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Review Article

Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature

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Building information modeling (BIM) is transforming the way of work across the architecture, engineering, and construction (AEC) industry, where BIM offers vast opportunities for improving performance. BIM is therefore an area of great interest across the AEC industry in general and for the structural engineering field in particular. This paper is aimed at providing a broad picture of published papers that relate BIM with structural engineering. This overview will enhance understanding of the state of the research work on this subject, drawing upon bibliometric analysis of 369 papers. Findings provide an updated picture of how now-available studies that link BIM developments and applications in structural engineering are distributed chronologically, across journals, authors, countries, and institutions. Detailed analyses of citation networks present the cooccurrence map of keywords, citation patterns of journals and articles, the most cited journals, and the top 15 most cited articles on BIM in the area of structural engineering. Discussions demonstrate that research on BIM applications for structural engineering has been constantly growing with a sudden increase after 2014. This study reveals that research attempts on this area have been dominated by exploring generic issues of BIM like information management; however, technical issues of structural engineering, to be resolved through BIM capabilities, have remained overlooked. Moreover, the research work in this area is found to be conducted largely in isolation, comprising disjointed and fragmented research studies. Gaps and important areas for future research include modeling of structural components, automation of the assembly sequence, planning and optimization of off-site construction, and dynamic structural health monitoring.

1. Introduction

Building information modeling (BIM) is becoming increasingly popular in the architecture, engineering, and construction (AEC) sector [1–3]; research shows that BIM has the potential to make changes to the way the AEC industry operates [4, 5]. Analyzing the feedback on the benefits associated with the use of BIM on projects is still a matter of investigation [6]. There is however evidence in the literature to acknowledge the advantages of BIM for various areas and disciplines across the AEC supply chain [7, 8]; BIM incorporates software and information processing procedures for designing, documenting, visualizing, and reporting on buildings and other facilities in integration with policies, standards, regulations, etc. [2]. It helps AEC specialists in visualizing a future building in a virtual environment, planning the forthcoming construction processes, and identifying any potential design, construction, or operational issues [1]. Such benefits can add value to the practices of all the disciplines involved, including that of civil engineering, in general, and structural engineering, in particular [9–12].

There have been some in-depth reviews on BIM in general [9, 13–15] and studies that have dealt with specific fields like transportation infrastructure, heritage buildings [16], civil infrastructure maintenance [17], collaborative management [18–20], health and safety [21–23], contractors [10], and academics aspects [24, 25]. Research on the integration of BIM within civil engineering is still in its infancy [9]. Few researchers have focused on civil engineering in particular [26]. Within the civil engineering field, a review run on the BIM literature reveals that some publications like that of Hunt [27] and Bartley [12] have promoted the benefits of BIM for structural engineers. No scholarly work is found with a focus on analyzing the now-available literature on the applications of BIM for structural engineering. Synthesizing the existing literature to raise awareness of the state of affairs of research and spot the gaps to be addressed by future studies is, however, an essential step in advancing the body of knowledge of any field of the study [9, 23]. Various types of review studies can be carried out to address this gap. Despite the undoubted value, an in-depth critical review of the content of existing studies can be prone to subjectivity and is restricted because of their incapability in producing a replicable broad picture of the field [28, 29]. As asserted by Markoulli et al. [30], manual reviews provide a picture of the "trees" but fail in offering a broad overview of the "forest." Since this paper is aimed at providing a broad picture of published academic papers that relate BIM with structural engineering, authors have not applied the content analysis technique for all papers in search results but have analyzed the content of the papers qualitatively.

With the above in mind, this study is targeted at conducting a scientific literature review through a bibliometric analysis of BIM papers related to structural engineering published between 2003 and 2018 (both included). This review, as well as the subsequent analysis, is focused only on scientific journal papers (included in the Scopus database); trade journals and professional magazines are not included here. Detailed analysis of the papers presents the coauthorship networks, the cooccurrence map of keywords, the citation network of journals, the citation network of articles, the list of the most cited journals, and the top 15 most cited articles on BIM in the area of structural engineering. It is deemed that this study contributes to the field in raising awareness of the following:

(1) The knowledge composition of BIM in structural engineering in the analyzed 16-year period
(2) Most recent studies and trends of applying the BIM methodology in structural engineering
(3) Dominant research topics on BIM-related applications in structural engineering
(4) Identifying gaps and defining future areas of research on the topic

The remainder of this paper is structured as follows: Section 2 provides a background on potential advantages and benefits of BIM for structural engineers. Section 3 provides an overview of existing review studies on BIM applications for various disciplines. Section 4 presents the methods used, followed by findings and results in Section 5. The key findings—literature gaps—are discussed and future areas for research are suggested in Section 6 prior to the concluding remarks in Section 7. This paper concludes with communicating the clear message of this study from a broad perspective.

2. BIM for Structural Engineers

Structural engineering comprises a wide range of skills and competencies that apply to all project types. This includes projects that entail minor slope strengthening, as well as large-sized structures of tall buildings [12, 31]. Structural engineers can create complex structural systems and are responsible for finding solutions for the efficient use of structural elements and materials in order to make a building and its systems safe, sustainable, and durable [32]. Usually, structural designs must be integrated with the outputs generated by other disciplines like architects and engineers of different building services [33, 34]. Other roles and responsibilities of structural engineers include supervising construction activities on-site and maintaining communication with manufacturers and suppliers to address production problems [35]. The complexity of the tasks, the required combination of many different competencies, and the abundance of different communication channels necessitate a reliable data exchange platform [19, 36]. That is, maintaining the quality of the final product requires tools that enable structural engineers to check the parameters of the system under development and verify the reliability of the information transmitted [25]. One available solution that provides all such capabilities is BIM [9, 12].

BIM models are 3D geometric encoded, in diverse proprietary formats with the potential to add time (4D) and cost data (5D) attached to them [37]. That is, the core concept of BIM relies on providing object-oriented digital representations of buildings in the form of data-rich models and enabling simulation and analysis of these models for design/construction/operation purposes [38]. Most vendors offer BIM software that incorporates the three required capabilities needed for structural engineering: geometry, material properties, and loading conditions for an analysis. These all can be derived directly from a BIM model, stored, edited, and applied by such BIM software. For example, Autodesk Revit can supplement the physical representation of the objects commonly used by structural engineers, and Tekla Structures allows users to specify the location of connection nodes on its objects and degrees of freedom and also has objects to model structural loads and load cases (see Sacks et al. [38] for details).

Moreover, using BIM in structural engineering can reduce the number of request for information (RFI) items from contractors and makes possible the visualization of design for clients and other stakeholders [39]. BIM can also provide all the stakeholders with the opportunity to explore various readily available alternatives and design scenarios [40, 41].

The digital models produced by structural engineers can be coupled with downstream activities, for manufacturing and assembly of structural elements as well as identifying coordination problems between structural elements and those of other disciplines [1, 34]. BIM can be a part of an effective solution for structural engineers in monitoring the health and life cycle performance of structural elements, seismic retrofitting optimization [42, 43], and risk assessment of structures [44]. Other applications of BIM for structural engineering include increasing its efficiency in modeling complex geological structures, generating shop drawings, and designing temporary elements and formwork [43, 45].

With the above in mind, structural design/analysis must be treated as one of the main areas of application for BIM, a point argued by Hosseini et al. [9]. This further justified the need for conducting this study.

3. Previous Discipline-Based Review Studies

Structural engineering is a subset of civil engineering [46]. Available studies have targeted different issues of civil engineering projects concerning BIM: developments of BIM implementations [13]; communication modes [47]; information management frameworks [10]; refurbishment of historic buildings using BIM [16, 48]; implementation of BIM to existing buildings [49]; sustainable buildings [8, 50]; BIM adoption in different civil infrastructure facilities [26]; roles and responsibilities of BIM practitioners [51]; conceptualization of a BIM-based facilities management framework [52, 53]; visualization technologies in safety management [21, 23]; data classifications [54]; BIM knowledge mappings [14]; BIM research categories [55]; application of laser scan technology [56]; challenges facing the facilities management sector [52, 57, 58]; application of semantic web technologies; issues and recommendations for BIM and life cycle assessment tools [59]; BIM and GIS [60]; green BIM [61]; collaboration in BIM networks [19]; transportation infrastructure; road infrastructure [62]; highway maintenance [17]; role of BIM in generating big data [37], etc. These studies have added much value to the BIM literature and have explored a wide range of fields associated with civil engineering. Civil engineering is however a broad field, with many subsets, as argued by Kosky et al. [46]. A list of major review studies that refer to BIM for civil engineering is tabulated in Table 1. As illustrated in Table 1, no review study has focused on BIM applications for structural engineering purposes. In fact, as argued by Hosseini et al. [9], BIM for structural engineering has remained an overlooked area in the extant literature, compared against other applications of BIM.

