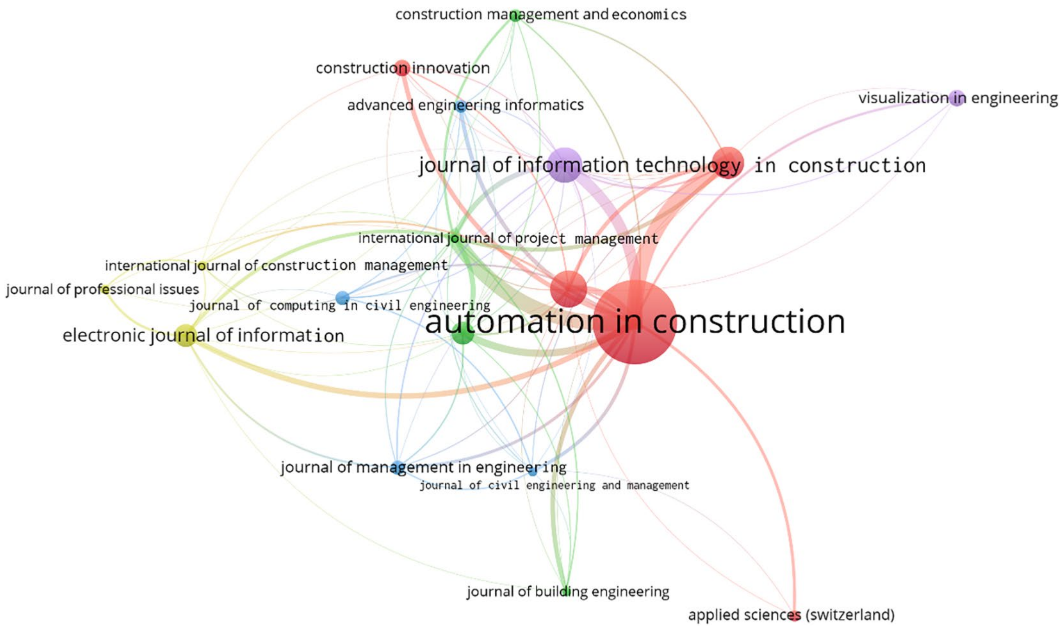

Figure 5. The network of journals

Table 3. The network of journals

Journal sources	Documents	Citations	Avg. citations	Avg. norm. citations
Automation in Construction	55	3974	72.25	2.64
Engineering, Construction and Architectural Management	22	504	22.91	1.07
Journal of Information Technology in Construction	21	422	20.10	0.81
Journal of Construction Engineering and Management	19	940	49.47	1.74
Architectural Engineering and Design Management	13	407	31.31	1.28
Electronic Journal of Information Technology in Construction (ITcon)	13	575	44.23	1.24
Construction Innovation	9	127	14.11	0.97
Visualization in Engineering	9	276	30.67	1.34
Journal of Computing in Civil Engineering	8	201	25.12	1.18
Journal of Management in Engineering	8	208	26.00	1.31
Advanced Engineering Informatics	7	370	52.86	0.71
Construction Management and Economics	7	151	21.57	0.99
Applied Sciences (Switzerland)	6	115	19.17	2.12
International Journal of Construction education and research	5	121	24.20	0.87
International Journal of Project Management	5	406	81.20	3.73
Journal of Building Engineering	5	129	25.80	1.64
Journal of Civil Engineering and Management	5	125	25.00	0.84
Journal of Professional Issues in Engineering Education and Practice	5	219	43.80	1.27

2.5. Literature citations analysis

The essential articles in the specific research field could be explored by the analysis of citations. The minimum selection number of citations was defined as 96. Excluding some items that have no connection with other ones from the filtered publications, 17 were visualized and presented in Figure 6.

