

Review

Evaluation of Complexity Issues in Building Information Modeling Diffusion Research

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Abstract: This study aimed to ascertain the research status of complexity issues in building information modeling (BIM) diffusion and identify future research directions in this field. A total of 366 relevant journal articles were holistically evaluated. The visualization analysis indicated that management aspects, emergent trends (such as green building, facility management, and automation), and theme clusters (such as interoperability, waste management, laser scanning, stakeholder management, and energy efficiency) are shaping BIM research towards complexity. Areas such as supply chain, cost, digital twin, and web are also essential. The manual qualitative evaluation classified the complexity issues in BIM diffusion research into three types (complexities of network-based BIM evolution, impact of BIM adoption circumstances, and BIM-based complexity reduction for informed decision making). It was concluded that BIM has been shifting towards information models and systems-based life cycle management, waste control for healthy urban environments, and complex data analysis from a big data perspective, not only in building projects but also in heritage and infrastructure, or at the city scale, for informed decision making and automatic responses. Future research should investigate the co-evolution between collaborative networks and BIM artefacts and work processes, quality improvement of BIM-based complex networks, BIM post-adoption behaviors influenced by complex environmental contexts, and BIM-based complexity reduction approaches.

Keywords: building information modeling; complexity; evaluation; network; waste control; diffusion



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1. Introduction

After building information modeling (BIM) was commercially promoted by Autodesk to generate and manage physical and functional information of facilities at the beginning of the 2000s, it has drawn much attention from both academics and practitioners. With the use of BIM, information can be stored, visualized, integrated, interacted with, shared, and exchanged effectively. This was verified in numerous studies and real-life construction projects. Nonetheless, the implementation situation of BIM is becoming increasingly complex.

In this study, BIM complexity refers to complexity issues in BIM diffusion, which include, but are not limited to, technical, project, cultural, organizational, and political complexities in BIM development and implementation. Firstly, BIM itself is technically complex. Successful BIM implementation in a construction project requires related primary participants to obviously change their traditional work processes, thereby placing high requirements on their technical capabilities [1]. Secondly, construction projects, especially megaprojects, are becoming increasingly complex, which would pose difficulties in project management. Moreover, since a variety of project delivery models such as integrated project delivery (IPD), IPD-ish, and IPD-lite have been adopted, new project roles constantly emerge, and relationships among primary stakeholders become complex [2]. In addition, at

the macro level, actual circumstances of BIM promotion policies, standards, and guidelines vary from one country or city to another. Some countries such as the United Kingdom and Singapore promote BIM using a top-down approach, whereas others tend to adopt a bottom-up approach [3,4]. An increasing number of governments encourage, specify, or mandate BIM adoption, especially in publicly funded building and construction projects [5], while others opt to adopt a wait-and-see attitude [3] or even see BIM adoption as an extra effort [6]. Organizational readiness and practices and project characteristics may also be totally different in different projects [4]. Furthermore, project management practices in the context of COVID-19 vary in different countries.

To handle the increasing complexity of project management, BIM tools have been rapidly developed. However, it was observed that the development and adoption of BIM may be fragmented within a complex project environment [7]. Due to the multidimensional complexity during project execution, construction projects often experience delays and miss project targets, posing pressure to BIM-based complexity analysis and reduction. Although a few construction project management studies have been conducted using complexity-related theories, such as complex systems theory [8,9], the overall status quo and trends of the research on the complexity issues in BIM diffusion remain unknown.

Literature evaluation has been deemed as an effective approach to understand a research field clearly and deeply. Through a structured evaluation of previous studies, state-of-the-art research themes and emergent trends can be identified, which helps the development of future research directions in the field. Given the importance of critical evaluation, a few recent studies have attempted to review and summarize BIM-based research, such as analyzing BIM for infrastructure research from a constructor's perspective [10], mapping overall BIM knowledge domains [7,11] and managerial areas of BIM [2], evaluating collaboration research in BIM-based construction networks [12], exploring practices and responsibilities of BIM coordinators [13], investigating various BIM applications [14] and those in facility operations and maintenance [15], and examining BIM adoption and its influencing factors in small and medium-sized enterprises [16]. However, no such work has yet been carried out in detail with regard to the BIM complexity field.

Thus, this study aimed to provide an objective and accurate evaluation of the complexity issues in BIM diffusion research articles published in peer-reviewed academic journals. The specific objectives of this study were to: (1) recognize the contributions made by various journals, institutions, and individuals to the BIM complexity research; (2) obtain a comprehensive status of the BIM complexity field through a keyword co-occurrence network and identify emergent trends in this field using keyword burst detection; (3) investigate research theme divisions through abstract term cluster analysis with a timeline view of each critical term; and (4) identify research directions for future studies on BIM complexity issues. An in-depth examination of the selected articles through a structured evaluation can help both academics and practitioners understand the current body of knowledge and inspire them to analyze and address the BIM complexity issues in the future.