4. Research Methods

The research design for reviewing papers on BIM in structural engineering is displayed in Figure 1. The procedure begins with a brief review of published papers on BIM in Scopus, proceeds to a detailed review of the refined dataset of publications, and concludes by analyzing the data.

This research process, as illustrated in Figure 1, comprises the following steps:

(1) *Defining Research Questions*. Research questions are defined in this step. The scope of the research questions depends on the type of the study. Therefore, according to Merschbrock and Munkvold [68] and Arksey and O'Malley [69], this study is a scoping study and designed to examine the available journal articles and to determine the range of spreading and usage of BIM and new trends of BIM developments in structural engineering. The research question is formulated as "What is known from the existing literature about the applications of BIM methodology and tools in structural engineering?"

(2) *Defining the List of Search Sources*. The Scopus (https://www.scopus.com) database was chosen, given that compared against similar databases like Web of Science (WoS), Scopus covers a wider range of sources and is quicker in indexing them, and therefore, it is treated as the preferred database for bibliometric purposes.

(3) *Defining Search Query Based on Keywords.* Searching keywords and their meaningful combinations are defined as the following search query, using keywords: (BIM AND "Building Information Model*" AND struct*).

Other terms, like "digital model" and "3D modelling," can also be used in the search. However, adding such terms increases the number of results but does not make it more specific. The term "BIM" was omitted, given that as recommended by previous bibliometric studies on the BIM literature [9], including BIM can result in adding research items from nonconstruction contexts like chemistry and economics and increase the likelihood of unrelated studies being added to the dataset.

Therefore, they were excluded from the search. Moreover, using the special character* in the query results in finding different variations of the same concept; for example, usage of "model*" allows to extend the search by adding different variations, like "models," "modelling," and "modeling." This is also the case for "struct*"; that is, it finds "structure," "structural," etc.

(4) *Searching*. The searching process is performed according to the query defined in step 3, and the preliminary results are presented in Figure 2.

(5) *Assessing Quality of Results*. Quality of results is assessed here. According to Kitchenham et al. [70], there is no commonly agreed definition of "quality." Therefore, quality issues presented by Zhang et al. [71] were the basis for consideration.

(6) *Bibliometric Analysis of Search Results*. The bibliometric analysis technique is used as the primary analysis method, with the reason being this

Table 1: Summary of major review studies on BIM for civil engineering.

Source	Review period in years	Number of analyzed articles	Source of articles (databases)	Focus	Key findings
Abdirad [13]	2007–2014	97 (selected out of 322)	ASCE, Elsevier, Taylor & Francis, Emerald, and ITcon	BIM implementation assessment	Developments of BIM implementations; metric-based BIM assessment; gaps and limitations
Bradley et al. [10]	2000–2015	259	Scopus, Engineering Village, ScienceDirect, WoS	BIM for infrastructure	4 research gaps in infrastructure and BIM; an information management framework
Bruno et al. [48]	2007–2017	120, 86 of them with international impact, and 1 project	—	Historic BIM	Gaps in historic BIM; methodology for diagnosis of historic buildings using BIM
Cheng et al. [26]	2002–2014	171 case studies and 62 articles	—	BIM for civil infrastructure	Current practices of BIM adoption in different civil infrastructure facilities; research gaps and recommendations; evaluation framework
Davies et al. [51]	2007–2016	36 articles and BIM guides	—	Roles and responsibilities of BIM specialists	Definition of roles and responsibilities of BIM practitioners
Edirisinghe et al. [52]	1996–2016	46 (selected out of 207)	—	BIM in FM	Conceptualization of a BIM-based FM framework; determining the path of future research
Guo et al. [21]	2000–2015	78	WoS and ASCE Library databases	The use of visualization technology	Usage of visualization technologies in safety management
Kylili and Fokaides [63]	2005–2016	Actual European policies and legislation	European policies and legislation	Existing European policies and legislation for the built environment and the construction materials	Future trends in construction
Laakso and Nyman [54]	1997–2007	The first 11 years of research on standard 938	—	Research and BIM standardization	Classification of data
Li et al. [14]	2004–2015		WoS	BIM knowledge map	60 key research areas 10 key research clusters A BIM knowledge map; a review of different issues concerning the usability of
Lopez et al. [64]	—	BIM software websites, articles, brochures, and videos	—	The readiness and development of 4D BIM	4D BIM; matrices for decision-making according to investment in BIM software
Olawumi et al. [55]	—	445	—	BIM research categories	BIM research categories in the project sectors; a visualization of the structure of the BIM literature
Pärn and Edwards [56]	1970–2015	—	—	Laser scanning, 3D modeling devices, modes of delivery, and applications within AECO	Hierarchy of laser scan devices; analysis of 3D terrestrial laser scan technology applications
Pärn et al. [57]	2004–2015	—	—	BIM for asset management within the AECO sector	Challenges facing the FM sector

Table 1: Continued.

Source	Review period in years	Number of analyzed articles	Source of articles (databases)	Focus	Key findings
Santos et al. [65]	2005–2015	381	—	BIM	New emerging areas in BIM research; topics related to the development of BIM tools
Soust-Verdaguer et al. [59]	—	—	—	LCA method for buildings based on BIM	Issues and recommendations for BIM and LCA tools
Zhao [15]	2005–2016	614	WoS	BIM	The most productive and cocited authors, countries, and institutions
Oraee et al. [19]	2006–2016	62	—	Collaboration in BIM-based construction networks	BIM-enabled projects have focused on technology, whilst project-related and managerial antecedents have remained underresearched
Martinez-Aires et al. [22]	1981–2016	76	WoS and Scopus	Occupational health and safety in building construction	BIM to improve safety in construction and identify potential hazards through 4D scheduling
Ganbat et al. [66]	2007–2017	526	WoS	BIM risk management in international construction	A framework of current research field; suggestions for future research directions
Jin et al. [67]		276	Scopus	Identifying research trends in the literature on BIM	A framework leading to needed research directions

Note. —: data not provided.

technique allows for an examination of the existing literature based solely on reported data, in which any potential for author bias is minimized, compared against conventional literature reviews that are prone to bias and subjective judgments [55]. The findings of studies based on bibliometric analysis are hence expected to provide a sound basis for the development of various hypotheses based on the observed trends extracted from published datasets for validation in future studies.

Various researchers, like Li et al. [14], Zhao [15], and Santos et al. [65], have used different science mapping tools, including VOSviewer, BibExcel, CiteSpace, CoPalRed, Sci2, VantagePoint, and Gephi, for analyzing, mapping, and visualization of bibliometric data. A detailed review of visualization tools is not the main aim of this paper, and hence, VOSviewer (http://www.vosviewer.com/) was used as the analysis tool, following the recommendations provided by Hosseini et al. [9]. VOSviewer generates a network from the given bibliographic data, i.e., a set of 369 articles. All networks consist of nodes and links. Nodes present documents (i.e., articles), sources (i.e., journals), authors, organizations, countries, or keywords. Nodes with a higher number of occurrences are bigger. Links present relationships among nodes. Thicker links present closer relationships among nodes. Closely related nodes are combined into clusters using the smart local moving algorithm presented by Waltman and Van Eck [72].