As presented in Figure 6, Azhar (2011) has the largest number of citations, with the most significant node indicating that it could be regarded as the most influencing publication in the field. Table 4 provides more details of the citations of articles. It suggests that the most concentrated BIM-based applications are BIM-based platforms (Porwal & Hewage, 2013; Singh et al., 2011), working environments (Grilo & Jardim-Goncalves, 2010; Plume & Mitchell, 2007), Mechanical, Electrical, and Plumbing (MEP) coordination (Khanzode et al., 2008), sustainable design (Bynum et al., 2013), and quality management (Chen & Luo, 2014).

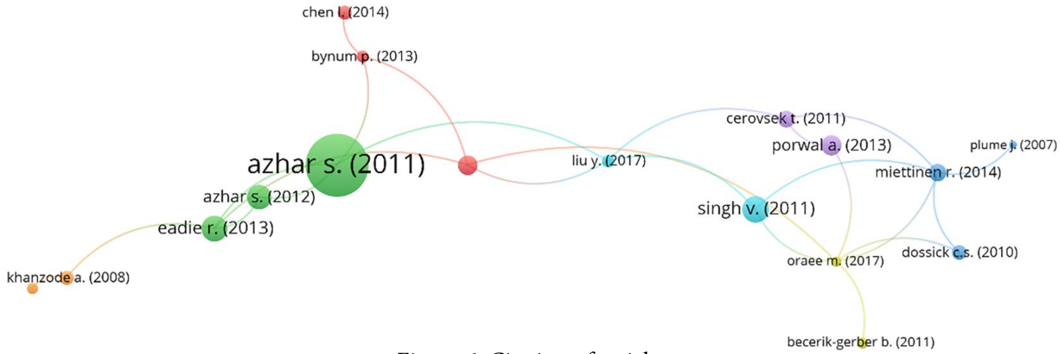

Figure 6. Citation of articles

Table 4. Citation of articles

Author	Title	Citations	Norm. citations	Pub. year
Azhar (2011)	Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry	945	8.25	2011
Singh et al. (2011)	A theoretical framework of a BIM-based multi-disciplinary collaboration platform	368	3.21	2011
Eadie et al. (2013)	BIM implementation throughout the UK construction project life-cycle: an analysis	356	7.86	2013
Azhar et al. (2015)	Building information modeling (BIM): now and beyond	333	6.42	2012
Porwal and Hewage (2013)	Building information modeling (BIM) partnering framework for public construction projects	274	6.05	2013
Grilo and Jardim-Goncalves (2010)	Value proposition on interoperability of BIM and collaborative working environments	265	4.88	2010
Miettinen and Paavola (2014)	Beyond the BIM utopia: approaches to the development and implementation of building information modeling	228	7.32	2014
Cerovsek (2011)	A review and outlook for a 'building information model' (BIM): a multi-standpoint framework for technological development	222	1.94	2011
Dossick and Neff (2010)	Organizational divisions in BIM-enabled commercial construction	189	3.84	2010
Khanzode et al. (2008)	Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project	187	9.19	2008
Chen and Luo (2014)	A BIM-based construction quality management model and its applications	181	5.81	2014
Liu et al. (2017)	Understanding effects of BIM on collaborative design and construction empirical study in China	161	5.83	2017
Bynum et al. (2013)	Building information modeling in support of sustainable design and construction	155	3.42	2013
Becerik-Gerber et al. (2011)	The pace of technological innovation in architecture, engineering, and construction education: integrating recent trends into the curricula	142	1.24	2011
Leite et al. (2011)	Analysis of modeling effort and impact of different levels of detail in building information models	139	1.21	2011
Oraee et al. (2017)	Collaboration in BIM-based construction networks: a bibliometric-qualitative literature review	131	4.75	2017
Plume and Mitchell (2007)	Collaborative design using a shared IFC building model-learning from experience	96	3.64	2007

2.6. Keywords co-occurring analysis

The word frequency analysis is the method that can reveal the representative information of the literature in a certain field so as to define the research hotspots and development trends. Regularly, the keywords of the document will enrich and refine the core content of the article. Therefore, a keyword that is reused in literature reflects the vital concept of an article. Following the suggestions of Oraee et al. (2017), this research used "Author Keywords" and "Fractional Counting" in VOSviewer analysis, with the least frequency of keywords defined at 6. In total, 40 out of 1788 keywords satisfied the selection criteria and had interactions were analyzed, as shown in Figure 7.

