Review

A review and scientometric analysis of global Building Information Modelling (BIM) research in the Architecture, Engineering and Construction (AEC) industry

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Abstract: In the recent decade, Building Information Modelling (BIM) has widely been adopted in the Architecture, Engineering and Construction (AEC) industry and completely upended the way we build. While BIM continues gain momentum in the industry, it has also attracted increasing attentions from researchers. However, most of the current study focuses on reviewing BIM for management, BIM for green building, BIM for infrastructure and BIM for Facilities Management (FM). There are few studies about Global BIM review and to discuss their complex inter-connections. In this study, we adopted a scientometric analysis method to review global BIM research from 2004-2019. A total of 1455 scholarly bibliographic records obtained from Web of Science Core Collection databased were established for the analysis. This study has identified the top productive and influential researchers, research institutes, regions/countries, subject categories and journals in the BIM field. In addition, 11 clusters of Global BIM research were also identified including construction project, green BIM, construction safety planning, automated IFC-based workflow and so on. Authors distinguished 11 clusters of global BIM research into 3 stages, namely formulating stage, accelerating stage and transforming stage. Furthermore, authors reviewed the BIM policy of Singapore and observed there is a co-production relationship between evolution of BIM policy and global BIM research. These findings provide valuable information for researchers, practitioners and policy makers by visualizing the current progress in the research field of BIM and highlighting future research needs.

Keywords: Building information modelling; Co-citation network; Literature Review; Research visualization; Scientometrics.

1. Introduction

The Architecture, Engineering and Construction (AEC) industry are undergoing a significant shift from traditional labour-intensive methods to automation through the use of information technology, Building Information Modelling (BIM) has played a crucial role in this transformation[1,

2]. The United States National Institute of Building Sciences (NIBS) gives the most authoritative definition: "A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward [3] ."

Literature review refers to a kind of academic paper which is written by making a comprehensive analysis for a large amount of collected information data on a certain topic. As a type of scientific literature, literature review is considered a stopgap for in-depth understanding of the research fields [4]. Through the systemizing of existing researches, the fronts and trends of current researches can be found, so as to provide strong support and argumentation for the establishment of new research topics in the future.

Most of previous researches focused on the research literature review of BIM and other fields, such as managerial areas of BIM [4], BIM for Green Buildings[5], BIM for infrastructure[6], BIM for Facilities Management [7]. To illustrate, Qinghua He et al. [4] reviewed 126 peer-reviewed journal paper on managerial areas of BIM (BIM-MA) and proposed an integrated conceptual framework to summarize current and future research of managerial BIM. Y Lu et al. [5] conducted a comprehensive and critical reflection on the relationship between BIM and Green Building and explained it systematically using the classification of "Green BIM Triangle" taxonomy through an in-depth review of hundreds of journal articles published from 1999 to 2016 and 12 kinds of BIM software widely used in AEC industry. Alex Braddly et. al [6] presented a review of 250 key publications in the area of BIM for infrastructure and analyses the trends for BIM development for infrastructure according to publication year, publication origin, project phase and publication scope. Mustafa Hilal et.al [7] adopted scientometric approach using science mapping techniques to examine BIM-FM articles using Web of Science (WOS) database for the period between 2000 and April, 2018.

There have only a few studies on regional and global BIM review. Among the handful, Saka and Chan[8] presented a scientometric review and metasynthesis of BIM development in the African AEC industry. They found a varying level of BIM growth in the African continent, with North Africa, West Africa, and Southern Africa leading the research development, while the other regions, namely the East Africa and Central Africa are lagging behind. In addition, the authors identified the major challenges encountered in BIM adoption are people/process-related barriers. X Zhao[9] conducted a scientometric review of scientific literature relating to BIM in 2005-2016, and identified the top hot-spots of BIM research, such as: mobile and cloud computing, laser scan, augmented reality, semantic web technology, automated generation, safety rule and code checking. In comparison, this study involved a higher corpus of papers (1455 articles). Moreover, compared with X Zhao[9]'s 12-year span of review, this span of review for this study is 16 years. In addition, no previous review focus on venation of BIM development, this study distinguished 11 clusters of global BIM research into 3 stages, namely formulating stage, accelerating stage and transforming stage. In addition, authors reviewed the BIM policy of Singapore and observed there is a co-production relationship between evolution of BIM policy and global BIM research.

This research adopts a quantitative and qualitative analysis method to analyze 1455 journal articles related to BIM published from 2004-2019. In the quantitative analysis, distribution of BIMs publication was analyzed by with times, authors, countries, research institute, subject categories and published journal. In the qualitative analysis, 1455 bibliometric record was imported into scientometric toolkit for visualization analysis, co-authorship network, network of countries/regions and institutions, network of co-occurring subject categories, network of co-occurring keywords,

89 journal co-citation network,   author co-citation network and document co-citation network. In
90 addition, co-citation clusters were identified and conducted critical review for the top three
91 documents in each cluster.

2. Research Method

93   The research framework includes defining literature database and search rules, conducting
94 preliminary retrieval, data processing and analysis, as illustrated in **Figure. 1**. The paper selection
95 process in this study was referred to the methods used in other review articles, such as [6, 8, 13].

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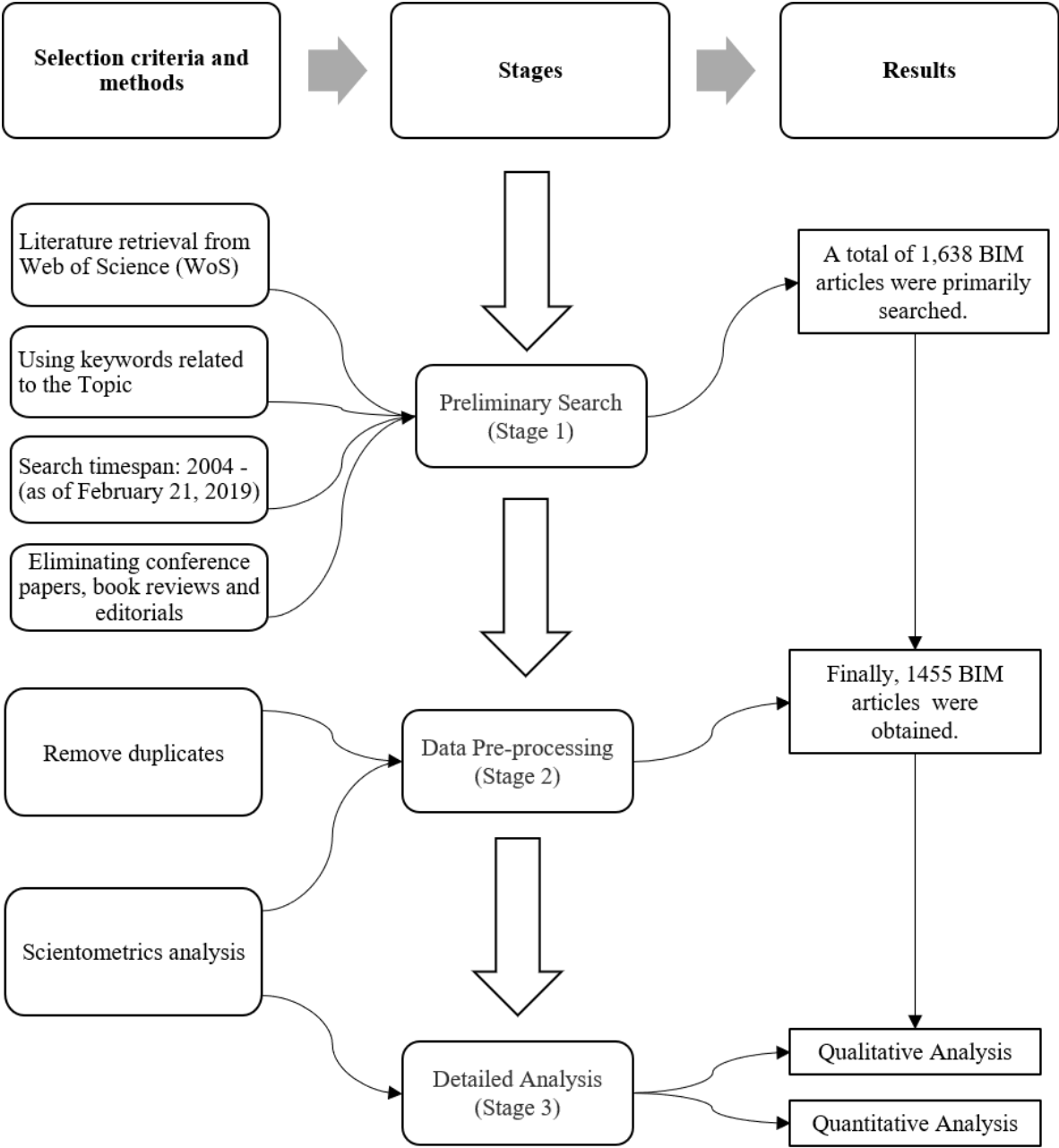
97   **Figure 1.** Research Framework

2.1. Preliminary Search

99   The research boundary have been defined by following the rules below. Firstly, the research data
100 is obtained from Web of Science (WoS) Core Collection. For scientific text data, all literature
101 information except the main body is included in the index database. The WoS, an authoritative
102 database in the research field, is selected for literature search.   The data structure of WoS is relatively

103 complete, including literature types, authors, journals, keywords, abstracts, institutes and references.
104 Engineering, architecture and information construction are also fully included in the database which
105 also contains major journals and conference papers. More than 18,000 influencing journals around
106 the world are covered by WoS, including open journals and more than 180,000 pieces of conference
107 proceedings, and over 80,000 books from around the world[10]. Information obtained from WoS is
108 considered sufficient for this study.