2. Research Methodology

To achieve the research objectives, academic journal papers pertaining to the complexity issues in BIM diffusion were identified and analyzed. The entire research process included three stages. Firstly, two academic databases, namely, the Web of Science (WoS) and Scopus, were used to obtain the list of BIM complexity publications. Both databases are among the largest online academic sources that are commonly used by BIM researchers to conduct literature reviews in the construction project management field [2,7,17]. Thus, integration of the literature searched from the two databases was considered relatively comprehensive and sufficient to justify broad conclusions regarding the overall development of BIM complexity [2]. The searching rule was ("building information model*" AND ("complex*" OR "complicat*")). The wildcard character * was used to capture relevant variations of the word "model" (including model, modeling, and modelling), the word "complex" (including complex and complexity), and the word "complicat" (including complicated,

complicating, and complication). Articles including these words in the Title, Abstract, and Keywords fields were selected. Only peer-reviewed English journal articles were selected for evaluation. Book reviews, editorials, and conference papers were excluded. The core collections of the search included the Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, and Emerging Sources Citation Index. The search was conducted on 25 May 2021, and a total of 687 articles were obtained. After preliminary screening, 366 articles that were more related to the topic were further analyzed. Secondly, these 366 articles were analyzed in terms of journals, institutions, individuals, and citations, followed by a visualization analysis of keywords, abstract terms, and the timeline view. Lastly, intensive qualitative evaluation was performed on these articles to discover new insights. Discussions were conducted, and future research areas were recommended.

3. Results and Data Analysis

3.1. Contribution Analysis

3.1.1. Contributions of Journals

Identifying influential journals and analyzing their influence can help readers obtain the best available information and select the journals that may be suitable for publishing their work. To recognize the journals that were closely relevant to the complexity issues in BIM diffusion research, the journals were ranked according to the number of BIM complexity research papers they published. As shown in Table 1, ten journals that had published the largest numbers of the selected articles were identified. Among them, *Automation in Construction* was ranked first, contributing a total of 46 related articles. This was followed by *Engineering, Construction and Architectural Management*, which contained 15 papers.

Table 1. Top ten journals ranked by the number of selected articles and their citation status.

Journal	Selected Articles		Citations		
	Number	Rank	Total	Per Article	Rank
Automation in Construction	46	1	1694	36.83	1
Engineering, Construction and Architectural Management	15	2	236	15.73	6
Sustainability	13	3	32	2.46	9
Journal of Computing in Civil Engineering	12	4	280	23.33	5
Journal of Construction Engineering and Management	12	4	333	27.75	3
Advances in Civil Engineering	11	6	36	3.27	8
Advanced Engineering Informatics	10	7	263	26.30	4
Applied Sciences-Basel	8	8	41	5.13	7
International Journal of Construction Management	8	8	10	1.25	10
Journal of Management in Engineering	8	8	234	29.25	2

Meanwhile, citations have increasingly been used to evaluate journals [17]. Table 1 also presents the citation status of the ten journals according to the selected BIM complexity articles they published. Among the journals, *Automation in Construction* was ranked first in terms of the number of citations per paper (36.83), and *Journal of Management in Engineering* (29.25) and *Journal of Construction Engineering and Management* (27.75) occupied the second and third positions, respectively.

3.1.2. Contributions of Institutions

Presenting contributing research institutions may facilitate potential academic collaboration and exchanges among researchers, which promote the advancement of professional knowledge. Table 2 shows the ten institutions that had published the most articles on BIM complexity issues. Among them, researchers from Tongji University, Hong Kong Polytechnic University, and the Georgia Institute of Technology have contributed the most to this research field. They have contributed 12, 12, and 9 related articles, respectively. The

ten institutions are well distributed in six countries, indicating that the research related to BIM complexity issues has attracted worldwide attention.

Table 2. Top ten research institutions ranked by the number of selected papers.

Rank	Institution	Country	Number of Selected Papers	Number of Researchers
1	Tongji University	China	12	15
1	Hong Kong Polytechnic University	China	12	19
3	Georgia Institute of Technology	United States	9	12
4	University of Melbourne	Australia	7	10
5	University College London	United Kingdom	6	7
5	Curtin University	Australia	6	8
5	Deakin University	Australia	6	8
5	University of London	United Kingdom	6	9
5	University of British Columbia	Canada	6	10
5	Yonsei University	South Korea	6	11

3.1.3. Frequently Cited Journal Articles

Cited frequency per year is a key indicator for evaluating the quality of an article circulated in the construction project management field [18]. Usually, the more frequent an article is cited, the more valuable it is and the more necessary it is to be studied. Table 3 presents the 10 most frequently cited articles among the 366 selected articles. Among them, half were published in *Automation in Construction*, suggesting that the journal has not only contributed the most articles related to BIM complexity issues (see Table 1) but also contains the most influential articles. Specifically, the paper of Singh et al. [19] received the most (260) citations and was cited most frequently (26.00/year) by the time of this study. This was followed by the papers of Kassem et al. [20] and Sebastian [21], which had been annually cited 15.83 and 15.80 times, respectively.

Table 3. Top ten journal articles ranked by cited frequency per year.

Rank	Author(s)/Year	Journal	Article	Volume (Issue)	Cited Frequency	Cited Frequency per Year
1	Singh et al. [19]	<i>Automation in Construction</i>	A theoretical framework of a BIM-based multi-disciplinary collaboration platform	20(2)	260	26.00
2	Kassem et al. [20]	<i>Built Environment Project and Asset Management</i>	BIM in facilities management applications: a case study of a large university complex	5(3)	95	15.83
3	Sebastian [21]	<i>Engineering, Construction and Architectural Management</i>	Changing roles of the clients, architects and contractors through BIM	18(2)	158	15.80
4	Lee et al. [22]	<i>Automation in Construction</i>	Specifying parametric building object behavior (BOB) for a building information modeling system	15(6)	232	15.47

Table 3. Cont.