As shown in Figure 7, the most frequent keywords are mainly divided into four clusters which are "project management", "sustainable development", "stakeholder coordination", and "construction innovation". "Building information modeling" and "BIM" are the most significant nodes as BIM is the foundation of coordination. Some outstanding keywords related to coordination included "collaboration", "collaborative design", and "communication", whereas the other significant keywords illustrated the BIM-based coordination adoption occasions, such as "project management", "integrated project delivery", and "sustainability".

The research hotspot trend has also been explored and visualized, presented in Figure 8.

The significance of the topic is expressed by the occurrence times and average citations of the keywords. According to the figure, the most concentrated topic in

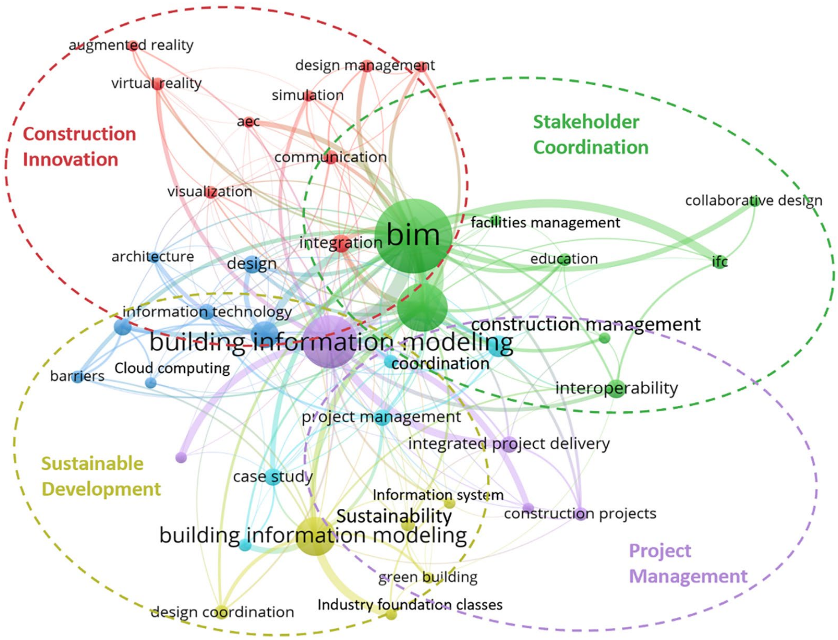

Figure 7. The network of keywords co-occurring

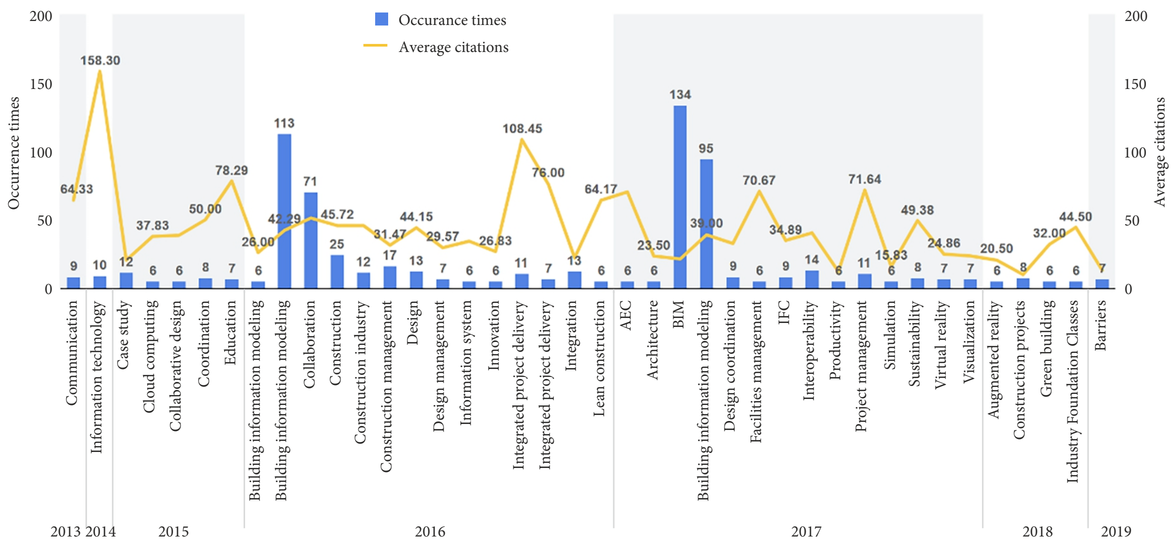

Figure 8. Research topics by year

2013 was "communication". It changed to the exploration of information technology and education in 2015. Since 2015, the performance of construction project management started to enter the attention of researchers and became the most prominent hot spot in 2016. By 2017, the research focus was gradually refined to interoperability, Industry Foundation Classes (IFC), and design coordination of the project, and an increasing amount of attention was paid to sustainability. By 2018, "green building" had become the most concentrated research topic and shifted to "barriers" in 2019, which may reveal the future research direction in the BIM-based coordination research field. Also, the keywords "information technology", "integrated project delivery (IPD)", "education", and "project management" have received significant attention over time. It means that these are the points that have always been emphasized in this field.

3. Discussions

An in-depth discussion of the main research topics is provided in this section based on previous analysis and results. The research gap and future research trends determined based on the discussion are also presented.