109 Secondly, the initial search takes the topics as follows: "Building information modelling",
110 "Building information modeling" or "Building information model", "" representing precise phrase
111 search. Taking into account articles comprehensively covering BIM and the avoidance of target
112 literature omission, the time span was set from 2004 to 2019. The first journal article [11] on BIM was
113 published in 2004, so the year 2004 was set as an the initial year. The retrieval was conducted on
114 February 21, 2019. In January 2004, John Haymaker et al. [11] firstly proposed "building information
115 modeling" in keywords of a paper and formalized a reusable reasoning module called "Perspectors"
116 which can automatically construct a task-specific engineering view known as "Perspectives" by
117 engineers. The method has been verified by a real project.

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119 Thirdly, only English articles and reviews are selected. To ensure the comprehensiveness and
120 reliability of the results of literature review, the literature referred to is limited to journals, excluding
121 book reviews, letters, news reports and conference abstracts. This is because journal papers usually
122 peer-reviewed, and can be considered to provide more comprehensive, robust and superior quality
123 of information than other types of publications. A total of 3,033 articles on BIM were retrieved for the
124 first time, with the database interface shown in **Figure. 2**.
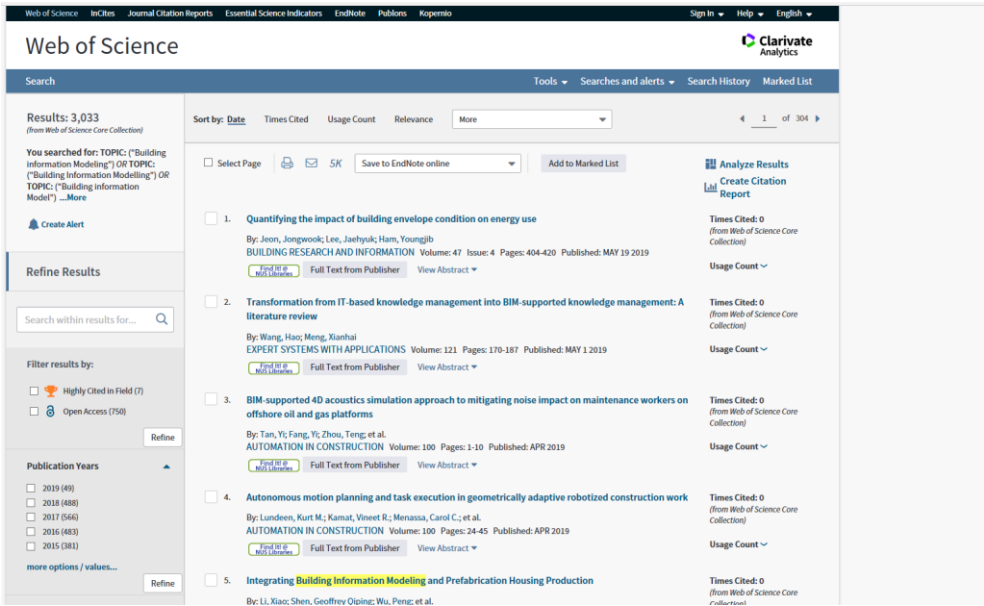

126   **Figure 2.** Article retrieved

127 Through refining and duplicate checking, 1,455 articles on BIM were obtained. The specific data
128 collection process is shown in **Table 1**.

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130   **Table 1.** Articles retrieved at different stages

Search Engine	Strings and Filter	Articles Retrieved

Web of Science	Topics: "Building information modelling"	
	Or "Building information modeling"	
	Or "Building information model"	3033
	Database: Web of Science Core Collection	
	Timespan: 2004 to 21Feb 2019	
	Languages: English	2943
	Exclude conference articles	2272
	Document Types: Article + Review	1638
	Remove duplicates	1455

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135   *2.2. Data pre-processing*

136   Before performing detailed analysis, data filtering and duplicate removal for WoS format of data
137   should be carried out. It can help to remove redundant data and could be used for removing identical
138   or similar files with the same content [12]. As shown in **Figure.3**, a total of 1,455 valid BIM articles
139   were obtained after data pre-processing.

140

141   *2.3. Research toolkits*

142   Common scientometrics toolkits are CiteSpace[13], Science of Science (Sci2) Tool[14],
143   BibExcel[15]. These toolkits can help scholars to quickly and effectively perform visualized
144   information analysis. CiteSpace is an open-sourced tool-kit which can be freely downloaded. It is
145   mostly used to detect, analyze, and visualize patterns and trends in scientific literature[16]. Its
146   primary goal is to facilitate the analysis of emerging trends in knowledge domain. Featuring perfect
147   functions, CiteSpace is characterized by spectral clustering and citation burst[16]. It emphasizes on
148   identifying critical points-in-time in the development of a field or a domain, in particular, intellectual
149   turning points and pivotal points of research [17].In the whole process of constructing knowledge
150   maps, the processing of each step by CiteSpace is reasonable, with the highlight of core items.
151   Therefore, CiteSpace is used to analyze literature in this study.

152   *2.4.* Parameters setting

153   The time span settings were from 2004 to 2019 for BIM bibliographic records. Each year was
154   selected as a time slice and 16-time segments were obtained. The Cosine algorithm was selected for
155   the correlation strength of network nodes. The threshold of time slice was set to 50, that is to say, the
156   first 50 (Top 50) were extracted. Finally, redundant links was removed by Pathfinder in network
157   pruning, which was recommended by Chen and Morris[18]. Moreover, the corresponding node types
158   were selected, and the corresponding scientific knowledge map was drawn according to the research
159   needs.

160   **3. Statistical overview**

161   This section aims to conduct a quantitative analysis for 1455 BIM bibliometrics record. The
162 development status of BIM research field can be reflected by the diachronic change trend of the
163 amount of publications in this field. In order to understand the research achievements of BIM in the
164 last decade, statistics of distribution of BIMs publication were analyzed by their publishing times,
165 authors, countries, research institute, subject categories and published journal.

166   *3.1. Distribution of BIM publications with times*

167   A total of 1,455 BIM publications collected from the WoS database are shown in **Figure. 3**,
168 temporal distribution of which is recorded. It can be found that the volume of research documents
169 related to BIM has been on a rise since 2008, with a sharp increase especially since 2012. BIM is
170 receiving extensive attention and ushering in the upsurge of development in the world. As shown in
171 **Figure.3**, published articles in the BIM field have been greatly increased since 2008. A total of 708
172 BIM papers were published in the last three years (from 2016 to 2018), accounting for approximately
173 half of the literature in this study.

174 Seen from **Figure. 3**, the development of BIM research has continued since the beginning of the 20th
175 century. In January 2004, John Haymaker et al. [11] firstly proposed "building information modeling"
176 in keywords of a paper. In 2005, Kenny TC et al. [19] tried to explore other dimensions of BIM. Low
177 frequency of BIM usage was mentioned in the paper. Traditional entity-based CAD software was still
178 taken as the actual drawing tool. Core obstacles include the difference between architectural design
179 and drafting, inadequate objects and object customization capability, the complex and time-
180 consuming modeling process, lack of training and technical support, lack of customer requirements,
181 additional file acquisition costs and incapability of obtaining free trial software. In addition, the
182 separation of design and drafting has become a common practice, which may be the most prominent
183 obstacle to the widespread use of BIM and the nD modeling in the future.

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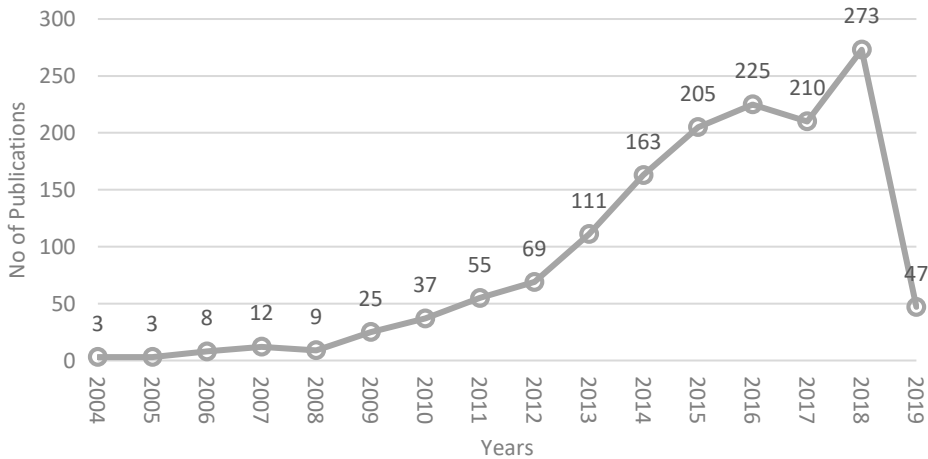
186   **Figure.3:** Distribution of BIM publications with times

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188   *3.2. Distribution of published papers with authors*

189   According to literature retrieved from WoS, the top 10 most productive BIM authors were
190 identified, as shown in **Table 2.** Xianyu Wang from Curtin University, Australia, tied for the first
191 place with 41 BIM publications, followed by Rafael Sacks from Israel Polytechnic University and Jack
192 C. P. Cheng. Among the top 10 productive authors, three come from Curtin University of Australia,
193 two from Hong Kong Universities, and another two from the University of Seoul and Yonsei
194 University, South Korea.

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Table 2. Top 10 productive BIM article authors

SN	Rank	Author	Country	Institution	Count	% of 1455
1	1	Xiangyu Wang	Australia	Curtin University	41	2.82
2	2	Rafael Sacks	Israel	Technion-Israel Institute of Technology	30	2.06
3	3	Jack C.P. Cheng	Hong Kong	Hong Kong University of Science and Technology	24	1.65
4	4	Raja R.A. Issa	USA	University of Florida	19	1.31
5	4	Heng Li	Hong Kong	Hong Kong Polytechnic University	19	1.31
6	5	Charles M. Eastman	USA	Georgia Institute of Technology	18	1.24
7	5	Kim Hyunjoo	South Korea	University of Seoul	18	1.24
8	5	Ghang Lee	South Korea	Yonsei University	18	1.24
9	5	Jun Wang	Australia	Curtin University	18	1.24
10	6	Heap-Yih Chong	Australia	Curtin University	17	1.17

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201
Seen from the number of publications in countries where the top ten authors are located, the top three countries are Australia (76 publications), Hong Kong (43 publications) and South Korea (36 publications). It is also worth mentioning that the volume of publications by top 10 productive authors accounts for approximately 15% of the total.