5. Results

5.1. Trend of Research. The results obtained from the bibliometric search demonstrate the trend of research on the topic, as illustrated in Figure 2. The number of publications on BIM for structural engineering has raised significantly from 2014 onwards, with two years of delay compared against the sudden increase in BIM research in 2012, as argued by Santos et al. [65]. This increase from 2012 onwards can be attributed to the 2011 mandate of the Government Construction Strategy of the United Kingdom on the use of Level 2 BIM on all public sector projects by 2016 [73]. There is a growing interest (see Figure 2 for the exponential growth of publications), acknowledging the necessity of further research in this area. This also highlights the importance of covering various areas related to this concept as topics for future research, as similarly argued by Hosseini et al. [9]. In fact, construction is composed of a wide range of loosely coupled disciplines [74–76], and the expansion of BIM across the construction supply chain has been sluggish [58]. Therefore, the number of studies on structural engineering and BIM is quite low; compared with the results obtained by

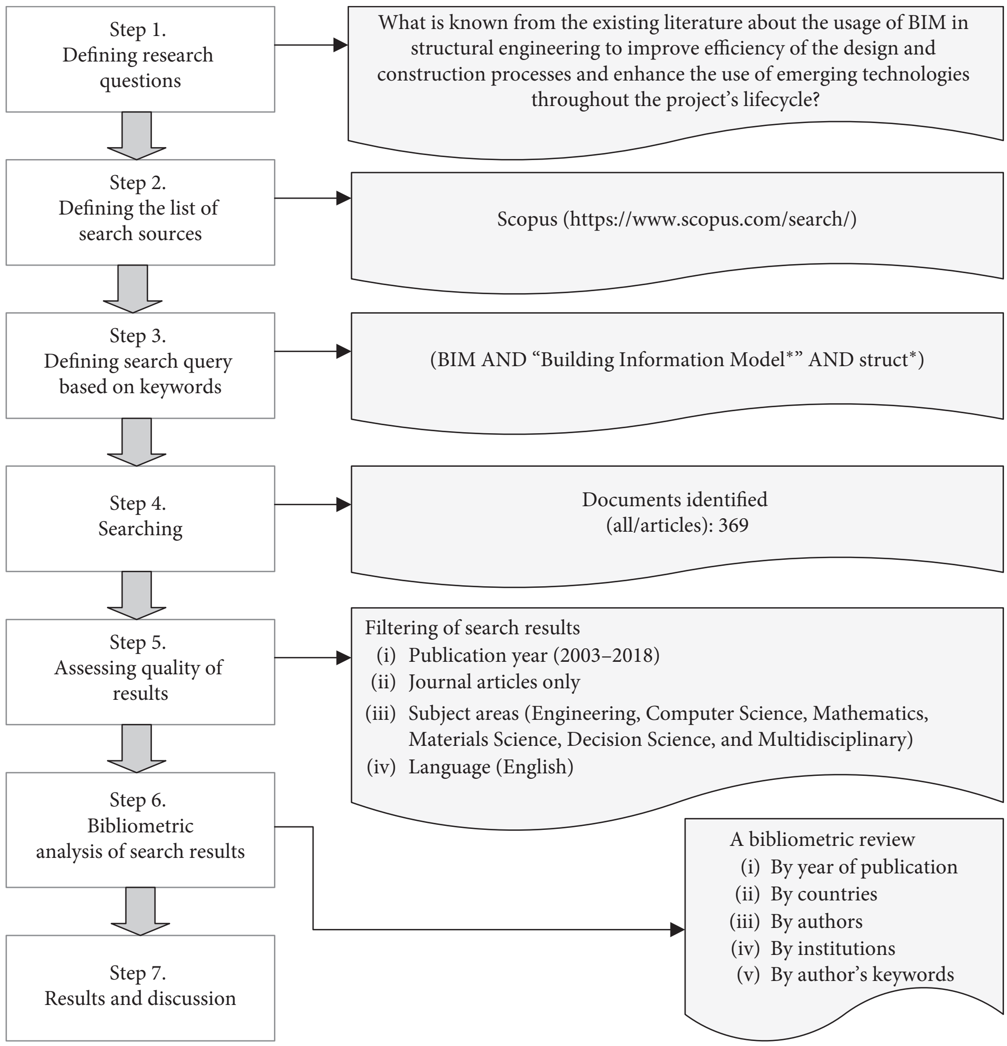

Figure 1: Research design for bibliometric analysis of retrieved papers.

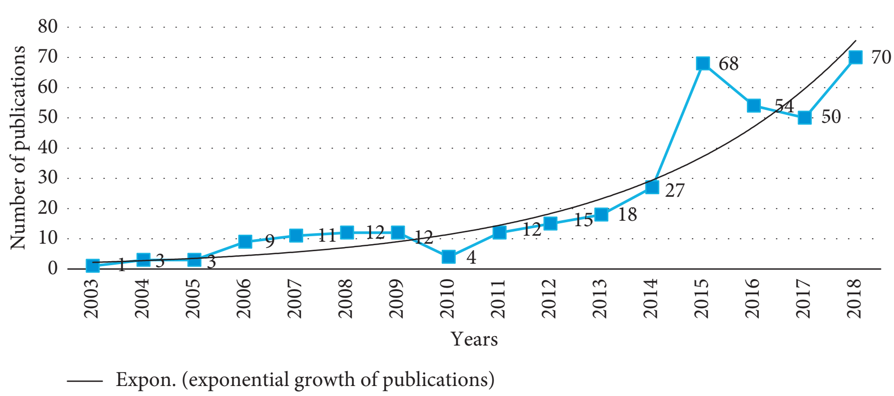

Figure 2: Variations in the number of BIM publications in the area of structural engineering.

Hosseini et al. [9], less than 20% of studies on BIM referred to structural engineering applications. This acknowledges the claims in the literature about the lack of attention paid to structural engineering in the BIM literature [9, 77, 78].

5.2. Coauthorship Networks. Identifying existing research collaboration networks on a topic has several advantages: (1) the awareness can facilitate access to funds, and needed, (2) the awareness will result in higher productivity, and (3) the awareness assists investigators to reduce silo-based and isolated research activities with boosting scholarly communications [79]. In Figure 3, a coauthorship network of authors is generated from the core dataset, as a result of which VOSviewer detects 836 authors. In Figure 3, a minimum of three