3.1. Main research topics of the BIM-based coordination

A knowledge domain map in BIM-based coordination research has been created based on the previous analysis, shown in Figure 9. The four main research themes are project management, stakeholder coordination, sustainable development, and construction innovation, which are further discussed.

Topic 1: Project management

The BIM-based coordination function has been highlighted in promoting project management efficiency. Applying BIM in the design and preparation phase could enhance the cooperation between different types of work, improve productivity, and minimize manufacturing errors and rework (Lee & Kim, 2017; Wu & Jeng, 2018). Also, in the planning stage, the adoption of BIM helps gather and exchange information to enable the most accurate prediction of potential failures and risks, thus facilitating the smooth operation of the project (Heigermoser et al., 2019; Zanni et al., 2014). Some researchers have developed frameworks and systems based on BIM to improve project performance from different perspectives. One of the most significant integrations proposed is between lean construction and BIM (Mahalingam et al., 2015; Sacks et al., 2010, 2013; Zhang et al., 2018). Teizer et al. (2020) have combined BIM, lean construction, and Internet of Things (IoT) to increase construction digitalization and manageability. In addition, Jang and Lee (2018) proved that a successful application of BIM-based MEP could help manage coordination activities. Moreover, Hu et al. (2019) developed a framework based on network analysis to enhance clash detection in BIM projects. BIM has also shown the advantage of benefiting multi-disciplinary, multi-actor, and lifecycle information management and cost overrun reduction (Chen et al., 2018a; Su, 2017). Furthermore, the dynamic AR support could be incorporated with BIM to train and manage practitioners by achieving a higher interaction level and immersion with spatial (Hou et al., 2015). The BIM-AR-based collaboration system could also improve risk identification (Wang & Piao, 2019), enhance structural quality (Mirshokraei et al., 2019), and advance construction project performance (Ratajczak et al., 2019).