202
3.3. Distribution of published literature with countries/regions

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206
The information of countries/regions in articles can be obtained from the published bibliographic records, so as to determine the main countries/regions of the publications.   According to the records in WoS, a total of 1,455 BIM articles were published in 75 countries/regions. Top 10 productive countries/regions are shown in **Table 3**.

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208
Table 3. Top 10 productive BIM articles countries/regions

SN	Country/Region	Count	% of 1455
1	USA	341	23.44
2	China	224	15.40
3	England	194	13.33
4	Australia	152	10.45
5	South Korea	151	10.38
6	Germany	70	4.81

7	Canada	60	4.12
8	Taiwan	55	3.78
9	Italy	41	2.82
10	Malaysia	36	2.47
11	Netherlands	36	2.47

209   With regard to the contribution of the total volume of BIM documents, publications in the top
210 10 countries accounted for approximately 93% of the total volume of BIM documents. The top three
211 countries, namely, the United States, China and the United Kingdom contributed 341, 224 and 194
212 papers respectively, accounting for more than half of the total volume. In four Asian
213 countries/regions among the top 10, including China, South Korea, Taiwan and Malaysia, they
214 accounted for approximately 30 percent of the total publications. In European countries, there were
215 194 publications in England, 70 publications in Germany and 41 publications in Italy, accounting for
216 about 20 percent of the total publications. In North American countries, 341 were published in the
217 United States and 60 were in Canada, taking up approximately 27 percent of the total publications.
218 In Oceania, Australia contributed more than 10 percent of the total.

219   *3.4. distribution of published documents with research institutes*

220   Information of research institutes in publications can be obtained from bibliographic records as
221 well, so as to determine the main research institutes of the publications. According to records in WoS,
222 a total of 1,128 research institutes have published 1,455 BIM articles. The top 10 productive institutes
223 are shown in Table 4.

224

225   **Table 4.** Top 10 productive research institutes

SN	Rank	Research Institute	Country/Region	Record	% of 1455
1	1	Curtin University	Australia	69	4.74
2	2	Georgia Institute Technology	USA	58	3.99
3	3	Hong Kong Polytechnic University	Hong Kong	42	2.89
4	4	Kyung Hee University	South Korea	40	2.75
5	5	Tsinghua University	China	29	1.99
6	5	University of Hong Kong	Hong Kong	29	1.99
7	6	Pennsylvania State University	USA	28	1.92
8	7	Yonsei University	South Korea	27	1.86
9	8	Hong Kong University of Science Technology	Hong Kong	26	1.79
10	8	Technion – Israel Institute of Technology	Israel	26	1.79
11	8	University of Florida	USA	26	1.79
12	8	University of Salford	UK	26	1.79

226   In terms of the contribution of the total volume of BIM literature, the top 10 research institutes
227   accounted for nearly 30 percent of the total volume of published BIM documents. The top three
228   research institutes were Curtin University, Georgia Institute Technology and Hong Kong Polytechnic
229   University Regionally, there were 3 Hong Kong research institutes among the top 10 The total
230   contribution of Hong Kong was 97, accounting for 23% and 7% of the top 10 literature volume and
231   the total volume, respectively. There were also 3 USA research institutes, Georgia Institute
232   Technology, Pennsylvania State University and University of Florida. In addition, among the top 10
233   research institutes, Asian research institutes contributed 193 publications, taking up 45% and 13% of
234   the top 10 literature volume and the total volume, respectively.

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236   *3.5. distribution of published documents with subject categories*

237   A total of 1,544 BIM bibliographic records loaded from WoS were allocated to 86 WoS categories.
238   The top 10 productive research institutes are shown in **Figure.5**. The top 3 categories were
239   Engineering Civil with 813 publications, Construction Building Technology and Engineering
240   Industry with 582 and 156 publications, respectively. Each of them accounted for 56%, 40% and 11%
241   of the total volume of publications.

242

243   **Table 5.** Top 10 productive WoS subject categories

SN	Web of Science Categories	Record	% of 1455
1	Engineering Civil	813	55.88
2	Construction Building Technology	582	40.00
3	Engineering Industrial	156	10.72
4	Engineering Multidisciplinary	155	10.65
5	Management	125	8.59
6	Computer Science Interdisciplinary Applications	109	7.49
7	Architecture	86	5.91
8	Computer Science Artificial Intelligence	71	4.88
9	Green Sustainable Science Technology	64	4.40
10	Environmental Sciences	60	4.12

244   *3.6. distribution of published documents with journals*

245   According to statistical data obtained from WoS core collection database, the top 10 Journals of
246   BIM research were determined. BIM literature publications are shown in **Table.6**. There were 294
247   papers published on Automation in Construction, occupying the first place in BIM research, followed
248   by the Journal of Information Technology in construction with 96 papers and the Journal of
249   Computing in Civil Engineering with 64 papers. Among these 10 journals, 4 were published in the
250   USA and 3 were published in the UK.

251   **Table.6**. Top 10 Journals for BIM research in 2004-2019

SN	Source Title	Host country	Count	% of 1455
1	Automation in construction	Netherlands	294	20.21
2	Journal of information technology in construction	Sweden	96	6.60
3	Journal of computing in civil engineering	USA	64	4.40
4	Journal of construction engineering and management	USA	61	4.19
5	Advanced engineering informatics	UK	54	3.71
6	Journal of management in engineering	USA	34	2.34
7	Architectural engineering and design management	UK	30	2.06
8	Engineering construction and architectural management	UK	29	1.99
9	Journal of civil engineering and management	Lithuania	25	1.72
10	Buildings	USA	24	1.65

4. The results of scientometric analysis

4.1 Co-author analysis

The information on the authors, research institutions and countries/regions can be obtained from bibliographic records, so as to determine the leading researchers, institutions, and countries/regions of BIM research [20]. Thereafter, a co-authorship network, as well as a network of co-authors' institutions and countries/regions, was generated.

4.1.1 Co-authorship network

The co-authorship network is shown in **Figure.4**. Each node represents an author, and links between the authors represent the collaboration established through co-authors in the article. The node size represents the number of publications, and the thickness of the links represents the level of the partnership in a specified year. Colors of the lines such as blue, green, yellow, orange and red correspond to different years from 2004 to 2019. The bibliographic records of 1,455 BIM documents were analyzed with CiteSpace. There were 312 nodes and 336 links for the co-authorship network.

As shown in **Figure.4**, there are multiple closed-loop circuits in the research of collaboration, indicating that researchers in these closed-loop circuits have established strong collaboration. For example, the closed-loop circuit of Rafael Sacks, Yeon-Suk Jeong and Charles M. Eastman implied strong cooperation by these authors in 2008 and 2009. Jochen Teizer and Markus König established strong cooperation in 2019. In addition, several research communities, including multiple authors and one or two productive authors, were identified after the co-authorship network analysis. For example, Xiangyu Wang and Jun Wang are two core authors of a research group which also includes Martijn Truijens, Yi Jiao and Shih-Chung Kang. Inhan Kim is the main author of a research group composed of Shen zhenghua, Jungho Yu etc. There is also a research community in recent years, such as Liang Ma, Poorang Piroozfar and Ruoyu Jin.
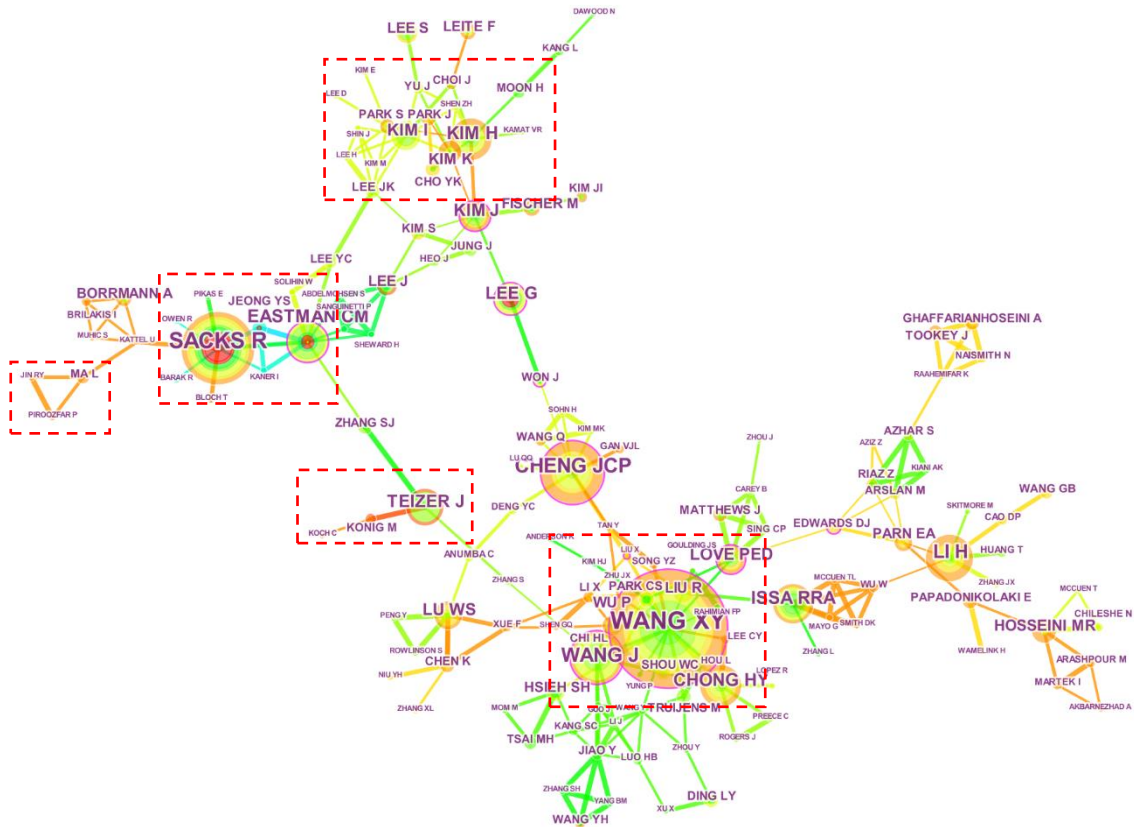
Figure.4: Distribution of BIM publications with times

The following two important indicators are usually used to measure the importance of authors, articles, research institutes and countries/regions:

- Betweenness centrality (noted with purple rings)

In the graph theory, the centrality of nodes is the theoretical property of a graph, which quantifies the position importance of nodes in the network. A commonly used centrality measure is betweenness centrality which is an index measuring the importance of nodes in the network. It is defined as the ratio of the shortest path between two nodes to the sum of all these shortest paths. Nodes with high betweenness centrality usually connect two or more large groups of nodes to each node. This index is used to discover and measure the importance of literature in CiteSpace, and a purple highlighted ring is used to highlight this kind of literature (or authors, periodicals and research institutes, etc.). Clusters in the network can be easily separated and influencing and revolutionary scientific publications can be identified by these nodes. In Figure.6, purple rings are used for nodes of Xiangyu Wang (centrality = 0.18), Jack C.P. Cheng (centrality = 0.13), Jun Wang (centrality = 0.12), Peter Love (centrality = 0.12) and other several authors, and they connect different groups of authors.