Rank	Author(s)/Year	Journal	Article	Volume (Issue)	Cited Frequency	Cited Frequency per Year
5	Jung et al. [23]	<i>Automation in Construction</i>	Productive modeling for development of as-built BIM of existing indoor structures	42	108	15.43
6	Murphy et al. [24]	<i>Structural Survey</i>	Historic building information modelling (HBIM)	27(4)	179	14.92
7	Kim et al. [25]	<i>Automation in Construction</i>	Developing a physical BIM library for building thermal energy simulation	50	84	14.00
7	Steel et al. [26]	<i>Software and Systems Modeling</i>	Model interoperability in building information modelling	11(1)	126	14.00
9	Motamedi et al. [27]	<i>Automation in Construction</i>	Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management	43	93	13.29
10	Isikdag et al. [28]	<i>Computers, Environment and Urban Systems</i>	A BIM-oriented model for supporting indoor navigation requirements	41	106	13.25

3.2. Keyword Co-Occurrence Network

Based on the above analysis, an overall increasing trend of complexity study has been witnessed in the BIM research. Thus, it was necessary to identify relevant topics. In general, a paper's authors typically use several keywords to clearly and concisely summarize their article's contents. Thus, analyzing the keywords is helpful to identify the topic of the paper. The keywords provided in the paper must have some type of correlation, which can be expressed in terms of the frequency of co-occurrence. By counting the frequency of co-occurrence of the keywords in the same article, a network composed of the associations of these word pairs can be formed, which is called a keyword co-occurrence network. Thus, once the keywords of all the literature related to the complexity issues in BIM diffusion are combined and analyzed, the topic coverage and emerging trends in this field can be better analyzed through indicators such as frequency and change over time. To visually and objectively map the topics of all the 366 selected papers, a keyword co-occurrence network of the reviewed papers should be created [29]. CiteSpace (short for "citation space"), an effective visual analysis software for conducting visualization analysis of emerging trends in a knowledge domain [30], was used in this study.

Among the 366 articles, some were obtained from the WoS database, which could be analyzed directly in CiteSpace. The others were retrieved from Scopus, which, after being exported, were converted to the WOS format for analysis. The common keywords such as "BIM", "building information modeling", "building information model", and "building information modelling" were removed after data collection and processing to make the classification clearer. After importing the required data files, some options needed to be predetermined, such as Time Slicing, Node Types, Selection Criteria, and Pruning. Specifically, Time Slicing was set to be "from 2004 to 2021" as the first relevant paper was published in 2004. To make the result more detailed, "# Year Per Slice" was set as "1". Node Types were set to be "keyword". During each time slice, the top 50 most cited or most frequently occurring keywords were selected for analysis. Moreover, "Pathfinder" and "Pruning sliced networks" were selected in Pruning for generating a clearer network.

Subsequently, the keyword co-occurrence network was generated, as shown in Figure 1. This network diagram was composed of 174 nodes and 495 edges. The nodes represented the keywords, and the edges depicted the connections between the keywords.

If two keywords appear in the same article, there would be a link between them. In this figure, the size of each node represents the frequency at which the corresponding keyword occurred, and the color of the links is intended to show the specific year a connection between two keywords was first established. The transition from cold to warm colors represents the time span from the past to the present.

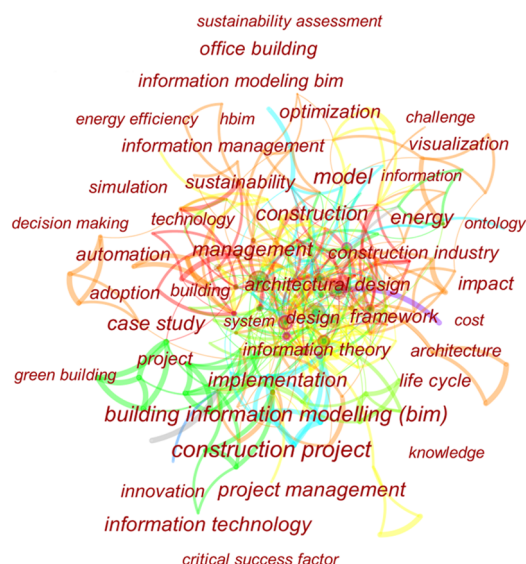


Figure 1. Keyword co-occurrence network: 2004–2021.

Figure 1 shows that, among all the keywords, “architectural design” and “management” had the highest frequency. BIM is essential in architectural design, but it is more than just modeling. BIM can be used to manage the whole life cycle of a building and construction project. Therefore, BIM has been increasingly used in the field of construction project management. However, this result is different from the observations by He et al. [2], who reviewed managerial areas of BIM research and argued that BIM was still treated as a technical issue, even in studies allocated to managerial aspects of BIM, and by Oraee et al. [12], who reviewed research on BIM-based collaborative construction networks and reported that, compared to other BIM-related research areas, BIM-based collaboration was not addressed from the standpoint of project management. Meanwhile, the distance between two nodes is an indicator of their relationship, where smaller distances indicate that stronger relationships exist among the relevant keywords. As illustrated in Figure 1, keywords such as “decision making”, “simulation”, “technology”, “automation”, and “sustainability” were closely related to “management”. The complexity of BIM development and implementation is also reflected by the use of simulation and automation technologies for informed decision making, which is critical to improving construction project management.

3.3. Keyword Burst Detection

Through the keyword co-occurrence network diagram, some general understanding of the BIM complexity field can be obtained, but the change in the frequency of the keywords over time is still unclear. Keyword burst detection can figure out the keywords with a surge in the occurrence frequency and thus determine emerging trends in different time slices in the research field. Figure 2 shows the keyword burst detection result from 2004 to 2021, suggesting 18 keywords with the strongest citation bursts, which were sorted by the beginning year of the burst.