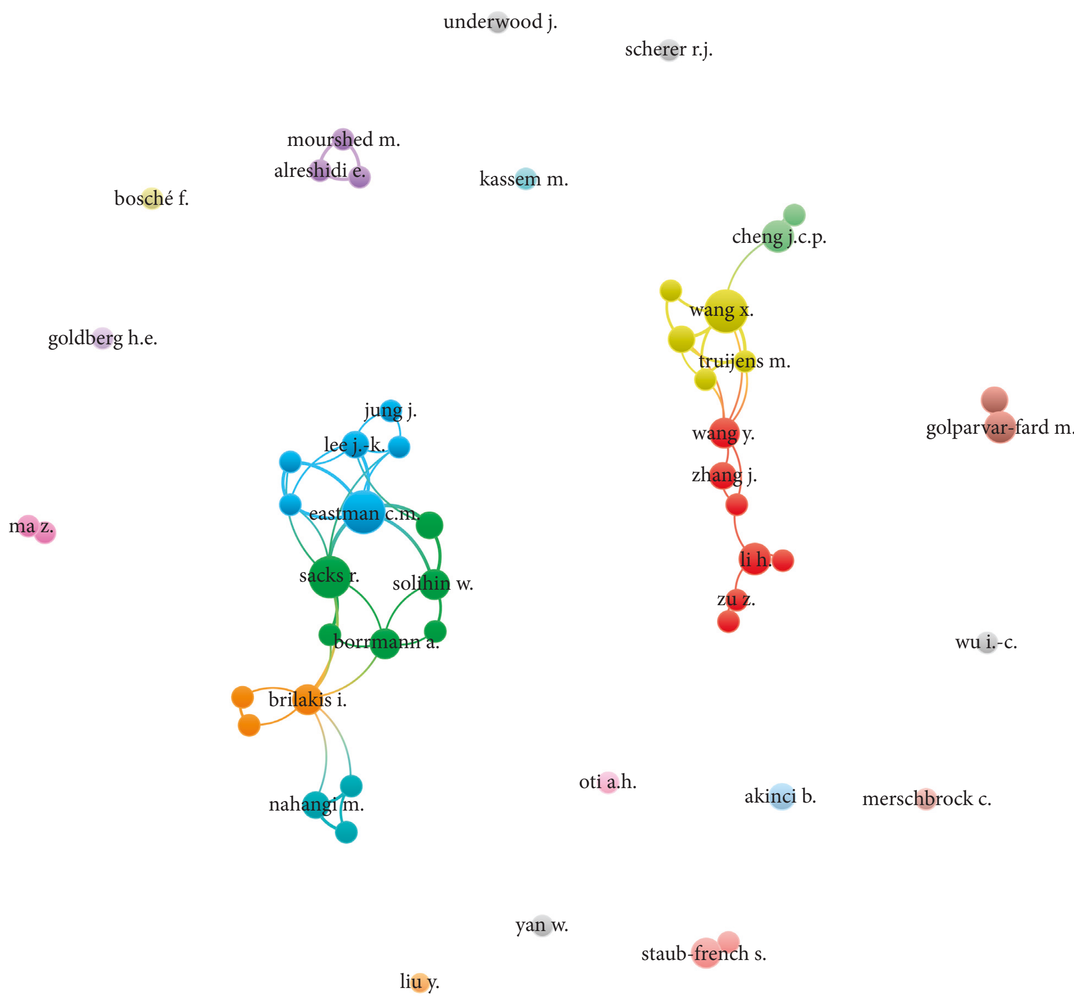

Figure 3: Coauthorship network of authors.

Table 2: The most active authors, whose number of articles focusing on BIM for structural engineering exceeds three.

Author	Number of articles	% of articles	Number of citations
C. M. Eastman	**11**	**13.75**	**704**
R. Sacks	**10**	**12.50**	**476**
X. Wang	**10**	**12.50**	**396**
M. Golparvar-Fard	6	7.50	278
A. Borrmann	5	6.25	46
I. Brilakis	5	6.25	172
S. Staub-French	5	6.25	31
B. Akinci	**4**	**5.00**	**318**
K. K. Han	4	5.00	155
L. Hou	4	5.00	93
J.-K. Lee	**4**	**5.00**	**299**
Y.-C. Lee	4	5.00	42
M. Nahangi	4	5.00	105
W. Solihin	4	5.00	33
Total	80	100	

Bold values depict the most cited authors in the set of leading authors in a group of coauthorship.

documents per author were chosen. After applying VOS-viewer algorithms, 52 authors were obtained. Figure 3 depicts eleven collaboration networks of authors in isolated groups and ten single authors disconnected from the network.

Authors with strong relationships and more articles are set as leading authors in a group of coauthorship. The most active authors, having more than three published articles, are presented in Table 2.

Ranking authors by the number of citations is different from ranking by the number of articles. Citations offer an indication of prominence, as a widely accepted measure for ranking the influence level of authors [80]. Therefore, a network of authors based on their citations was analyzed (see Figure 4). In Figure 4, a minimum of 10 citations of an author were chosen to make the analysis manageable. After applying VOSviewer algorithms, the result of the citation network of 49 authors is obtained. The most cited five authors are as follows: Eastman (704 citations), Sacks (476 citations), Wang (396 citations), Akinci (318 citations), and Lee (299 citations).

In view of the outcomes from Figures 3 and 4, several findings are worth mentioning. First, some large collaboration networks contribute to a major part of research on BIM in structural engineering, in the form of a "linked research enterprise," as termed by Newman [81].

Though presenting a promising picture, this also demonstrates that a major part of research on BIM in structural engineering is dominated by several researchers in a closed circle, calling for more investigation from other authors outside the identified research circle.

Second, a clear intellectual isolation from the mainstream of research on the topic is illustrated, where those who do not belong to the existing clusters form very small and disconnected clusters disjointed from the remaining parts of the network. This calls for more effort to integrate the existing disconnected clusters into one large linked research enterprise, not dominated by few investigators in a closed circle.

A coauthorship network of countries generated from the core dataset presented is illustrated in Figure 5.

A set of 50 countries is identified by VOSviewer (see Figure 5). After applying VOSviewer algorithms, the result of 26 countries is obtained. Finland, India, Norway, Sweden, and Taiwan have no interconnections with other countries; therefore, they are not presented in Figure 5. However, as can be seen in Table 3, the distribution of countries according to the number of citations differs. Here, the five leading countries are United States (2074 citations), United Kingdom (968 citations), South Korea (941 citations), Australia (656 citations), and China (592 citations), which were also referred by Jin et al. [82], as the current leaders in BIM adoption. This shows that many countries, including European countries (Germany, Italy, France, Netherlands, Spain, and Belgium), have had technological advancements in terms of applying BIM for various civil engineering purposes. That said, research activities in these countries and the level of influence of investigators from these countries in facilitating the integration of structural engineering with BIM have a noticeable gap with those in the five leading countries in the field, as discussed.

Table 4 introduces the top organizations that have published more than five papers. As can be seen, the most active four organizations are the Georgia Institute of Technology (16 articles), Curtin University (14 articles), Tsinghua University (13 articles), and Technion-Israel Institute of Technology (10 articles). This also reiterates the findings as discussed: other than few leading countries, institutions in other countries, even in countries with advanced BIM technology like European countries, have overlooked the importance of conducting research to facilitate and expedite the permeation of BIM-based structural engineering and stand far away from their counterparts in leading countries identified in Figure 4.

5.3. Cooccurrence Network. The cooccurrence analysis is usually performed using keywords, to present the main content of articles and the range of researched areas in any domain of the study [83]; it provides a picture of a domain, main areas of research, and trends of development. The cooccurrence analysis of the keyword network is performed using authors' keywords. VOSviewer creates the keyword network by considering the closeness and strength of existing links. The closeness and strength are calculated from the number of publications, in which both keywords have occurred together [80].

VOSviewer identified 2869 keywords from the initial set of 369 articles. Applying VOSviewer algorithms and limiting the minimum number of occurrences of a term to five times, the result was obtained from 147 keywords. The generated set of keywords must be refined again. That is, VOSviewer is capable of identifying synonyms and words with identical meaning, even with different orthography, like "modelling" and "modeling" and "technology" and "technologies." Moreover, similar keywords, like BIM, and building information model have the largest number of occurrences, given the nature of the topic at hand [9]. Therefore, in order to avoid distortion of the results, the resultant set of keywords was refined to omit such unnecessary items in the list. The refining procedure includes the following steps following the lessons by Hosseini et al. [9]:

(i) Elimination of terms related to BIM and having the same meaning, like "BIM," "building information model," and "building information modelling." The primary search of articles was made according to those terms, and it is natural that these terms will be repeated in each analyzed paper and will have the highest number of occurrences and total link strength calculated by VOSviewer.

(ii) Elimination of generic terms, like "construction industry," "architectural design," and "information theory," since those terms have the highest number of occurrences and total link strength, calculated by VOSviewer, because of searching query specifics in this area.

Moreover, as can be seen from Figure 6, the keyword map is visualized using various colors to show the chronological order of items.

In Figure 6, the most occurred keywords are presented. From Figure 6 and Table 5, the most occurred keywords in three periods are presented next. In the period 2010–2012 (colored in blue), the most popular keywords are "project management," "three dimensional," "productivity,"