- Citation burst detection (noted in red)

Citation burst detection is an important index for studying the most active field. One of CiteSpace's breakthroughs is to provide a burst item analysis method based on the word frequency growth algorithm, which detects rapidly growing specialized words in a short period of time by counting citation keywords. The characteristics of temporal distribution and dynamic variability of the burst items can better reflect the research fronts and development trend in the knowledge domain. Citation burst detection is used for emergencies, which can last for a year or several years. Citation burst detection can be used as an evidence to show that a particular publication is heavily cited at a

302   certain time. In other words, the publication has attracted great attention from the scientific
303   community in that period of time. Burst detection in CiteSpace is based on Kleinberg algorithm. As
304   shown in Figure 2.9, the four authors received citation bursts of different intensities by red notes.
305   According to the burst strength, the rank was Sacks R (strength = 6.09, 2009-2013), Eastman CM
306   (strength = 3.82, 2009-2012), Jeong YS (strength = 3.32, 2009-2010) and Lee G (strength = 3.13, 2012-
307   2014)

308   *4.1.2 Network of countries/regions*

309   In order to understand the research status in the field of BIM in the world, a network of
310   countries/regions was generated. There are 51 nodes and 113 links in the network. In **Figure.5**, the
311   size of nodes represents the appearance frequency of the country in which the author is located in.
312   The larger the circle is, the higher appearance frequency of authors in the country is. The color of the
313   rings represents the authors' literature publication time in the corresponding country, and the wider
314   the single ring is, the higher appearance frequency of authors in the country is within a certain time
315   period.

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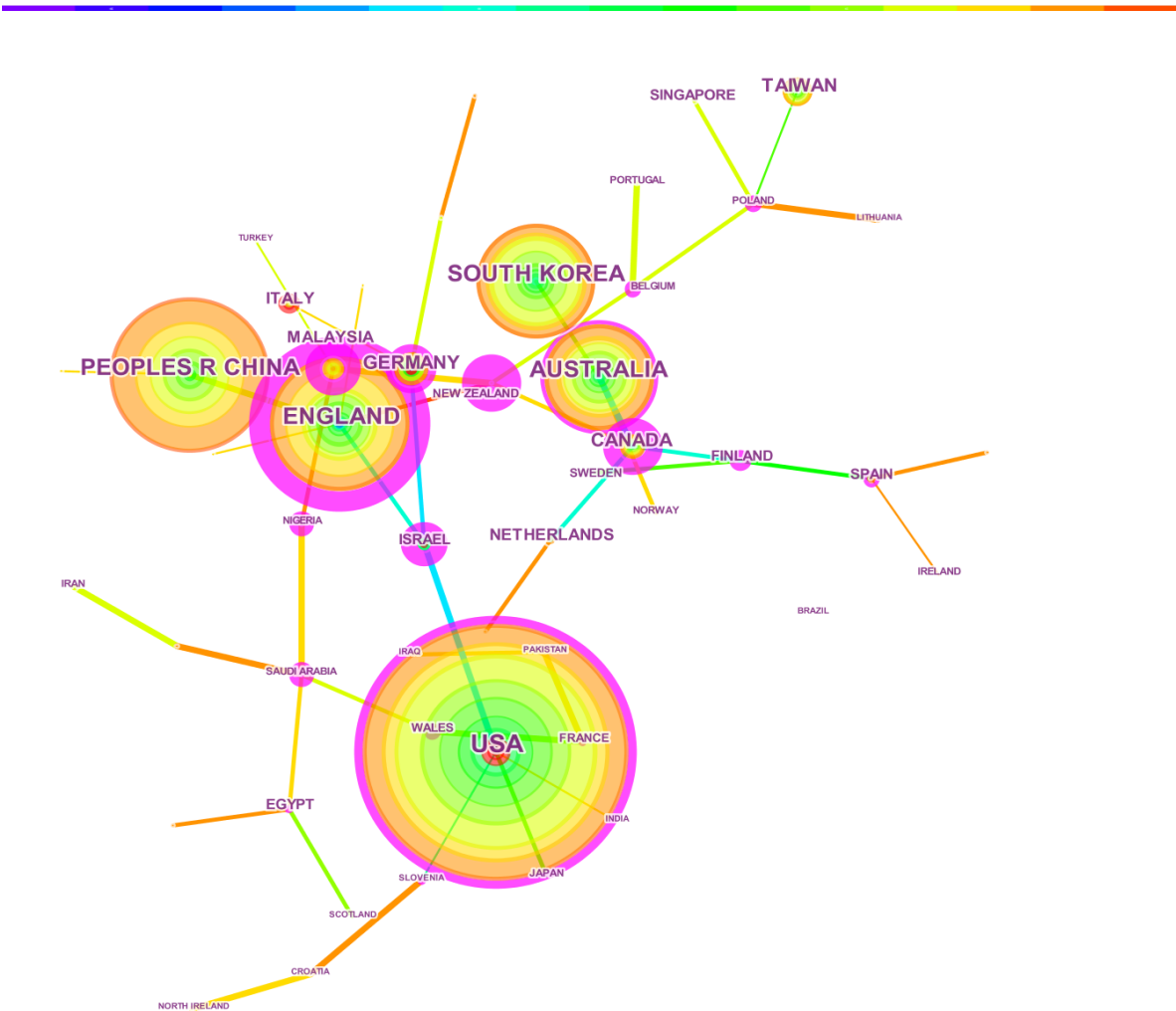
318   **Figure.5:** Network of countries/regions

319   As shown clearly in **Figure.5**, the circle area of the USA is the largest in the field of BIM research
320   with absolute advantages. It shows that the United States has strong research strength and influence
321   in the field of BIM. China ranks the second, suggesting the moderate BIM research power of the
322   country. The United Kingdom ranks the third, South Korea ranks the fourth and Australia ranks the

323 fifth with the frequency 156. It indicates that progress has been achieved in these countries on BIM
324 research. It can also be seen that European and Asian countries attach great importance to the
325 development of BIM, and that they actively carry out relevant researches in the field of BIM.

326 In addition, in the area of international cooperation, Canadian researchers have cooperated
327 extensively with researchers from Australia, South Korea, Finland and other countries. The U.K.,
328 New Zealand and Germany are connected by relatively thick golden/red lines, indicating a strong
329 partnership between these countries in 2018 and 2019.

330 Furthermore, nodes with high betweenness centrality have been identified with purple outer
331 rings. As shown in **Figure.5,** the representative countries/regions include New Zealand (centrality =
332 1.25), the United Kingdom (centrality = 0.84), Malaysia (centrality = 0.68), Canada (centrality = 0.64)
333 and Israel (centrality = 0.63). These countries with nodes of high betweenness centrality play an
334 important role in BIM research.

335 As for citation burst detection, the following 5 countries received citation bursts with different
336 strengths at different times. Ranking according to the burst strength, the sequencing is as follows: the
337 United States (strength = 10.49, 2004-2012), Israel (strength = 5.31, 2009-2010), Germany (strength =
338 4.01, 2009-2011), Italy (Strength = 3.65, 2017-2019), and Finland (strength = 3.26, 2009-2015).

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340 *4.1.2 Network of research institutes*

341 Other than the distribution network of countries/regions, the network of the research institutes
342 in the field of BIM were established as well. It includes 195 nodes and 240 links in total, as shown in
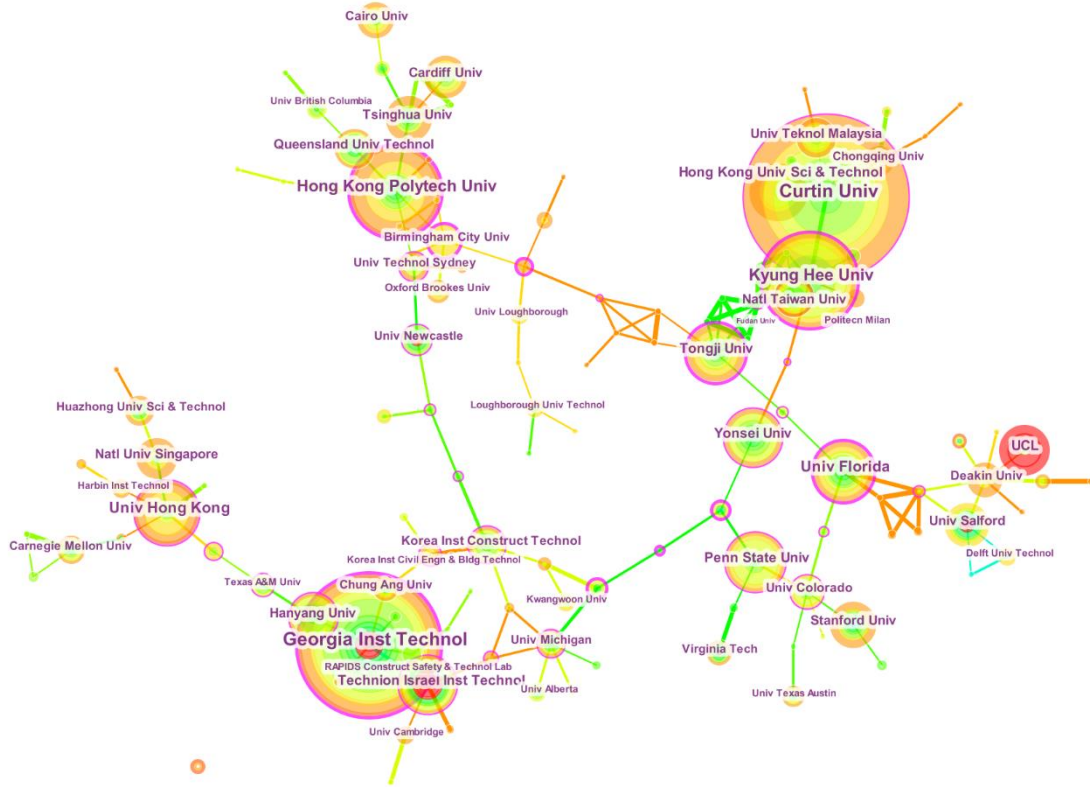343 **Figure.7**.