Top 18 Keywords with the Strongest Citation Bursts

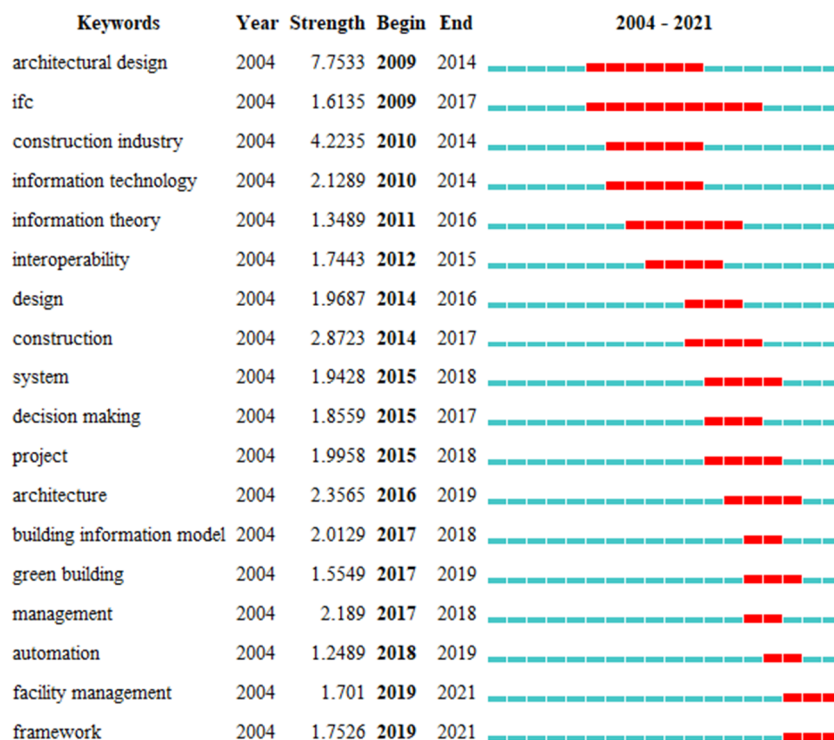


Figure 2. Keyword burst detection: 2004–2021.

Specifically, the frequency of “architectural design” drastically increased from 2009. This result echoes that of Won et al. [31], who found that during the first BIM wave, the primary function of BIM was to assist in the design and modeling of building projects. Architectural modeling needs to be coordinated with other design disciplines. This was why the keyword “industry foundation classes” (IFC), representing an open international standard for building information model data that are exchanged and shared among software applications, also burst at the same time. Following this, since 2010, the keywords “information technology” and “interoperability” have attracted the interests of BIM scholars. This indicates that the scholarship started to concentrate on how to integrate work processes and software for information management in the project life cycle. Subsequently, the frequencies of the keywords “system” and “decision making” suddenly increased from 2015, while “management” burst in the following years, which is in line with the result presented in Figure 1. It could be concluded that with the development and updating of technology, BIM deployment became increasingly complex and specialized. It was not just a modeling tool and a technological process, but also a platform that can manage the entire life cycle of the projects through information exchange and cooperation among various stakeholders. Various tools or systems may be developed to facilitate decision making in different scenarios.

Eventually, as BIM was increasingly used to meet more complex requirements or cater to a wider range of applications, the keywords “green building”, “automation”, “facility management”, and “framework” continued to proliferate from 2017 to 2021. This result indicates that these keywords represent the current emerging trends in the BIM complexity field and are at the forefront of the construction industry. More studies are anticipated to be conducted on these topics in the future. In particular, the continuous surge in “automation” implies that practitioners and researchers are developing BIM-based applications. Such tools are becoming increasingly automatic, saving time and efforts. The burst of “green building” and “facility management” indicates that as the implementation situation of BIM becomes complex, the operations and maintenance aspects tend to be more popular. A possible explanation is that this is not only the next logical step while exploring

n-dimensional BIM. It may also be the notion of developers seeking to lock in additional value of using BIM in the market where the previously developed models with an immature technological solution are not as clear as they would like. In the meantime, the frequent occurrence of “framework” also reflects the complexity of BIM implementation. BIM is a complex system that involves many participants, benefits, costs, and applications. Building proper frameworks to guide the effective operation of this system is necessary. This is in line with the finding of Li et al. [7], who reviewed BIM knowledge domains and found that a multi-standpoint framework (such as stakeholders and decision-making processes) is essential in managing various aspects of BIM development and implementation during the life cycle.

3.4. Abstract Term Cluster Analysis

The keyword co-occurrence network and keyword burst detection alone cannot clearly clarify the main areas and structure of the research on the complexity issues in BIM diffusion. Therefore, cluster analysis needed to be conducted in this study, which can identify prominent theme groupings by gathering similar keywords [32].