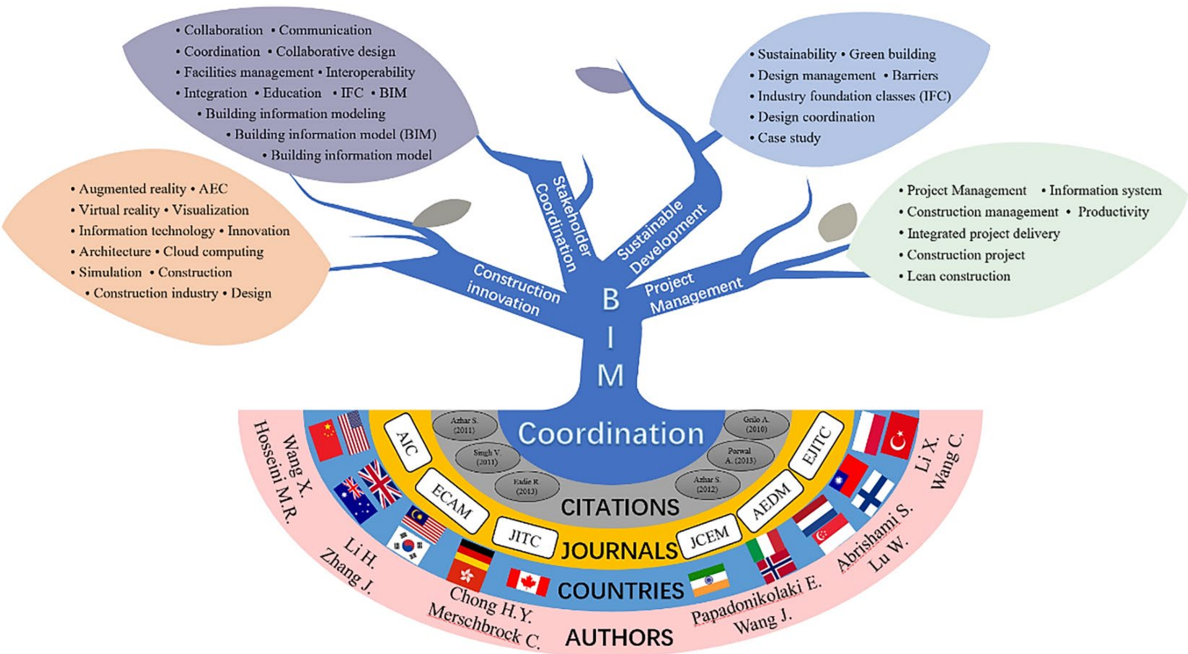

Figure 9. Knowledge domain map in BIM-based coordination research

Topic 2: Stakeholder coordination

Owing to the large number of parties involved in the construction project and their different professional knowledge levels, stakeholder coordination has always been an unneglected challenge faced by construction industries. Raouf and Al-Ghamdi (2019) found that various stakeholders often have asymmetric information during the construction of the project, which may delay the construction period, affect the quality of the project, and result in conflicts. Since the satisfaction of stakeholders significantly influences the project's success, the advanced coordination function of BIM has received remarkable attention in the research field and practice (Mostad et al., 2004; Succar, 2009). BIM ensures the information flow and exchange throughout the project in time, enabling the stakeholders to communicate and understand the project status (Mostad et al., 2004). BIM has also been highlighted to facilitate stakeholder management through virtual reality (VR) or visualization function (Goulding et al., 2014; Hilfert & König, 2016; Zaker & Coloma, 2018). Besides, some researchers attempted to create BIM-based management systems starting with meeting the requirements of stakeholders and enhancing their participation. For example, Akinade et al. (2018) assessed the expectations of stakeholders on the BIM application in construction demolition waste management and further proposed BIM-based coordination strategies for waste management. Jang et al. (2019) proposed a two-phase BIM-based subcontracting system to increase the involvement of the stakeholders.