344

345 **Figure.6**: Network of research institutes

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347   It can be found in **Figure.6** that the frequency (Circle) of Curtin University is the highest. It has
348 published the most articles in the field of BIM with absolutely high research strength, followed by
349 Georgia Institute of Technology in the USA, Kyung Hee University in South Korea and Hong Kong
350 Polytechnic University in Hong Kong. It is implicates that the four institutions have strong research
351 potential in BIM. It is observed that half of the top 10 research institutes are located in Asia, which
352 can be seen merely from the volume of publications. In recent years, BIM has been widely concerned
353 and actively studied in Asia.

354   Additionally, the cooperation between different institutes is explored, as shown in **Figure.6**. The
355 node is the name of the research institutes. The connection between nodes is used to describe the
356 collaboration strength of different research institutes. The color of the connection indicates the time
357 of the first collaboration of the node. The thickness of the connection indicates the collaboration times
358 between the institutes. The thinner the lines are, the fewer times of cooperation there are. Hong Kong
359 Polytechnic University has established extensive collaboration with a number of research institutes
360 in the field of BIM such as Tsinghua University, Queensland University Technology and the
361 Birmingham City University. University of Florida, University of Oklahoma, University North
362 Carolina Charlotte, Calif State University Fresno and DKS Informat Consulting LLC have jointly
363 formed a research group for close collaboration in 2018, these research institutes were connected by
364 thicken golden lines.

365   Furthermore, high betweenness centrality points were identified and displayed by purple outer
366 rings, representative research institutes of which were Hong Kong Polytechnic University (centrality
367 = 0.26), University of Washington (centrality = 0.24, Research institutions such as Tongji University
368 (centrality = 0.23) Georgia Institute of tech (centrality = 0.22) and Kyung Hee University (centrality =
369 0.20). These research institutes with high betweenness centrality are the hub nodes connected with
370 other research institutes and different clusters.

371   In terms of citation burst, seven research institutes have received varied strength of citation burst
372 at different time. According to the burst strength, the sequences were Georgia Institution of
373 Technology (strength = 6.63, 2006-2012), Technion-Israel Institute of Technology (strength = 6.57,
374 2009-2013), University of Salford (strength = 5.69, 2007-2012) and University of Newcastle (strength =
375 4.26, 2011-2013), UCL (strength = 3.62, 2017-2019), Virginia Polytechnic Institue and State University
376 (strength = 2.98, 2011-2013) and University of Reading (strength = 2.98, 2013-2014).

377 *4.2 Co-word analysis*

378   With more and more countries and research institutes focusing on BIM research, there are
379 various researches on different topics, subjects and keywords. Co-word analysis aims to study the
380 internal correlation and scientific structure of the literature through the statistical analysis of the
381 keywords that reflect the subject of the literature. Co-word can help to estimate trends and conduct
382 front research.

383 *4.2.1 Network of co-occurring subject categories*

384   Each journal publication from Web of Science Core Collection database is assigned to one or
385 more subject categories based on relevant journals. A network of subject category research was
386 generated with 62 nodes and 135 links. This network was used to analyze the emerging trend of BIM
387 research, as shown in **Figure.7**.

Figure.7: Network of co-occurring subject categories

In **Figure. 7**, the node size represents the number of articles in each category. Among them, the frequency of Engineering is the highest, followed by Engineering Civil, Construction & Building Technology, Computer Science, Engineering, Multidisciplinary and Engineering Industry. It manifests that most of BIM articles were assigned to these categories.

It should also be noted that, in the past two years, subjects like Green & Sustainable science and technology, Science and Technology-Other Topics and Environmental Studies have also attracted the attention of scholars. What's worth mentioning is that there are 58 articles in the category of Green & Sustainable Science/Technology and 187 articles about computer science. Thus, it implies that the potential of BIM in energy and environmental analysis and sustainable design has been recognized and attached with great importance by the academic community.

Furthermore, nodes with high betweenness centrality were highlighted by purple outer rings , representative categories of which were computer science, artificial intelligence (centrality = 0.80), engineering, electrical & electronic (centrality = 0.76), computer science, information systems (centrality = 0.68) engineering, multidisciplinary (centrality = 0.66), and operations research & management science (centrality = 0.65). They represent the turning point connecting different stages of research, which has a significant impact on the development of BIM research.

Nine categories have received citation burst of different strengths at different time. According to the burst strength, the sequences were Green & Sustainable Science & Technology (burst strength = 7.53, 2017-2019), Remote Sensing (burst strength = 6.19, 2017-2019), other topics of Science & Technology (burst strength = 5.72, 2017-2019), Architecture (burst strength = 5.41, 2004-2019), Geography, Physical (burst Strength = 5.16, 2017-2019), Physical Geography (burst strength = 5.16, 2017-2019), Robotics (burst strength = 4.89, 2014-2015) and Engineering, Environmental (Burst Strength = 3.70, 2017-2019). It indicates that these categories of publications are on behalf of the most active fields in the research and development of BIM.

4.2.2 Network of co-occurring keywords and clusters analysis

415   Keywords play a role in highly summarizing the content of literature researches. To a certain
416   extent, they represent the research content of an article. The centrality of network nodes is one of the
417   key indexes reflecting the core degree of nodes, which can be used to measure the importance of some
418   node in the network as well as its correlation with other nodes. Therefore, the core issue or the focus
419   of researches that scientific researchers commonly concerned can be reflected by the keywords with
420   high centrality and frequency. There are two types of keywords in the literature database of Web of
421   Science: "author keyword" provided by the authors and "keyword +" identified by journals. The co-
422   occurring keyword network is constructed by the two types of keywords in bibliographic records.
423   There are similar keywords in all bibliographic records, such as "BIM", "building information
424   modeling", " Building information modelling", " building information modeling (BIM) ", and
425   "Building information modelling (BIM)". The function of merging similar keywords in CiteSpace is
426   used to merge these similar keywords to the "Building Information Model".

427   When analyzing the research hotspots of BIM, the network node was set to "Keyword", and the
428   synonymous keywords were merged after running the software to obtain the keyword co-occurring
429   network in the research literature, as shown in **Figure. 8**. Each keyword in the map was represented
430   by a square node. A larger block size represents a higher frequency of the keyword shown in the field
431   of BIM research, therefore, they are high frequency keywords. What needs to be concerned is the
432   square node with purplish red light which represents a high centrality of keywords and its close
433   correlation with other keywords. For this, there were 160 nodes and 516 links in the co-occurring
434   network.

Figure.8: Network of co-occurring keywords

The keywords with high frequency and high centrality in BIM research literature in the recent decade are shown in **Table.7**. The top 10 keywords in the literature were Building Information Model (frequency = 738), Construction (frequency = 359), Design (frequency = 213), System (frequency = 195), Management (frequency = 190), Model (frequency = 138), Framework (frequency = 97), Project (frequency = 95), Industry (frequency = 87), and Performance (frequency = 85). Combined with high centrality keywords, we can find that the hot areas of global BIM research in the recent decade include design, project, framework, industry and model. Keywords with high betweenness centrality are correlated with different research subjects, which have a significant impact on the development of BIM research as well.

Table.7: High Frequency keyword of BIM research from 2004-2019

SN	Keyword with high frequency		Keyword with high centrality	
	Keyword name	Frequency	Keyword name	Centrality

1	Building Information Model	738	Design	0.66
2	Construction	359	Project	0.42
3	Design	213	Framework	0.39
4	System	195	Project Management	0.34
5	Management	190	System	0.32
6	Model	138	Simulation	0.32
7	Framework	97	Interoperability	0.29
8	Project	95	Tracking	0.29
9	Industry	87	Industry	0.27
10	Performance	85	Model	0.25

448   Besides, citation burst was observed in the following eight keywords: Building information
449 model (burst strength = 11.66, 2008-2014), Adoption (burst strength = 5.80, 2017-2019),
450 Interoperability (Burst strength = 5.63, 2007-2013), 4D CAD (burst strength = 4.57, 2011-2014), Cloud
451 Computing (burst strength = 4.38, 2012-2014), Generic Algorithm (burst strength = 4.26, 2014-2016),
452 Energy Efficiency (burst strength = 4.25, 2014-2016) and Augmented Reality (burst strength = 4.04,
453 2013-2015), indicating that these are the hotspots of BIM research in corresponding years.

454   Clustering in data mining is a process of aggregating and classifying data in complex networks
455 according to similarity. In keyword clustering analysis, the similarity of nodes in the network is
456 reflected, which is conducive to identify and detect representative knowledge subgroups in a certain
457 field of research, that is, the hot subject in the research field. The network node is set to "Keyword"
458 For clustering on the basis of the generation of keyword co-occurring network. Finally, the keyword
459 clustering network in the field of BIM research is obtained, as shown in **Figure. 9**.