As a tool for progressive knowledge domain visualization, CiteSpace can decompose a network into clusters and automatically label clusters with terms from the titles, keywords, or abstracts [30]. In this process, three statistical methods including the log likelihood ratio (LLR) test (comparing the likelihood of finding a term in one cluster against that of finding this term in another cluster), term frequency–inverse document frequency (reflecting how relevant a word is to a text), and mutual information tests (measuring mutual dependence between two random variables) can be used [33]. In this study, the LLR test was used, because it is useful to identify the uniqueness of the term to a cluster. Figure 3 shows the cluster analysis result, which demonstrates the labeled clusters. Each cluster was composed of a certain number of closely related keywords. The largest cluster was numbered as #0 and the smallest cluster as #8. The smaller the number, the more terms were contained in the cluster and the larger the cluster’s size. The nine clusters were labeled as interoperability, project delivery, waste management, process map, construction management, Autodesk Revit, laser scanning, stakeholder theory, and building energy efficiency. Each of them could be regarded as a research theme. These themes were relatively independent of each other and partially overlapped. The cluster analysis involved two important indicators in CiteSpace, namely, modularity Q (measuring the strength of division of a network into clusters) and mean silhouette (measuring how similar an object is to its own cluster compared to other clusters). A value of modularity Q over 0.3 indicates that the cluster structure is significant, and a value of mean silhouette greater than 0.5 implies that the structure is reasonable. In this network, the values of modularity Q and mean silhouette were 0.4965 and 0.6474, respectively, suggesting a robust and reasonable cluster structure.

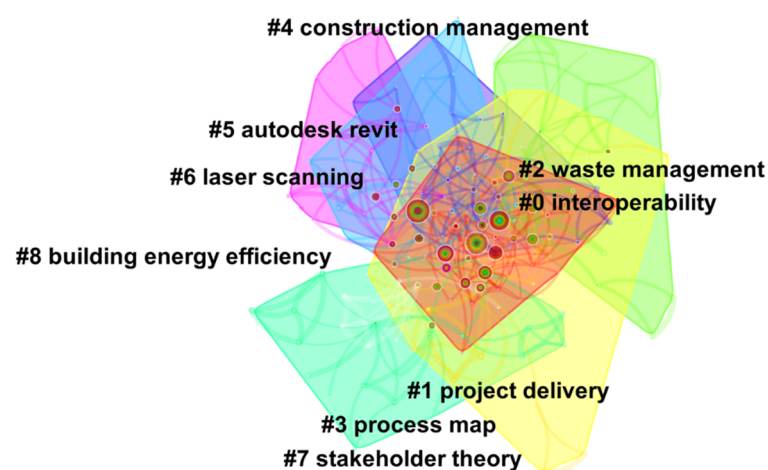


Figure 3. Abstract term cluster analysis: 2004–2021.

For each cluster, three abstract terms with the highest frequencies were selected to represent the cluster. Table 4 shows the nine clusters and their sizes and representative terms. Unlike most previous studies that obtained clusters based on the authors' subjective understanding of a specific field, the abstract term cluster analysis adopted in this study provides a more objective way to investigate the overall cluster structure of the BIM complexity research field.

Table 4. Research clusters and respective top three terms.

ID	Cluster Name	Size	Silhouette	Top Three Terms
#0	Interoperability	27	0.582	Interoperability, construction projects, life cycle
#1	Project delivery	25	0.559	Project delivery, building, evaluation
#2	Waste management	24	0.815	Waste management, construction and demolition waste, spatial query
#3	Process map	22	0.847	Process map, design process, information technologies
#4	Construction management	20	0.828	Construction management, social network analysis, process mining
#5	Autodesk Revit	19	0.774	Autodesk Revit, green building studio, optimization
#6	Laser scanning	18	0.819	Laser scanning, facility, historic building information modeling
#7	Stakeholder theory	7	0.879	Stakeholder theory, social sustainability, green building
#8	Building energy efficiency	4	0.959	Building energy efficiency, BIM operational management, renewable energy integration

The cluster analysis result was analyzed. Specifically, among the BIM complexity literature, the most significant cluster was interoperability, indicating that the complexity in the collaboration among different participants and integration among different tools has elicited much attention. The second and eighth most significant theme groupings were related to project delivery and stakeholder theory. This result implies that BIM-based delivery models, such as virtual design and construction and IPD [4], and the respective stakeholder management have been a focal point in construction project management [7]. This situation, along with a variety of contractual systems and legal frameworks in different countries, would contribute to the complex BIM implementation. Moreover, the term with a high frequency, construction and demolition waste, in the third most critical cluster (waste management) suggests that BIM has been increasingly useful in managing waste generated in both the construction and demolition phases. For example, building demolition waste and the associated life cycle carbon emissions may be measured by accurate information models, and the integration of BIM and geographic information systems has been used to visualize waste disposal and transportation situations in a real-time manner at the city scale [34]. Another remarkable cluster was associated with laser scanning. This result indicates that BIM is often used with 3D laser scanning for restoring original buildings, especially historic buildings, and performing secondary design in the virtual environment [35–37], so that they can be reconstructed. This would add much value in repairing and protecting cultural heritage to ensure cultural inheritance. In addition, it is worth noting that in the research theme of building energy efficiency, the emerging trends are the identification of low-energy behaviors and strategies, with support from BIM-based platforms and big data technology.

3.5. Timeline View of Keyword Co-Occurrence Network

The keyword co-occurrence network mentioned earlier is a static representation of the BIM complexity research field, which does not consider the changes in the way the terms have been used over time. However, CiteSpace can provide a timeline view where each term is arranged in chronological order to show the interaction between the development trends and clusters. As shown in Figure 4, each cluster on the right side corresponds to a line. On this line, the keywords included in the corresponding cluster are spread out according to the years in which they appeared. Once a keyword appeared, it would be fixed in the place where it first appeared. Although the keyword may still appear in subsequent articles, it would no longer be displayed on the map. The lines connecting the keywords

indicate that two keywords appeared in the same article or articles. In fact, the timeline view is essentially a cluster analysis diagram, but the time factor is added to show the development of the keywords in each cluster.