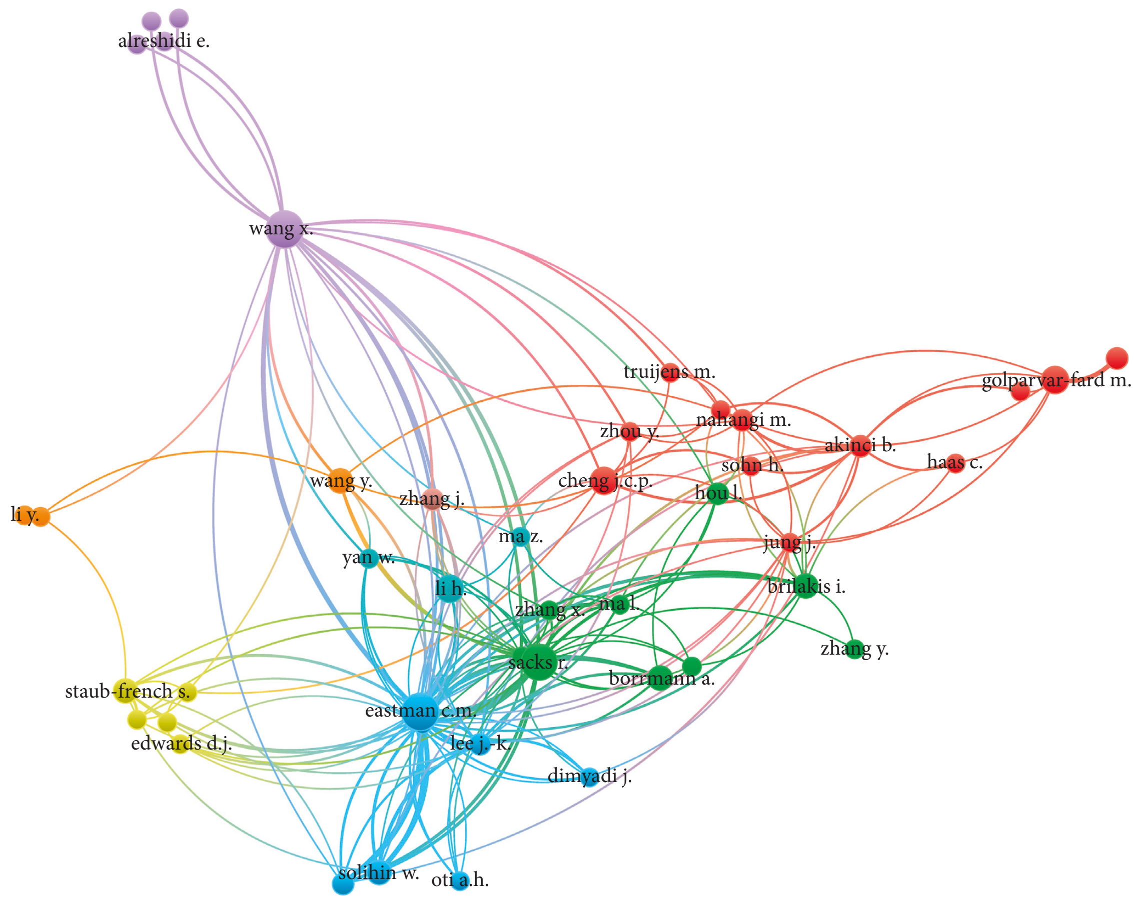

Figure 4: Citation network of authors.

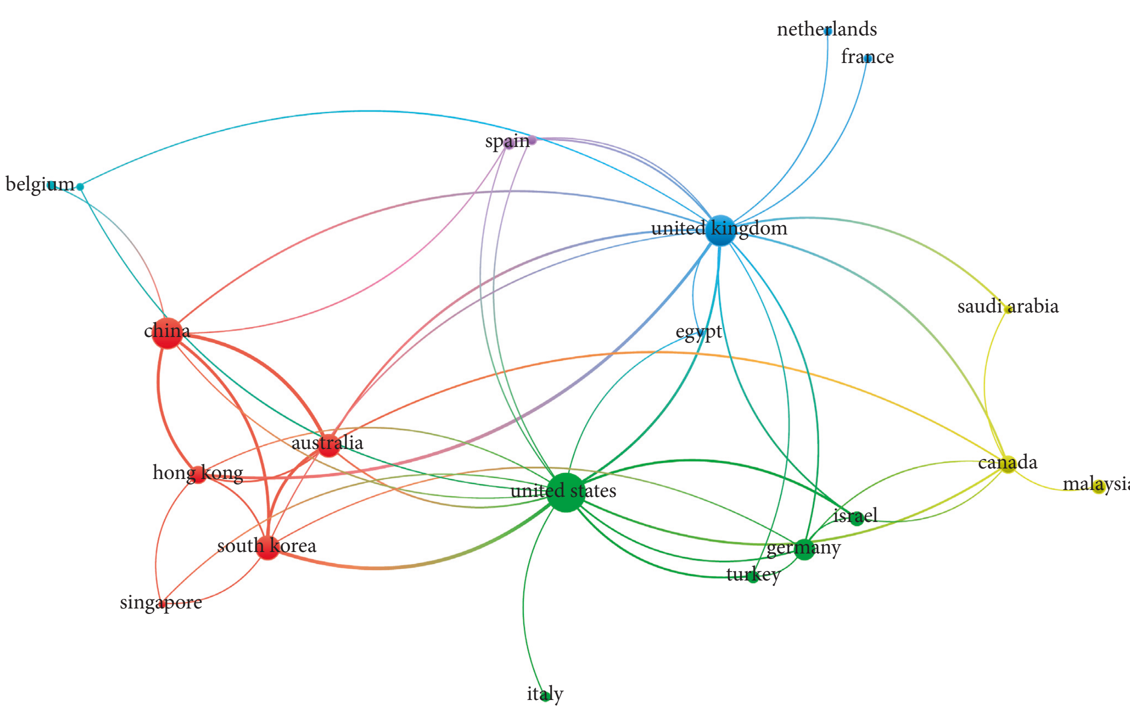

Figure 5: Coauthorship network of countries.

Table 3: The most active countries, where the number of articles exceeds or equals 5 (Scopus, December 2018).

Country	Number of articles	% of articles	Number of citations
United States	**87**	**20**	**2074**
United Kingdom	**57**	**13**	**968**
China	**55**	**13**	**592**
South Korea	**34**	**8**	**941**
Australia	**30**	**7**	**656**
Germany	25	6	272
Canada	19	4	316
Hong Kong	18	4	201
Israel	11	3	477
Malaysia	11	3	34
Taiwan	9	2	41
Spain	8	2	258
Turkey	8	2	231
Ireland	6	1	155
Italy	6	1	82
Finland	6	1	71
India	6	1	42
Norway	5	1	39

Table 4: The most active organizations, whose number of articles exceeds and equals 5.

Organizations	Number of articles	% of articles
Georgia Institute of Technology (United States)	**16**	**3.87**
Curtin University (Australia)	**14**	**3.39**
Tsinghua University (China)	**13**	**3.15**
Technion-Israel Institute of Technology (Israel)	**10**	**2.42**
University of Salford (United Kingdom)	9	2.18
Hanyang University (South Korea)	9	2.18
Kyung Hee University (South Korea)	8	1.94
Hong Kong University of Science and Technology (Hong Kong)	8	1.94
Hong Kong Polytechnic University (Hong Kong)	8	1.94
Cardiff University (United Kingdom)	8	1.94
University of Illinois at Urbana-Champaign (United States)	6	1.45
University of Waterloo (Canada)	6	1.45
Technical University of Munich (Germany)	6	1.45
Texas A&M University (United States)	6	1.45
Carnegie Mellon University (United States)	6	1.45
University of Cambridge (United Kingdom)	6	1.45
Pennsylvania State University (United States)	5	1.21
The University of British Columbia (Canada)	5	1.21
Yonsei University (South Korea)	5	1.21
University of New South Wales (UNSW) (Australia)	5	1.21

The bold values depict the most active four organizations.

"computer aided design," "database systems," "algorithms," "software design," "virtual reality," "standards," etc. The most occurred keywords in the period from 2013 to 2015 (colored in green) are "information systems," "information management," "industry foundation classes," "life cycle," "interoperability," "decision making," "energy efficiency," "semantics," etc. The most occurred keywords in the period 2016–2018 (colored in yellow) are "simulation," "automation," "data handling," "point cloud," "object detection," "cost benefit analysis," "risk assessment," "efficiency," "model view definition," etc. Arranging the keywords according to the citation score (see "Average citations" column in Table 5) results in generating a slightly different picture. That is, the popularity of terms according to the citation score in the three periods is as follows:

(i) 2010–2012: "in-buildings," "three dimensional," "productivity," "concrete construction," "computer aided design," "database systems," "algorithms," "software design," "virtual reality," etc.

(ii) 2013–2015: "model checking," "AEC," "planning," "scanning," "scheduling," "geometry," "interoperability," "design and construction," "collaboration," "precast concrete," etc.