460
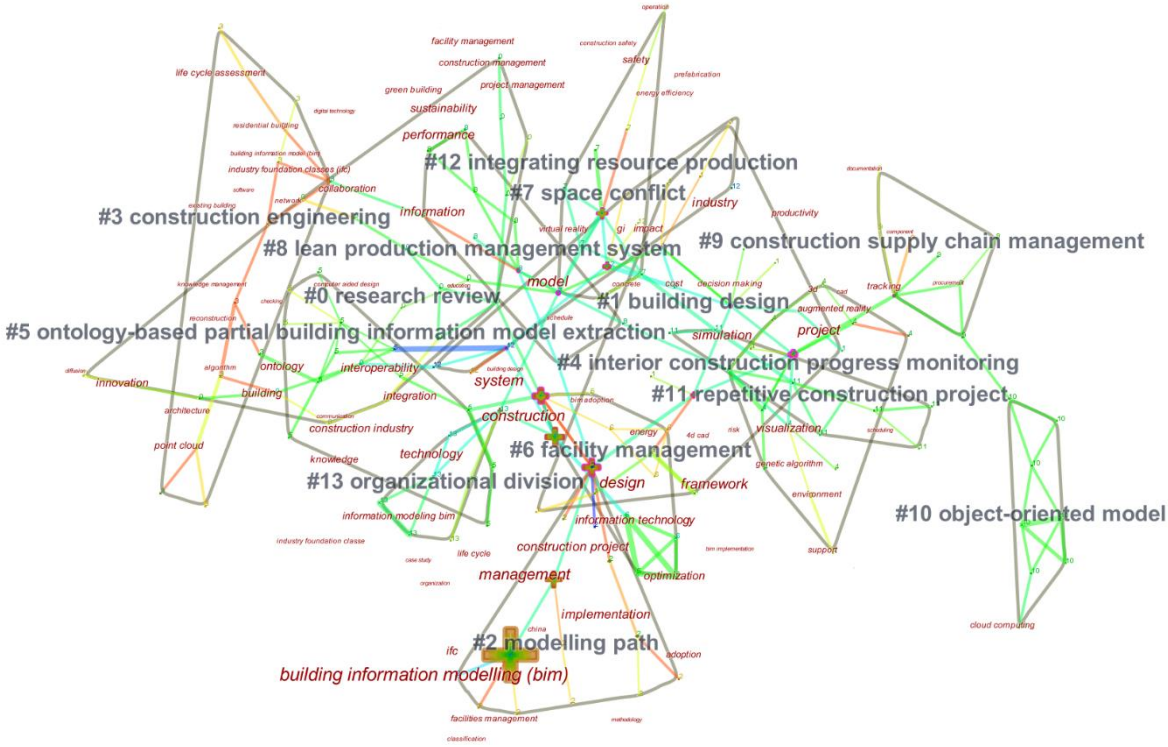
461   **Figure.9:** Network of co-occurring keywords- Clusters

462

463   BIM research hotspots can be summarized into 13 subjects: #0: research review (Silhouette = 0.79,
464 Size = 19), #1: building design (Silhouette = 0.832, Size = 16), #2: modelling path (Silhouette = 0.971,
465 Size = 14), #3: Construction engineering (Silhouette = 0.838, Size = 13), #4: interior construction
466 progress monitoring (Silhouette = 0.913, Size =13), #5: Ontology-based partial building information
467 model extraction (Silhouette = 0.826, Size = 12), #6: facility management (Silhouette = 0.872, Size = 10),
468 #7: space conflict (Silhouette = 0.853, Size = 10), #8: lean production management system(Silhouette =
469 0.765, Size = 9), #9: construction supply chain management (Silhouette = 0.914, Size = 8), #10: object-
470 oriented model(Silhouette = 0.938, Size = 8), #11:repetitive construction project (Silhouette = 0.918,
471 Size = 8), #12: integrating resource product (Silhouette = 0.856, Size = 8),   and #13: Organization
472 Division(Silhouette = 0.962, Size = 7). The larger the value of silhouette is, the more obvious the cluster
473 effect will be, while a smaller value of sihouette will lead to an insignificant effect.

474 *4.3 Co-Citation analysis*

475   When two documents are cited by a third document simultaneously, there will be co-citation
476 relationship between the two documents[4, 16]. The citation frequency of literature can objectively
477 reflect the degree to which the literature can be recognized by the academic community or the
478 knowledge domain, as well as the position of the literature in the network. Continuously highly cited
479 literature is considered classical in a certain field, while the early foundational literature and seminal
480 literature in a field could reflect the development and research basis of the researches in that field.
481 CiteSpace software was used in this section to perform co-citation analysis of journals, authors and
482 documents. BIM's co-citation network was generated, in which the meaning of the size and color of
483 the nodes and the thickness and color of the links are similar to the interpretation of the previous
484 networks.

485 *4.3.1 Journal co-citation network*

486   The journal co-citation network in the field of BIM was established using CiteSpace software.
487 There were 261 nodes and 644 links in the network.

488   As shown in **Figure.10**, the five most influential journals were Automation in Construction
489 (frequency = 1071), Journal of Construction Engineering and Management (frequency = 548), BIM
490 Handbook (frequency = 475) , Advanced Engineering Informatics (frequency = 451) and Journal of
491 Computing in Civil Engineering (frequency = 447) in turn. These five journals are also the most
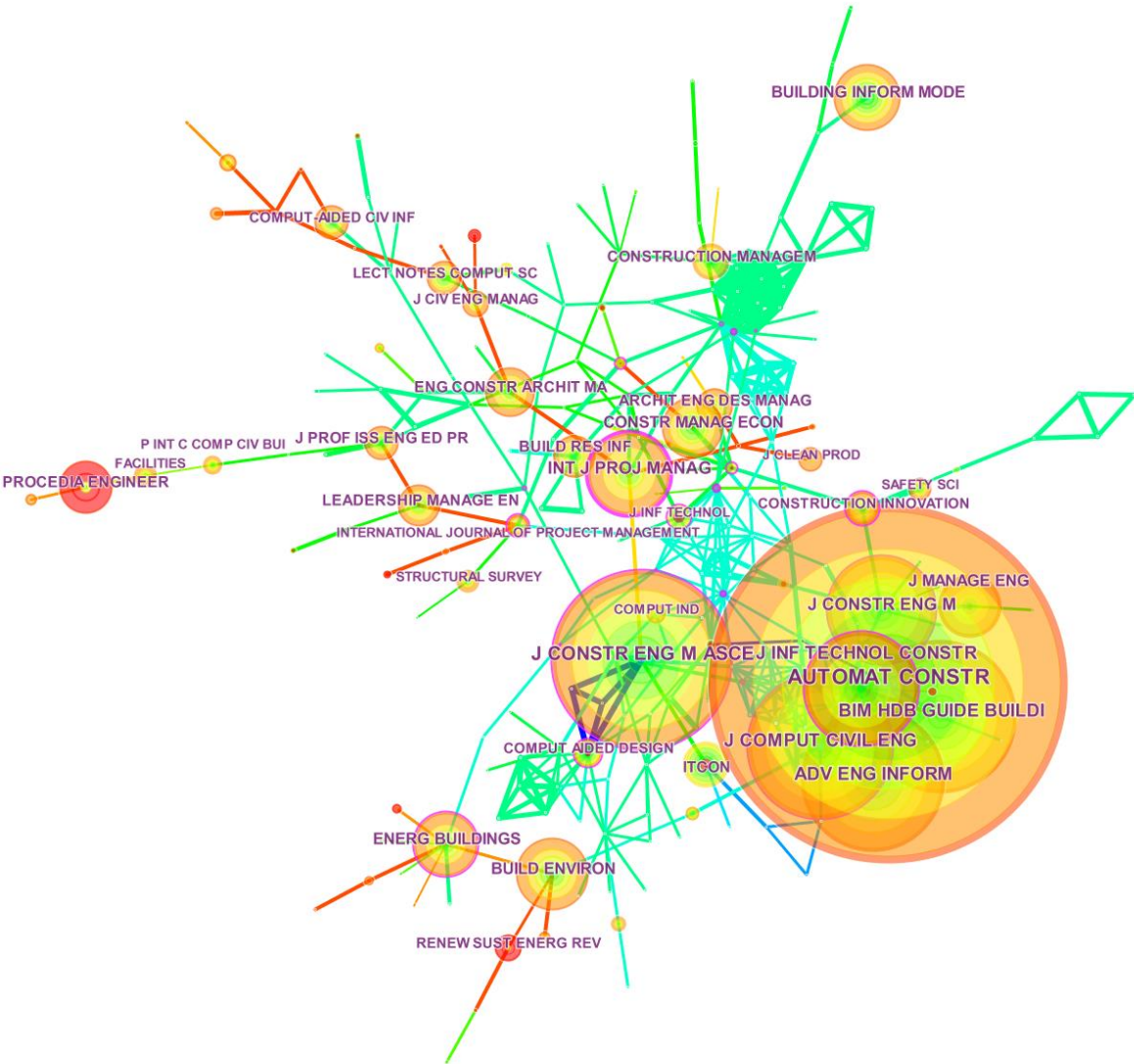492 published source journals in the field of BIM.

Figure.10: Journal co-citation network

As shown clearly in Figure.10, some nodes with high betweenness centrality were highlighted with purple rings, such as International Journal of Project Management (centrality = 0.22), Journal of Construction Engineering and Management (centrality = 0.20) and Energy and Buildings (centrality = 0.11). These journals represent major academic turning points and interrelated journals published at different stages.