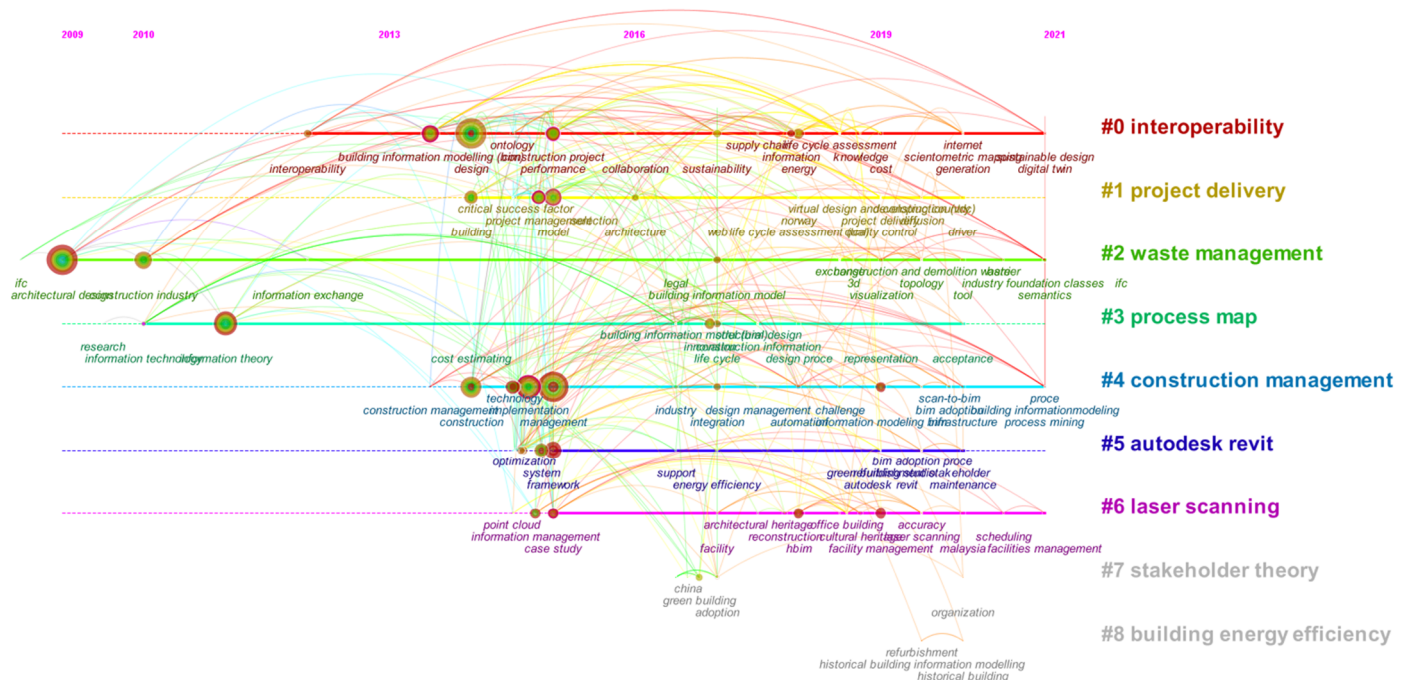


Figure 4. Timeline view of keyword co-occurrence network: 2004–2021.

As shown in Figure 4, earlier keywords tended to focus on the preliminary implementation of BIM, such as “architectural design”, “information exchange”, “ontology”, “critical success factors”, and “cost estimating”. However, in recent years, both academics and practitioners have been increasingly interested in “cost”, “infrastructure”, “digital twin”, “waste”, “web”, “supply chain”, “legal”, “automation”, “energy efficiency”, “facilities management”, “heritage”, “organization”, “refurbishment”, “green building”, etc.

In summary, BIM has become increasingly complex and powerful over time, such as evolving from simply design modeling to model-based project life cycle management including operations (for example, energy saving) and demolition, from building and construction projects to historical buildings and infrastructure, from single project management to waste control at the city scale, from organizational adoption to supply chain collaboration, and from simple data retrieval to complex data analysis from a big data perspective for informed decision making and automatic responses. The implementation situation of BIM also tends to be complex, considering the cost benefit and legal frameworks.

4. Discussion and Implications

4.1. Qualitative Evaluation

After an intensive content evaluation of the 366 selected articles, it was found that the complexity issues in BIM diffusion could be categorized into three aspects, including: (1) complexity of network-based BIM evolution and interactions; (2) complexity of BIM adoption; and (3) complexity reduction for informed decision making. Each aspect is discussed below.

Firstly, the complexity of network-based BIM evolution and interactions, which was generally analyzed by social network analysis (SNA), is discussed. SNA is the process of investigating social structures through the use of networks and graph theory [38]. A complex BIM-related network is often formed among different factors, actions, or stakeholders. Only through the transmission and communication of information in the network can the functions of BIM be realized. The BIM-related issues presented in a network can usually be

solved by the application of SNA, because the complex BIM implementation is, by itself, a social system. This finding resonates with the observations of Zheng et al. [17], who reported that the SNA method has become a hot research field and has been increasingly used to study group interaction behaviors in construction project management research. In the selected articles, SNA was frequently used to solve BIM-related problems for social and managerial insights.