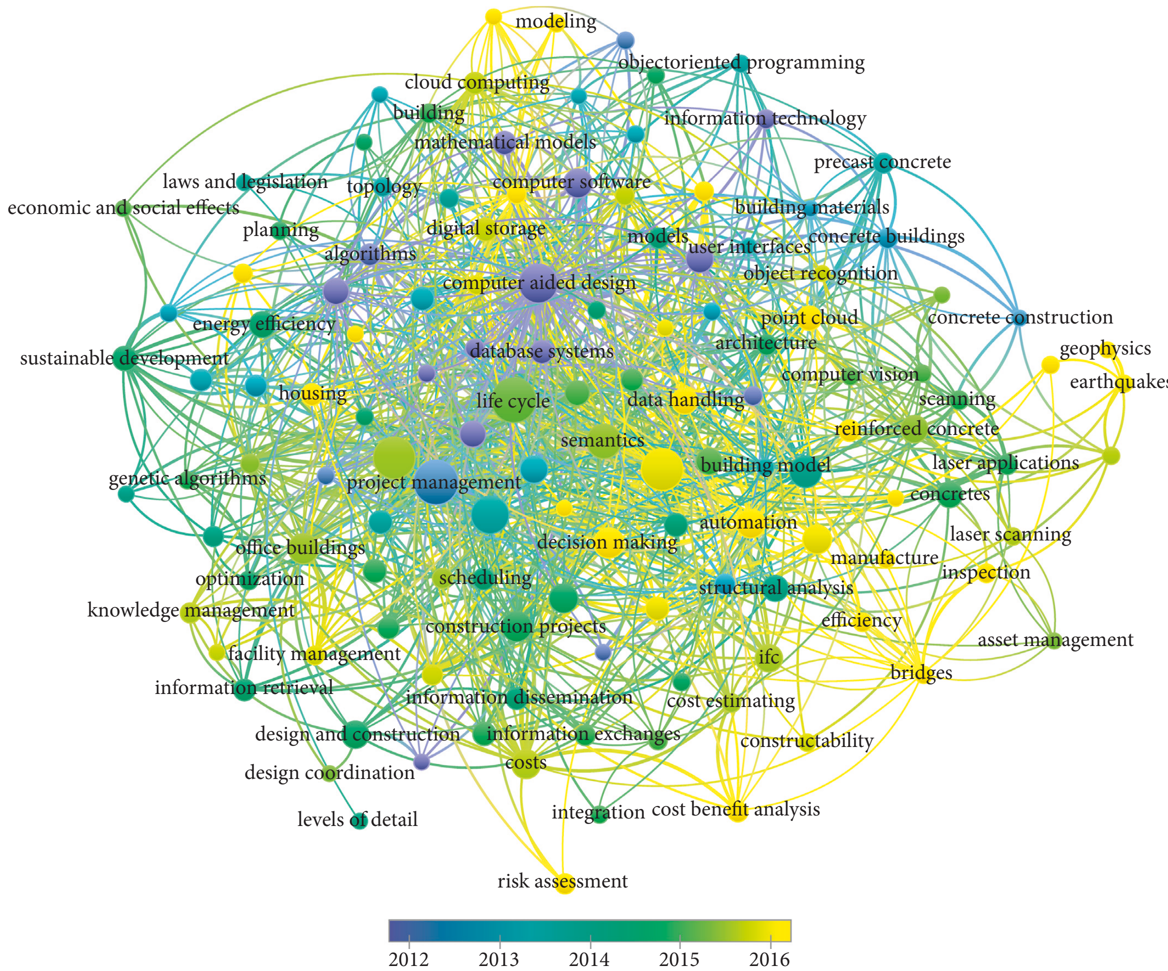

FIGURE 6: Cooccurrence map of keywords according to years.

(iii) 2016–2018: "simulation," "point cloud," "object detection," "automation," "classification," "model view definition (mvd)," "efficiency," "data handling," "inspection," "robotics," etc.

This analysis reveals the evolution of the BIM domain in the area of structural engineering has started with fundamental concepts like parametric design, computer simulations, and analysis of data structures, followed by a focus on the information management, interoperability, and collaboration in construction projects; the trend has shifted towards recent ideas of automation and big data analyses, decision-making, and development of knowledge management systems [75]. The interesting finding here is revealing the delayed attention paid to technical features and specific application of structural engineering within the BIM literature. That is, specialized applications of structural engineering are illustrated as isolated and small nodes in yellow color at the border of the circle of the network. This applies to all areas such as concrete construction, damage detection, floors, and retrofitting (see Figure 6). As such, research on BIM has been largely concerned with generic issues of integrating BIM into structural engineering practice and addressing common barriers that hinder BIM implementation on projects. The

TABLE 5: Keyword analysis (Scopus, December 2018).

Keyword	Links	Occurrences	Average citations
2010–2012			
project management	91	38	11.37
three dimensional	138	33	33.59
computer aided design	95	28	22.96
software design	111	26	14.37
database systems	74	16	21.92
algorithms	47	9	20.44
productivity	35	7	26.86
virtual reality	28	7	19.71
standards	37	6	9.00
civil engineering	28	6	5.17
in-buildings	33	5	76.00
building materials	30	5	16.40
concrete construction	28	5	25.60
2013–2015			
architectural design	146	258	14.84
information systems	181	140	14.00
structural design	130	126	15.80
information management	274	87	15.36
industry foundation classes (ifc)	254	71	19.20
construction	122	44	18.94

Table 5: Continued.

Keyword	Links	Occurrences	Average citations
life cycle	95	38	10.68
design	96	33	13.12
interoperability	76	27	30.93
decision making	109	26	15.81
cost estimating	99	23	7.77
energy efficiency	91	22	5.68
semantics	81	22	19.32
concrete buildings	94	21	14.27
construction projects	69	18	17.56
sustainable development	75	17	14.84
structural optimization	70	17	13.51
office buildings	63	17	27.53
visualization	52	16	15.31
laser applications	75	14	27.71
reinforced concrete	58	14	6.21
design and construction	51	14	29.93
structural analysis	55	13	8.62
facility management	79	12	27.73
AEC	58	11	50.55
digital storage	57	10	13.10
building codes	49	10	11.80
construction management	48	10	14.70
product design	48	10	4.60
data visualization	44	10	11.20
application programs	49	9	5.00
scheduling	48	9	38.11
intelligent buildings	46	9	19.56
model checking	43	9	62.00
cloud computing	38	9	20.78
information retrieval	35	9	10.78
ontology	48	8	16.50
quality control	47	8	15.38
precast concrete	41	8	28.50
knowledge management	39	8	13.00
architecture	37	8	22.50
artificial intelligence	45	7	14.71
building components	44	7	13.43
building	34	7	17.71
scanning	33	7	48.43
topology	30	7	12.71
compliance control	30	7	6.71
social networking	29	7	17.43
collaboration	27	7	28.71
cost engineering	44	6	16.00
specifications	42	6	9.67
genetic algorithms	39	6	21.50
software testing	37	6	13.67
planning	36	6	50.17
object oriented programming	35	6	11.50
historic preservation	32	6	18.00
damage detection	29	6	10.67
integration	28	6	8.00
earthquakes	26	6	4.67
walls (structural partitions)	25	6	43.67
constructability	21	6	12.17
software prototyping	41	5	14.40
user interfaces	36	5	17.00
geometry	29	5	32.20
conceptual design	28	5	12.20
economic and social effects	27	5	16.00

Table 5: Continued.