In addition, citation burst was found in the following representative journals in turn: Journal of Information Technology in Construction (burst strength = 19.09, 2008-2013), Automation In Construction (burst strength = 18.5, 2006-2014), Building Product Models: Building Product Models: Computer Environments, Supporting Design and Construction (Book) (burst strength = 14.63,2005-2012), Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industry (Book) (burst strength = 8.12, 2009-2014) and Computer-Aided Design (burst strength = 8.05, 2006-2013). It shows that the articles published on these journals were widely cited in a short period of time, therefore, they are worthy of paying attention to.

4.3.2 Author co-citation network

Author co-citation analysis can be used to identify the relationship between the authors cited in the same article and analyze the evolution of the research group. The author co-citation network in

511   the field of BIM is shown in **Figure.11**, consisting of 308 nodes and 757 links. The meaning of the size
512   and color of nodes as well as the thickness and color of links in the map is interpreted similarly to
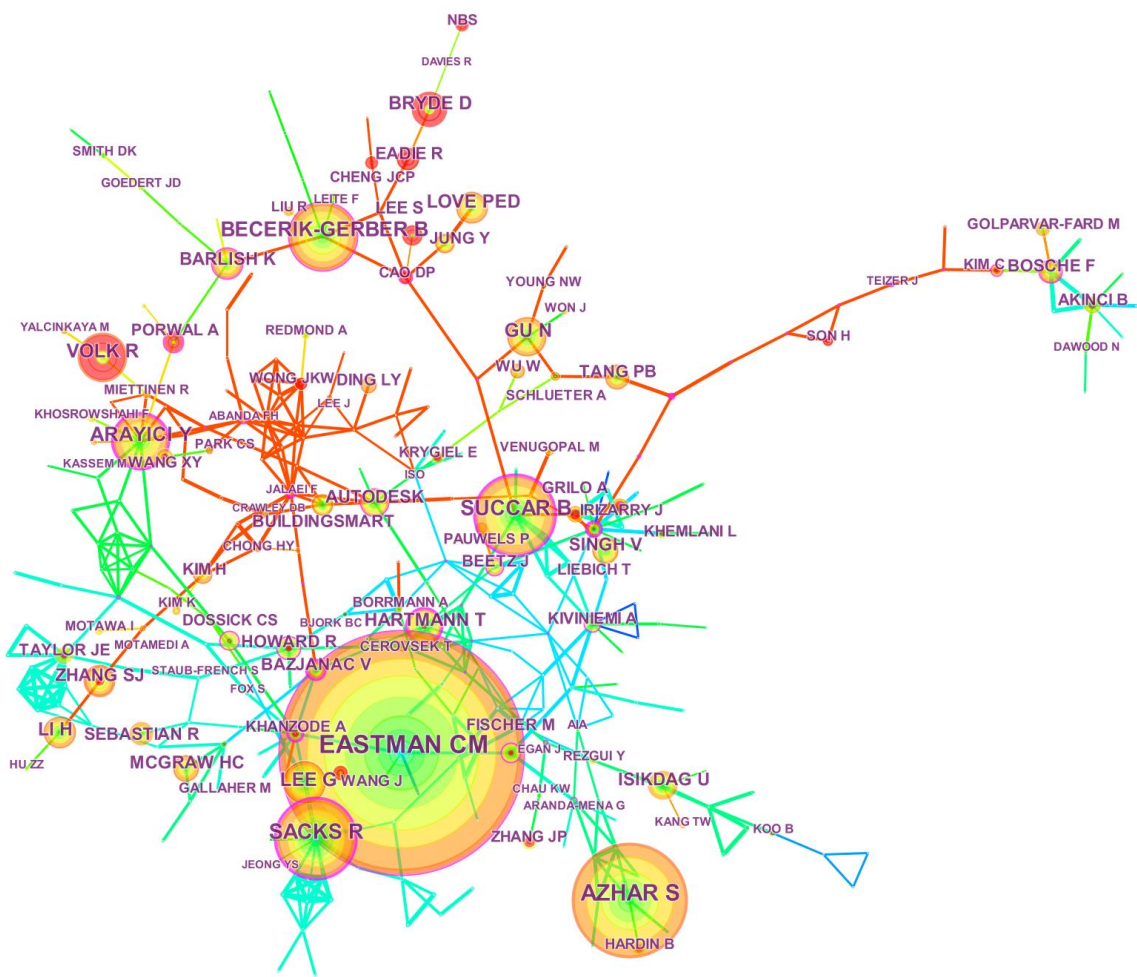513   that of the previous map.

514

515   **Figure.11:** Author co-citation network

516   Seen from the figure, the top 10 authors were Charles M. Eastman (frequency = 621, USA),
517   Salman Azhar (frequency = 300, USA), Rafael Sacks (frequency = 212, Israel), Bilal Succar (frequency
518   = 208, Australia), Burcin Becerik-Gerber (frequency = 184, USA), Yusuf Arayici (frequency = 145,
519   Turkey), Rebekka Volk (frequency = 127, Germany), Ghang Lee (frequency = 125, South Korea), Ning
520   Gu (frequency = 115, Australia), and Heng Li (frequency = 100, Hong Kong). The diversity of the most
521   cited authors' locations indicates that BIM research has been widely carried out around the world.

522   Authors with high betweenness centrality were also identified with purple rings. The nodes with
523   purple rings means that the authors enjoy high betweenness centrality, representative authors of
524   which are Arayici Y (centrality = 0.25), Succar B. (centrality = 0.24), Sacks R (centrality = 0.23), etc.
525   They are the main intellectual drivers of BIM research and interrelated research in different research
526   groups.

527   Several authors have experienced citation burst with the frequency of citations increasing
528   rapidly in a short period of time. According to citation burst strength, the top five authors are Michael
529   P. Gallaher (burst strength = 10.8136, 2009-2014), Lachmi Khemlani (burst strength = 10.59 2009-2013),
530   Kiviniemi Arto (burst strength = 10.26,2007-2012), Bo-Christer Björk (burst strength = 8.27, 2009-2012)
531   and Bonsang Koo (burst strength = 7.86, 2009-2014). These authors may usually affect the direction of
532   BIM research, thus their articles are worthy of paying attention to.

533

4.3.3 Document co-citation network

535   Document co-citation analysis can be used to analyze the underlying structure of a knowledge
536 field and show the number and authority of citations. During the analysis of this document co-
537 citation, the co-citation clusters were also confirmed by CiteSpace. The document co-citation network
538 is shown in **Figure.12**, with 394 nodes and 851 links. Each node represents a document and is marked
539 with the name of the first author and the year of publication. Each link represents the co-citation
540 relationship between two corresponding documents. The node size shows the co-citation frequency
541 of documents. Documents with high betweenness centrality and citation burst were highlighted by
542 purple rings and red rings, respectively.

543

544
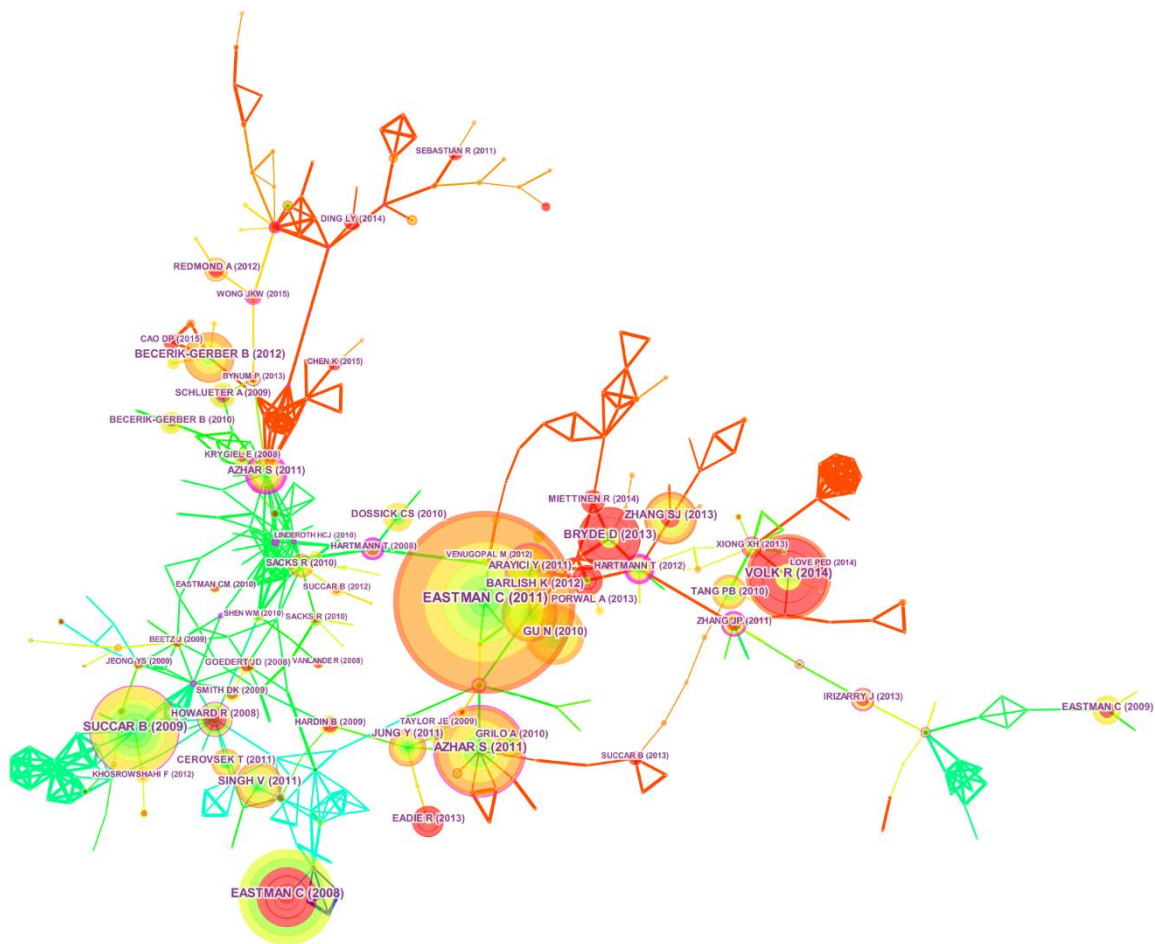
545   **Figure.12:** Document co-citation network

546

547   As shown in **Figure.12**, the 2011 and 2008 versions of BIM Handbook [22][45] published by
548 Charles M. Eastman et al. received 266 and 143 co-citations, respectively, followed by 134 co-citations
549 of Salman Azhar [2], 130 co-citations of Bilal Succar[24] and 129 co-citations of Rebekka Volk[25].
550 These articles are worthy of paying attention to. Representative documents with high betweenness
551 centrality were Arayici Y et al. [26](centrality = 0.52), Timo Hartmann et al. [27] (centrality = 0.49),
552 Salman Azhar[28] (centrality = 0.46), Timo Hartmann et al. [29](centrality = 0.46) and Stefan Boddy et
553 al. [29](centrality = 0.40).