Topic 3: Sustainable development

The traditional construction industry mainly focuses on project performance in time, cost, and quality. But nowadays, under the increasing advocacy and demand for sustainability, the construction industry is gradually developing towards green and sustainability (Rosayuru et al., 2022). Hence, the performance of BIM in sustainable development has been an attention focus in recent years. Some researchers focus on the BIM-based sustainability assessment. For example, Carvalho et al. (2019) analyzed how the usage of BIM could contribute to optimizing building sustainability assessment methods. Kensek et al. (2016) proposed the BIM-assisted framework to investigate whether the building design meets the green building standards. Moreover, some researchers assess the ability of BIM in practice. Ma et al. (2018) proposed a dedicated collaboration platform for IPD to achieve more efficient collaboration and reduce waste. Similarly, Cheng and Ma (2013) created a system that could extract data from BIM to estimate construction waste. Besides, Chen and Thanh Chuong (2019) presented a decision support tool that integrated BIM and web map service for sustainable construction materials selection, which is of great significance in construction supply chain management. Kaewunruen et al. (2020) even proposed the potential application of 6D BIM-based lifecycle systems for large infrastructure projects to achieve sustainability. Furthermore, Habibi (2017) indicated that BIM-based models could meet industry standards for sustainable buildings to reduce greenhouse gas emissions and global energy consumption.

Topic 4: Construction innovation

As an intelligent digital model, BIM could be the bridge and tool for digital and innovation transformation in the construction field (Lindblad & Guerrero, 2020). Integrated with cloud computing and IoT, BIM can achieve real-time energy monitoring (Wu et al., 2015), simultaneous resource management (Edmondson et al., 2018), and supply chain management (Dave et al., 2016). BIM could also assist in designing the emergency rescue plan based on its restored real-time information (Chen et al., 2018b). Wang et al. (2015) proposed a BIM-based fire safety improvement structure. For other innovative adoptions, Sakin and Kiroglu (2017) raised a proposal for combining BIM and 3D printing technology to create cost reduction and energy efficiency buildings. 4D simulation and information coordination functions of BIM have also been examined in novel modular construction projects that require simultaneous management of both the manufacturing plant and the construction site (Lee & Kim, 2017). Correspondingly, Muller et al. (2017) presented an interoperability assessment of a BIM system, taking cast-in-place into primary consideration. Through literature review, Deng et al. (2021) analyzed the development trajectory from BIM to the digital twin that synchronizes the virtual system with the physical world to enable better control and management throughout the project life cycle. Moreover, Chen and Tang (2019) proposed an innovative management workflow design. Their design integrated digital programming with BIM to achieve cost planning and efficient scheduling for building fabric maintenance.

3.2. Research trends of the BIM-based coordination

Through an in-depth discussion of the core research domains, a framework of BIM-based coordination research is constructed in Figure 10, indicating the current research gaps and future research trends.

Future research trends of BIM-based coordination in project management

The extensive amount of data generated by construction projects require the multi-disciplinary application of BIM to improve project management efficiency. The emerging digital technologies have indicated their advances in properly solving supply, maintenance, safety, waste, and other issues. However, some technical problems remain to be addressed. Thus, the further development of digital technology (such as big data (Zheng et al., 2019), machine learning (Braun & Borrmann, 2019), blockchain (Martínez et al., 2022), and digital twin (Wang et al., 2020)) and BIM integration strategies are of great potential in project management. The creation of dynamic real-time project management systems is one of the most important trends.