Keyword	Links	Occurrences	Average citations
search engines	27	5	5.40
laws and legislation	26	5	4.60
levels of detail	25	5	26.40
floors	25	5	51.00
design coordination	23	5	21.40
asset management	13	5	8.80
2016–2018			
simulation	62	18	40.19
automation	77	16	27.88
data handling	65	13	7.54
point cloud	43	11	37.45
housing	47	9	9.89
maintenance	46	9	4.67
cost benefit analysis	28	8	4.88
risk assessment	25	8	4.88
efficiency	38	7	8.43
model view definition (mvd)	33	7	11.86
human resource management	32	7	17.86
classification	44	7	13.00
inspection	32	7	7.43
bridges	34	6	6.67
information modeling	33	6	6.50
manufacture	22	6	2.67
geophysics	21	5	3.20
big data	26	5	5.80
robotics	16	5	7.20
object detection	61	10	32.70

specialized and technical capabilities of BIM in various areas of structural engineering are hardly studied. The existing ones also remain isolated efforts disjointed from the main body of the BIM literature. This shows that the body of knowledge on the capabilities of BIM for integration with structural engineering practices is in its infancy. This can be explained in view of the fact that structural engineers still remain unsure of the risks and/or benefits of using BIM in performing their day-to-day activities and hence are uncertain of the potential to redesign their practices to align with the BIM methodology [84]. Moreover, the findings demonstrate fragmented and loosely coupled efforts in the absence of a coherent strategy or vision for integration of BIM into the structural engineering domain, and as a result, further research on these areas is much needed [9, 12, 78].

5.4. Citation Network. Analysis of citation networks determines cocitation of journals and documents, demonstrating an analysis of the number of times papers cite each other [9]. A journal network was generated using the dataset; 116 journals were detected by VOSviewer. After applying VOSviewer algorithms and limiting the minimum number of citations of a source to 50, the results pulled out 13 journals to form the main citation network (see Figure 7).

As it can be seen in Table 6, the most cited five journals are Automation in Construction (2374 citations, 82 articles),

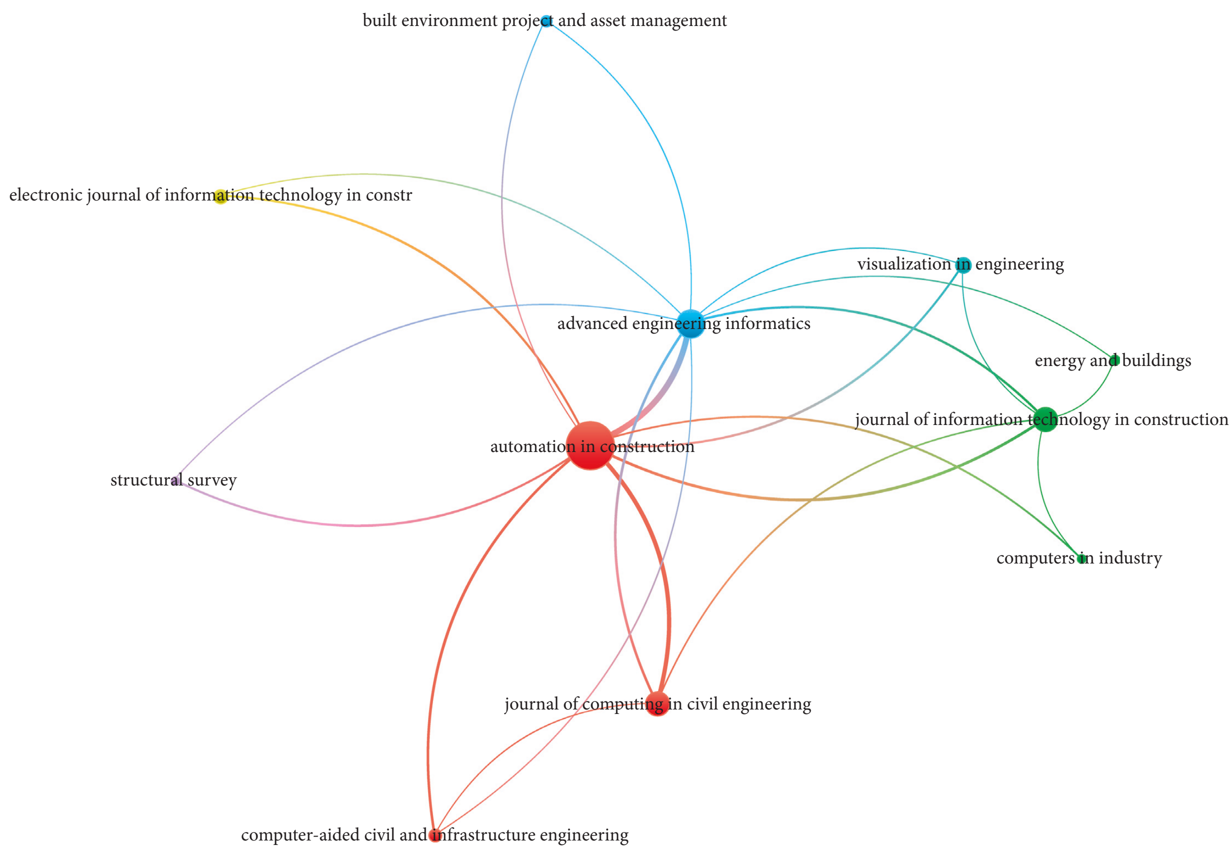

FIGURE 7: Citation network of journals.

Advanced Engineering Informatics (697 citations, 29 articles), Journal of Information Technology in Construction (337 citations, 28 articles), Journal of Computing in Civil Engineering (295 citations, 21 articles), and Visualization in Engineering (95 citations, 9 articles).

The citation network of articles is presented in Figure 8. After applying VOSviewer algorithms and limiting the minimum number of citations of an article to 15, the results are shown in the form of a network with 85 articles as its nodes. Of these, only 55 articles have cited each other.

Eliminating self-citation in Scopus, an overall view emerges that slightly differs from that of Figure 8 (see Table 7). The most cited four articles are as follows: Zhang et al. [85] (198 subtotal and 225 total citations), Xiong et al. [86] (195 subtotal and 220 total citations), Singh et al. [87] (122 subtotal and 186 total citations), and Lee et al. [88] (77 subtotal and 167 total citations).

TABLE 6: The most cited journals.

Journal	Number of citations*	Number of articles	% of articles
Automation in Construction	**2374**	**82**	**22.22**
Advanced Engineering Informatics	**697**	**29**	**7.86**
Journal of Information Technology in Construction	**337**	**28**	**7.59**
Journal of Computing in Civil Engineering	**295**	**21**	**5.69**
Visualization in Engineering	**95**	**9**	**2.44**
Construction Innovation	48	7	1.90
Computer-Aided Civil and Infrastructure Engineering	79	6	1.63
Built Environment Project and Asset Management	57	5	1.36

*Journals cited more than 40 times are included.

6. Gaps and Future Areas for Research

The analysis of results reveals that research on the topic of BIM in structural engineering has been an area experiencing significant growth, confirming the importance of applying BIM in structural engineering [12, 84]. This growth, however, is merely a reflection of the growth of the overall number of articles on BIM triggered by the 2011 mandate of the Government Construction Strategy of the United Kingdom [73]; while the noticeable increase in BIM research appears in 2012 [9, 65], structural engineering and BIM, as a topic, has come to the fore only after 2014. Previous studies have identified similar delays in conducting research on various BIM areas, where evidence refers to the delay for infrastructure, people side, and managerial areas of BIM [18]. This study highlights an analogous delay in research on structural engineering, revealing it as an area with major potential for implementing BIM. With the above in mind, this study, as an original insight provided, reveals that the now-available scientific literature on applications of BIM in

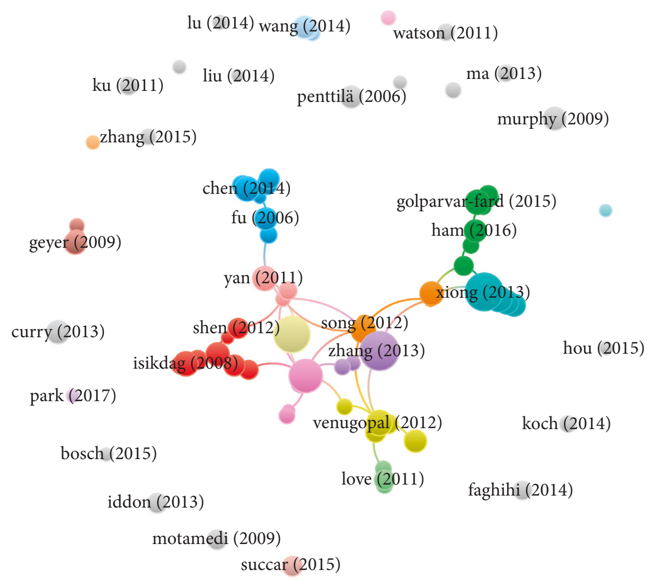

Figure 8: Citation network of articles.