Some of the network-related BIM complexity research articles investigated the complex evolution or dynamics issues of BIM in different contexts. Specifically, as mentioned earlier, BIM implementation has evolved and spread to architectural heritage maintenance projects [39] and utility relocation projects [40], which involve quite different and complex networks of stakeholders. Moreover, the range and contingencies of causal structures shaping the evolution of BIM-based operations were studied. It was found that BIM emerged as a digital infrastructure in a network of design and construction companies [41]. Nonetheless, relevant BIM tools developed for new ways of working in the Finnish heating, ventilating, and air conditioning industry tended to stall. To understand how BIM-based construction networks work and respond to disruptions, Merschbrock et al. [42] compared two highly technologically advanced BIM-enabled hospital projects and pointed out that attentive management should be in place to identify inevitable disruptions to the network equilibrium and actively adjust with corrective measures. Meanwhile, the evolution mechanism of a project-based collaborative network for BIM implementation at the macro level and related underpinning micro mechanisms of the network dynamics were explored. The network was found to become increasingly dense over time by Cao et al. [8] and Li et al. [43], who used stochastic actor-oriented models with longitudinal data on registered BIM-based construction projects in Shanghai and Hong Kong, respectively. However, the network persistently exhibited small-world properties and the core-periphery structure, with a few super-connected star organizations (nodes). To enhance collaboration in BIM-based construction networks, it was advocated that the dynamic nature of organizational discontinuities should be fully considered in virtual teams [44], and that communication, conflict management, negotiation, and teamwork are needed to complement digital skills [45]. In addition, integration of bidding, enterprise quotas, and process management into 4D information models [46] and novel process mining frameworks for automated process discovery from BIM event logs [47] can help capture, monitor, and optimize complicated workflows and collaboration.

Other network-related articles mainly focused on the application of SNA in BIM-based complex networks to analyze interactions among the nodes in different project contexts. For example, Okakpu et al. [48] examined a method of optimizing the interactions of different refurbishment project stakeholders in a BIM-based network for enhanced BIM benefits. The SNA method was used to model the interactions and consequently facilitated the development of a virtual prototype BIM interaction process. This method was also adopted to study BIM-based collaborative management mechanisms for better partnerships in complex interorganizational networks in construction projects [49,50] and airport expansion projects [51]. Moreover, researchers also combined the use of SNA and other simulation methods such as agent-based modeling to analyze stakeholder interaction mechanisms and information flow dynamics in BIM-based design [52]. Complex network theory was also used to analyze the interaction among the main obstacles of BIM application in the construction industry [9].

Secondly, the complexity of BIM adoption is discussed. Although BIM plays an important role in the whole life cycle of construction projects in the global construction industry, its popularity is far from enough. Many projects still do not use BIM or even discard it [6,53]. Additionally, the adoption of BIM itself is relatively complex due to the diversity of actual circumstances in different parts of the world [5]. While the relative advantages of BIM enabled BIM adoption, the complexity of BIM was deemed as a critical inhibitor [54]. The intense manual evaluation suggested that complex BIM adoption circumstances, such as complexities of building characteristics [55] and work processes [56], contractual chal-

allenges [57,58], interoperability trends [59], risk factors [55], political and organizational contexts [60,61], dynamics of drivers [62], and emergencies [63], have drawn the interest of many researchers. For instance, Mayouf et al. [56] elicited implications of shortfalls impacting 5D BIM adoption as well as complexities facing quantity surveyors within BIM processes in the United Kingdom's construction industry. Saka et al. [62] investigated the dynamics of major drivers of sustainable BIM adoption in small and medium-sized enterprises in developing countries and highlighted the importance of organizational readiness [4]. Hetemi et al. [60] revealed the complexities in institutional demands and actual interorganizational processes involved in BIM adoption in sustainability-oriented infrastructure projects.

Meanwhile, the manual evaluation also revealed that researchers tended to apply useful tools such as adoption impact maps [49], analytical frameworks [9,54], or conceptual models [64] to integrate groups of complex driving and inhibiting factors and willingness and evaluate their impacts on BIM adoption, especially in complex unexpected events. Specifically, Wang et al. [63] developed a model to explore the COVID-19 crisis's influence on practitioners' willingness to adopt BIM, which was directly driven by the COVID-19 event criticality and perceived usefulness of BIM. Gurevich et al. [49] proposed a BIM adoption impact map that defined a structured process for analyzing complex relationships between public facility agencies' actions, the actions' intermediate impact on designers, contractors, and project managers, and the eventual value added to the occupants. It was found that public facility agencies governed by the United Kingdom's BIM adoption mandate can use the adoption impact map to achieve better and more effective BIM uses within the complex networks of their service providers. The framework from a technology–organization–environment perspective was especially effective in providing an integrated picture of both internal and external antecedent factors to explain BIM adoption [54]. Moreover, Wang et al. [64] proposed and tested a model of factors predicting stakeholders' resistance behaviors to BIM implementation during the post-adoption stage in construction projects. Perceived ease of use, usefulness, and equity perceptions were found to be essential but relatively independent in determining behavioral resistance, which was shaped by different levels of contextual factors at the individual, team, and project levels. Enegbuma et al. [65] investigated BIM adoption in Malaysia from the perspectives of people, processes, and technology, which effectively captured BIM adoption constructs including embedded cultural influences. Okakpu et al. [48] established an optimization process to motivate effective BIM adoption for complex refurbishment buildings in New Zealand. All the analysis results identified suggestions for controlling and eliminating BIM obstacles from the perspective of the overall factor network [9].