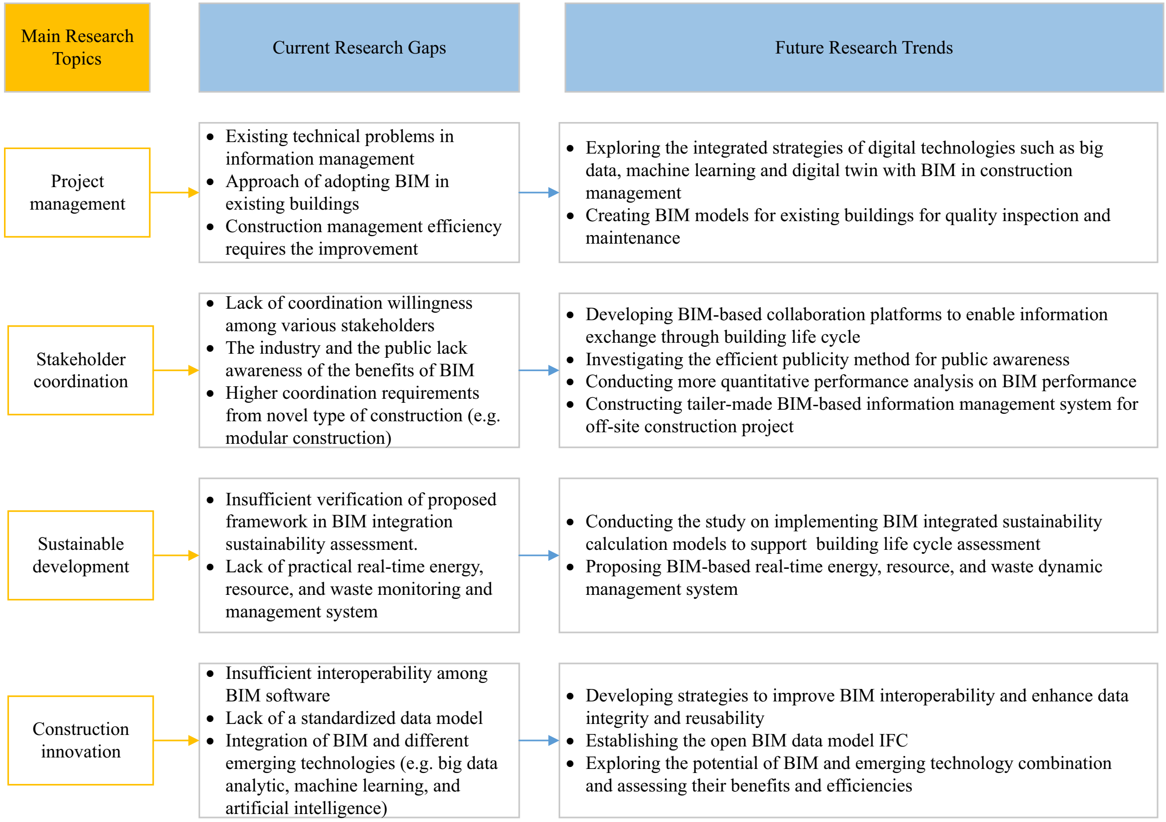

Figure 10. The framework proposes trends in BIM-based coordination research

In addition, the strategies of BIM employment for existing buildings remain to be studied (Lee & Kim, 2017). Adopting BIM under existing building conditions can improve building quality monitoring, maintenance management, and safety control. It also greatly contributes to building renovation and conforms to the needs of urbanization development.

Future research trends of BIM-based coordination in stakeholder coordination

As an information exchange platform, BIM is essential to better complete collaborative work between stakeholders (Zheng et al., 2017). It allows each participant to put forward their own opinions, reduce and eliminate possible errors, and improve efficiency (Li et al., 2018). However, in practice, the stakeholders still showed insufficient motivation to integrate BIM into their workflow. There are several reasons for this phenomenon that require further effort in exploration and improvement. This phenomenon has driven the comprehensive examination of the quantitative benefits and obstacles of BIM. First is that the industry and public lack awareness of the long-term benefits of BIM adoption. Therefore, future research may try to investigate the efficient publicity method, like the network media (Xie et al., 2020), to enhance public understanding and acceptance. More quantitative performance analysis on BIM-based project performance should also be conducted to indicate the advantages and attract the stakeholders to involve. Another reason is that the mature and standardized BIM-based collaboration platform that enables information exchange through the building life cycle is still lacking (Oraee et al., 2019). Immature platforms make stakeholders worry about the rate of return on investment, thereby reducing their use willingness. Hence, proposing and developing practical BIM-based collaboration platforms is of potential in the future. Moreover, the adoption of BIM needs specific professionals. Thus, the supporting policies of promotion and technical training strategies are in demand. Furthermore, with the construction transformation towards off-site construction, higher requirements are raised for BIM coordination (Zhang et al., 2017b). Under this circumstance, constructing tailor-made BIM-based information management systems for off-site construction projects should be concerned.