Table 7: The most cited articles on BIM in the area of structural engineering excluding self-citation.

Year	Reference	2015	2016	2017	2018	Subtotal (2015–2018)	Total*
2013	*Zhang et al. [85]*	**29**	**47**	**59**	**60**	**198**	**225**
2013	*Xiong et al. [86]*	**38**	**40**	**52**	**60**	**195**	**220**
2011	*Singh et al. [87]*	**14**	**24**	**43**	**37**	**122**	**186**
2006	*Lee et al. [88]*	**20**	**16**	**19**	**20**	**77**	**167**
2015	Pătrăucean et al. [89]	4	16	23	39	84	84
2008	Isikdag et al. [90]	6	11	15	12	44	82
2011	Yan et al. [91]	13	10	15	18	56	77
2014	Chen and Luo [92]	8	15	23	29	75	75
2009	Jeong et al. [93]	9	5	13	8	35	75
2012	Steel et al. [94]	16	10	18	10	57	74
2012	Venugopal et al. [95]	11	19	13	8	54	72
2009	Murphy et al. [96]	4	10	18	23	56	68
2008	Arayici [97]	9	11	13	13	47	68
2015	Golparvar-Fard et al. [98]	8	17	13	18	56	66
	Total count	428	685	1057	1310	3594	4439

*All years covered by Scopus.

structural engineering has been mainly concerned with generic issues of BIM like information management. As a result, BIM has much unexplored capacity for solving complex technical issues in specialized areas of structural engineering, another evidence for the infancy of BIM applications in the civil engineering field [9] and, in particular, structural engineering applications.

Another novelty of this study lies in its approach to bring together various applications of BIM in structural engineering from isolated studies in the literature, in the chronological order. The outcome is a point of reference that showcases all these applications, as a readily available reference frame for researchers, as well as practitioners. Research studies refer to much unexploited potential for using BIM in structural engineering, in integration with a bulk of available technologies for information management like classification tools based on [9] ontology rules, cloud computing, laser scanning, visualization techniques, simulation software, etc. Interested readers are referred to Sacks et al. [38] for details.

As another contribution of this study (illustrated in Figure 9), the findings demonstrate the evolution of BIM developments in areas associated with structural engineering, starting from the development of standards for computer-aided design, database systems, algorithms, software tools, and approaches to rise productivity. These developments are followed by shifting the focus towards information management, interoperability, and decision-making, eventually moving to the automation of processes, big data analytics, and simulation practices [19]. As the outcome, gaps and important areas for future research are identified, a description of which is as follows.

Automated modeling is deemed an essential element of various key applications like progress monitoring, status

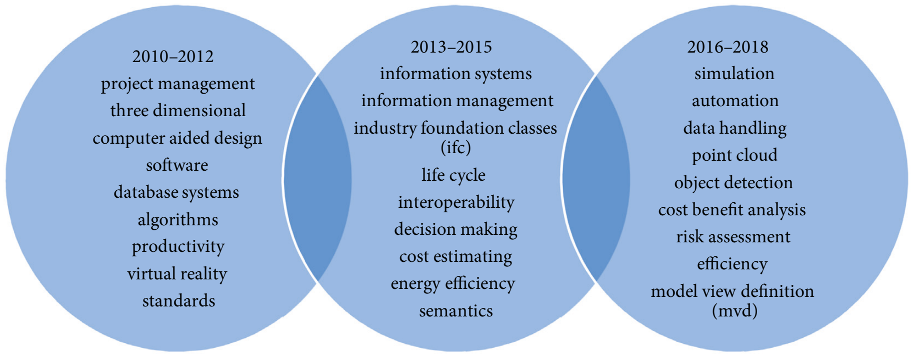

Figure 9: Evolvement directions of BIM in structural engineering.

assessment, and quality control. Therefore, an exponential growth of research efforts on automated construction progress monitoring is detected, in recent years.

The area, however, is still in its infancy [99]; that is, automated detection of structural elements within BIM models still is seen as a challenge, and hence, improving techniques and methods for accurate automated object identification—structural elements—within models is a ripe area for future studies [100].

With the sudden increase of interest in off-site construction—prefabrication—in many countries [101], increasing the prefabrication rate of precast concrete structures, automation of the assembly sequence and planning, and optimization must be topics important on the agenda within the domain of structural engineering [102]. With BIM in mind, future studies can target the unique characteristics of cast-in-place concrete in developing future versions of IFC, overlapping of structural elements, use of reinforcement bars, and the need for precision in loads and material considerations [103]. Automated creation of centralized accurate semantically rich as-built building information models of structural elements also remains a fertile area for future research, given various challenges that affect successful implementation of BIM for such purposes [104–107].

Dynamic structural health monitoring is another research area of paramount importance, to be considered for future investigation of BIM in the structural engineering domain. There is increasing demand for integration of BIM with data generated through sensors for live monitoring the health of structural elements [108]. Several ideas about automatic generation of BIM models of structural monitoring systems that include time-series sensor data that support dynamic visualization in an interactive 3D environment exist [109, 110], and the area remains in need of empirical studies to validate the proposed designs. These are hence future areas for research to promote the use of BIM in structural engineering.

7. Conclusions

This study is the first attempt in its kind in exploring the state of published research studies that link BIM with structural engineering. The area has attracted much interest, and some research efforts in the form of literature reviews are available in related fields like infrastructure engineering and civil engineering applications. Nevertheless, this study stands out. This is because this study offers a picture of the landscape of the body of BIM knowledge in relation to structural engineering, as an area that remains unexplored and unassessed. This study contributes to the field by diagnosing the problems of the literature from a holistic vantage point. It provides original insight into the issues revolving around technical aspects of structural engineering being overshadowed by challenges of BIM process implementation. This study also provides a point of reference to demonstrate what areas of BIM for structural engineering have been explored and what remain to be investigated, acting as an agenda for future research on the topic. In methodological terms, this study draws upon a quantitative analysis of citation networks, which involves minimal subjective judgment, making the findings reliable and reproducible. The findings presented contribute to the field by spotting the gaps to be addressed, trends to be redefined, and main areas of focus for future research. That is, the findings reveal that research on structural engineering applications of BIM is still in its infancy with many gaps; much remains yet to be done in making it an established domain of inquiry.

The clear message is that BIM-related issues like challenges of BIM implementation on projects have overshadowed the potential of BIM for structural engineering, and as such, existing studies have overlooked the technical issues of structural engineering to be resolved through the use of BIM. Moreover, the extant literature on the topic presents fragmented, isolated research efforts. And the isolation applies to the research subjects, active investigators, and their institutions, alike. These trends need reassessing and redefining, as highlighted by the findings of this study.

With the above in mind, future work—in the area of structural engineering and BIM—must target bringing in issues of structural engineering to be addressed and solved through applying BIM capabilities. Future research is needed through forming research collaborative networks that have enhancing dialogue, debate, and intracountry and intraorganization cross-fermentation of initiatives and ideas, as their priorities. These findings raise awareness and enhance understanding of the necessity of addressing the identified gaps and neglected areas within the BIM literature. This contributes to directing deeper, more carefully selected, research into the field and assists policy-makers and industry partners of research projects in their plans for supporting and funding.

Despite the contributions associated with this study, all research studies have limitations, and this study is no exception. First, the analysis only covered the literature in English, using a certain set of keywords for searching. Second, the analysis was based on the dataset retrieved from Scopus; hence, it is affected by the limitations of Scopus in terms of coverage. Therefore, the findings may not fully reflect the entire available corpus of the BIM literature. Furthermore, this study, because of space limitations, was focused on providing a broad picture of the available literature on BIM for structural engineering through a bibliometric analysis of citation networks and less concerned with an in-depth content analysis of available studies. Nevertheless, before the bibliometric analysis of citation networks, authors made an in-depth qualitative analysis of the retrieved papers. A complementary study to analyze the content of available studies remains a ripe area for research on the topic.

Data Availability

The data generated in this research are available from the corresponding author on request.

Conflicts of Interest

The authors declare no conflicts of interest.

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