Lastly, the rest of the research articles on the complexity issues in BIM diffusion were mainly related to BIM-based complexity reduction for informed decision making. Construction projects often incur horizontal fragmentation and conflicts among different disciplines, delays, and missed targets because of their multidimensional complexity during project execution, which would pose pressure to complexity analysis and reduction [66–68]. Furthermore, based on a systematic analysis of BIM research, it was observed that the evolution of BIM policies was co-produced with global BIM research, which contributed to a more complex implementation situation of BIM [69]. Specifically, the relation between organizational complexity factors and delays in BIM-based coordination processes was investigated particularly for mechanical, electrical, and plumbing systems from the decision making perspective. The complexity factors included the number of participants involved in a decision-making process, the highest level of the decision makers involved in a problem resolution process, and the heterogeneity of related trades. It was found that the coordination time linearly increased as each factor increased, and the number of participants mattered the most and the heterogeneity of participating trades the least [70]. It was advocated that a central model server may be used to incorporate an end user private collaborative workspace. The complex process of obtaining IFC files from stored persistent models was studied for performance improvement [71]. To reduce the complexity of model

interpretation, the method of evaluating building information models from the perspective of different disciplines was investigated. This approach would allow decision makers to follow the status and performance of the models at each project milestone, from different aspects, in a comparable manner [72].

4.2. Future Research Directions

After discussing the three major aspects of the existing BIM complexity studies, this study identified corresponding future research directions. Firstly, regarding the complex evolution or dynamics of BIM in different contexts, this study suggests that future research can explore how a project's collaborative network involving a wider range of stakeholders may co-evolve with project-wide BIM artefacts, implementation practices, and work processes. In terms of the application of SNA in BIM-based complex networks to analyze interactions, it is recommended that researchers use SNA to analyze the complexity of BIM with respect to more specific cases and explore how to improve the quality of BIM-based complex networks or network models such as through the use of sensitivity analysis at different scales in the future.

Secondly, based on the discussion of the complexity of BIM adoption, it is suggested that future studies investigate BIM post-adoption behaviors and analyze the environmental context's impact on BIM adoption, such as from the perspectives of policies, markets, organizations, emergencies, etc. The behaviors should be studied in a systemic manner, including both acceptance and resistance at the firm, project, and user levels [73]. Considering the interdependent and evolutionary nature of the behaviors, cross-cultural, cross-national, and longitudinal research should also be conducted [64]. Other theoretical perspectives may also be applied to discover new insights into the complex implementation situation of BIM.

Lastly, in terms of BIM-based complexity reduction for informed decision making, much future research should be conducted to explore the methods of reducing BIM-based complexity, such as from the political, organizational, financial, and emergency management perspectives. For example, a possible way is to explore the critical differences and commonalities of BIM adoption behaviors at different levels, followed by the study of developing applicable complexity reduction methods and decision support techniques. The efficiency of each method with different levels of management support should be evaluated, such as from the perspectives of project performance and user satisfaction, and improved on purpose.

5. Conclusions and Recommendations

This study has drawn findings from a body of literature pertaining to the complexity issues in BIM diffusion and published in major peer-reviewed academic journals. A total of 687 articles were obtained from the WoS and Scopus databases for a structured evaluation. After preliminary screening, 366 articles more related to the topic were further analyzed. A statistical analysis was conducted to quantitatively analyze all these BIM complexity studies in terms of journals, institutional and individual contributions, and citations, followed by a visualization analysis of research themes and emergent trends. Firstly, the top ten journals and institutions contributing the most to the research field and the ten most influential articles were identified. Secondly, the keyword co-occurrence analysis result suggested that "management" co-occurred the most frequently, especially with keywords such as "decision making", "simulation", "automation", and "sustainability". The keyword burst detection result was consistent with the evolution of the BIM complexity research and implied that "green building", "facility management", and "automation" represent the current emergent trends in this research field. The abstract term cluster analysis result and timeline view indicated that the BIM complexity research has been focused on issues related to interoperability, project delivery, waste management, process mapping, laser scanning, and energy efficiency, and areas such as "cost", "infrastructure", "digital twin", "web", "legal", "supply chain", and "heritage refurbishment" are drawing increasing

attention from both academics and practitioners. Overall, BIM has been shifting towards life cycle management based on information models and systems, waste control for healthy urban environments, multi-party collaboration, and complex data analysis from a big data perspective, not only in building projects but also in heritage and infrastructure, or at the city scale, for informed decision making and automatic responses.

Moreover, the manual qualitative discussions categorized the complexity issues in BIM diffusion into: (1) complexity of network-based BIM evolution and interactions, where SNA was often used to analyze the dynamic interactions in BIM-based complex networks; (2) complexity of BIM adoption; and (3) BIM-based complexity reduction for informed decision making. Correspondingly, future research directions were recommended in this study: (1) exploring how project-based collaborative networks co-evolve with project-wide BIM artefacts and practical practices, and how to improve the quality of BIM-based complex networks or network models; (2) investigating BIM post-adoption behaviors in different environmental contexts and through the lens of more theories; and (3) exploring more approaches of reducing BIM-based complexity and evaluating their efficiencies in future research, considering political, organizational, financial, and emergent contexts.

The insights drawn from the evaluation of the research on the complexity issues in BIM diffusion and the future research directions proposed contribute to the scholarship, especially when construction project management issues such as project-wide BIM implementation are increasingly studied from the complexity perspective. Further, the methodology adopted in this study can be conducted as needed to provide comprehensive BIM complexity knowledge updates, compared with the commonly used traditional literature review.

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