Future research trends of BIM-based coordination in sustainable development

Although some existing studies have already proposed BIM integration sustainability assessment frameworks (Carvalho et al., 2019; Kensek et al., 2016), it lacks sufficient verification for practice. Thus, future research could pay attention to further validating and improving the BIM integrated sustainability calculation models to support building life cycle assessments. Moreover, with the assistance of emerging digital technologies, some real-time management systems that can achieve dynamic energy, resource, and waste monitoring and planning are of vital needs and significant potential.

Future research trends of BIM-based coordination in construction innovation

In the era of big data, the interactivity of information is essential. It has been proved that interoperability can improve the collaboration between the different functions of buildings during their construction (Karan & Irizarry, 2015). Also, the open BIM environment could benefit the construction and building management and urban governance in the large picture. Some researchers have started to improve the interoperability of BIM information. For example, Zhang et al. (2017a) designed a private-cloud-supported information-sharing approach based on the demand of cross-party to handle data privacy and ownership issues, thereby enhancing interoperability. However, the existing models still perform poorly in interoperability, data integrity, and reusability, making it difficult to establish an open BIM environment for effective data transfer. IFC is an outstanding novel concept that has been recognized as the future of BIM to handle the challenge of interoperability and various automation tasks. Thus, future research may effort more in solving the interoperability, data integrity, and reusability problems and establishing the open BIM data model IFC. Furthermore, since information technology is constantly evolving (Adamides & Karacapilidis, 2020), exploring the possibility and performance of the combined utilization of BIM and more digital technologies would be the direction of construction innovation.

Conclusions

Coordination is a central function of BIM that has recently been regarded as a research hotspot. This study has undertaken bibliometric literature searching, scientific mapping, and in-depth analysis to explore the knowledge from the publications in the field of BIM-based coordination between 2006 and 2020 to provide an overall picture of research development status. The study found that the most concentrated topic changed from communication function, information technology exploration, construction project performance, interoperability potential, and sustainability to barriers investigation from 2013 to 2019. The cross-category cooperation among scholars in this field has already existed, which has blossomed the research field. Moreover, four main topics in this research field were identified as project management, stakeholder coordination, sustainable development, and construction innovation. Based on the research results, the current research gaps and future research trends were discussed. Specifically, the integration with emerging digital technologies and information networks, the exploration of adoption in construction transformation, the development of collaboration and real-time monitoring systems, and the establishment of the open BIM data model IFC were highly recommended in future research.

This research makes contributions in both theoretical and practical ways. Firstly, the study determines and analyses the publication patterns, research principles, changing hotspots, and development trends in BIM-based coordination, contributing to the body of knowledge. Secondly, the methodological approach of this study provides a reference for future research in other fields. Thirdly, the study presents a clear picture of the BIM-based coordination field by discussing the emerging technology evolution tendency, main research themes, existing research gaps, and future research directions, offering recommendations for future research and guidance for related stakeholders in practice. Still, there remain some limitations to this research. For example, this study only collected publications in the English language, which might miss some valuable works in other languages. Thus, future research could be conducted through similar methods to explore the BIM-based coordination research development status in a certain country/region.

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Author contributions

Zezhou Wu, Kaiwen Deng, and Changhong Chen were responsible for conceptualization, software, data curation, and original draft preparation. Kaiwen Deng, Heng Li, and Maxwell Fordjour Antwi-Afari were responsible for manuscript revision. Zezhou Wu and Ying Wang were responsible for supervision. Ying Wang was also responsible for manuscript revision and edit.

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