554   A number of documents have received citation bursts, of which the representative ones include
555   Charles M. Eastman   (burst strength = 19.65, 2009-2015), Rob Howard et al.[30] (burst strength =
556   9.78,2010-2015), Timo Hartmannt [27] (burst strength = 7.86, 2011-2015), Rafeal Sacks et al. [31] (burst
557   strength = 6.92, 2006-2012) and Rafael Sacks [32] (Burst Strength = 6.55, 2012-2014), which indicates
558   that there was a significant increase in the number of citations of these documents over a short period
559   of time in the corresponding years.

560   **5. A revolution in global BIM research**

561   BIM is a revolutionary technological development that is rapidly reshaping the AEC industry
562   and transforming the way we build. This aim of this section is to identify the significant co-citation
563   clusters to determine the key or anchor representative research and categorize the global BIM
564   research over the past 16 years into 3 stages, namely: infancy stage, maturity stage and expansion
565   stage.

566   As the core and essence of articles, keywords could be used as proxies to summarize research
567   hotspots in terms of directions and topics[33]. A significant feature and function of CiteSpace is to
568   probe and identify the research hotspots in related fields through the analysis of keyword
569   frequencies[33].There are three cluster analysis algorithms in CiteSpace, namely, latent semantic
570   indexing (LSI), loglikelihood ratio (LLR) and mutual information (MI). In this study, LLR algorithm
571   was used to select the optimal cluster label according to uniqueness and coverage, which was also
572   recommended by Chen Chaomei [34].

573   Based on the keywords of the documents cited in each cluster, a total of 12 significant co-citation
574   clusters were identified, as illustrated in **Figure.13**. There were 40 members in#0 "building
575   information model", which was the largest. The number in cluster #11 "total construction as-built
576   documentation" was the smallest, with only 5 members.

577

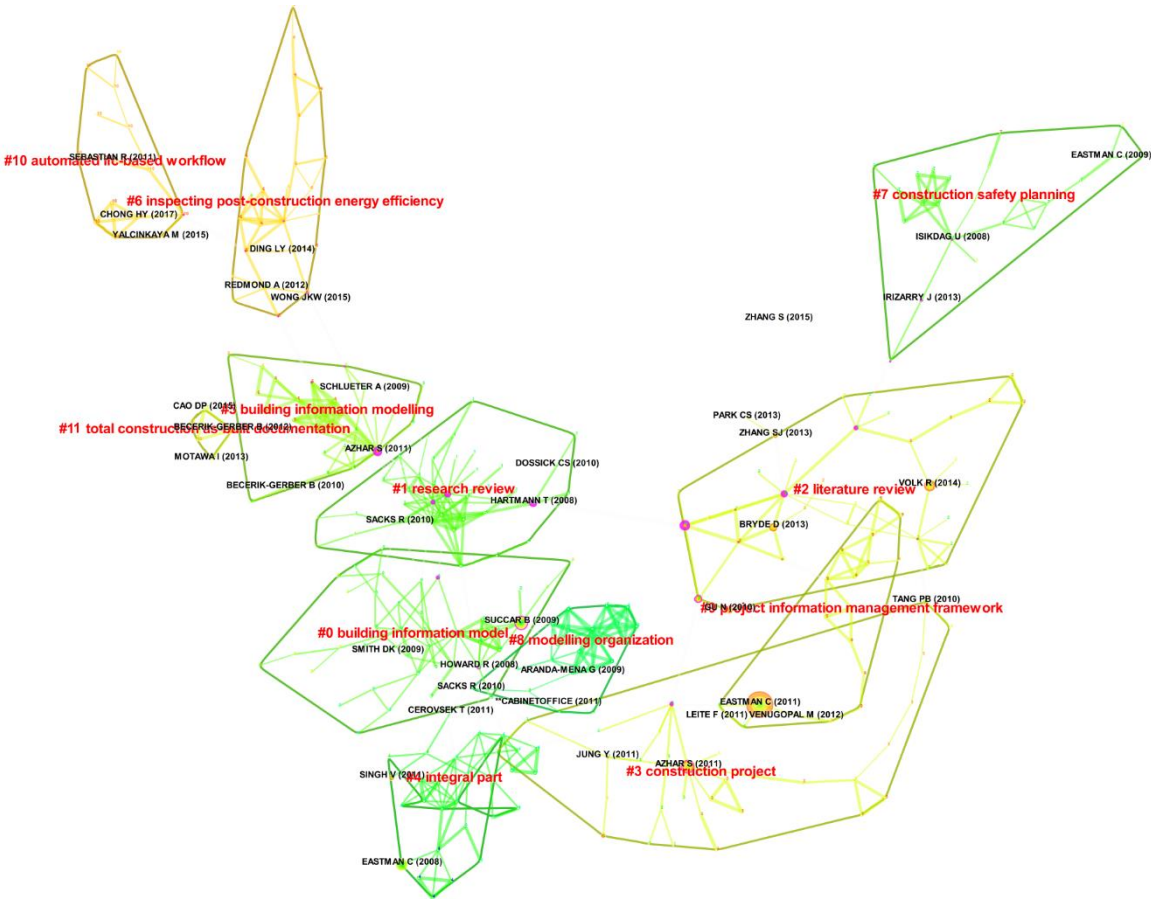578   **Figure.13:** Document co-citation network- Clusters analysis

579

580   The top three representative articles in each cluster were also shown in **Figure.13**, for instance,
581 In Cluster#7 Construction safety planning, the top three representative articles were Chuck Eastman
582 et al. [35], Javier Irizarry et al. [36] and Umit Isikdag et al. [37].Alternative tags with the second and
583 third highest LLR scores were also shown in **Table.8**, clusters of which were sorted by size (i.e. the
584 number of documents/members).

585   Sihouette metric in clusters was used to measure the average homogeneity of the clusters. A high
586 silhouette score indicates high consistency of cluster members in clusters of similar sizes. The score
587 range of the above 11 clusters was between 0.858 and 0.996, suggesting high consistency of members
588 in each cluster. Mean year of publications suggests whether the cluster consists of the latest published
589 documents or the old ones, through which it can be found that Cluster #4 "integral part" consists of
590 old documents, while Cluster #6 and #10 consist of new documents. In addition, representative
591 documents of each cluster refer to the top three documents with most co-citation frequency in a
592 cluster. These representative documents have a profound impact on the label of the cluster, which is
593 worthy of paying attention to.

594   **Table.8:** Co-citation clusters of BIM research in 2004 - 2019

Cluster ID	Size	Silhouette	Mean (Year)	Cluster Label (LLR)	1st Alternative Label	2nd Alternative Label	Representative documents
#0	40	0.858	2008	building information model	multi-standpoint framework	technological development	Succar Bilal [24] Rob Howard et al [30] James D.Goedert et al [38] Dana K. Smith et al[39]
#1	36	0.94	2008	research review	symphony	digital construction design	Carrie S. Dossick et al [40] Rafael Sacks et al[41] Timo Hartmann et al [27]
#2	33	0.913	2012	literature review	project information management framework	automated monitoring	Rebekka Volk et al [25] David Bryde et al [42] Ning Gu et al [43]
#3	31	0.88	2012	construction project	project information management framework	operational critical success factor	Salman Azhar et al [44] Youngsoo Jung et al [45] Pingbo Tang et al [46]
#4	28	0.945	2006	integral part	civil engineering education	teaching building information modeling	Chuck Eastman et al[47] Vishal Singh et al [48] Tomo Cerovsek [49]
#5	27	0.912	2012	building information modelling	green building	project information management framework	Salman Azhar et al[50] Arno Schlueter et al [51] Burcin Becerik-Gerber et al [52]
#6	24	0.934	2015	inspecting post-construction	Life cycle assessment	environmental potential	Alan Redmond et al [53] Johnny

				energy efficiency			Lieyun Ding et al [54]
							Kwok Wai Wong et al [55]
#7	23	0.969	2008	construction safety planning	geographic information system	space conflict	Chuck Eastman et al [35]
							Javier Irizarry et al [36]
							Umit Isikdag et al [37]
							Rafael Sacks [56]
#8	21	0.924	2008	modelling organization	structural adjustment	pilot study	Cabinet Office [57]
							Guillermo Aranda-Mena et al [58]
#9	18	0.982	2014	project information management framework	construction project	building information modelling	Chuck Eastman et al[47]
							M. Venugopal et al [23]
							Jim Steel et al [59]
							Rizal Sebastian[60]
#10	14	0.985	2015	automated ifc-based workflow	diagnosis approach	auto-deployed model-based fault detection	Mehmet Yalcinkaya et al[61]
							Heap-Yih Chong et al [62]
							Burcin Becerik-Gerber et al [63]
#11	5	0.99	2014	total construction as-built documentation	lift planning	benefit sharing	Dongping Cao et al [64]
							Ibrahim Motawa et al [65]

Note: rows for clusters #0, #1, #2, #3, #4 and #9 are classified to the formulating stage; rows for clusters #5 ,#6, #7 and #8, to the accelerating stage, and clusters #10 and # 11 to the transforming stage.

5.1 Evolution of global BIM research

Clustering is essentially, the grouping of a set of objects in such a way that objects in the same group, herein called a cluster, are more similar in traits or features to each other than to those in other groups. It is an iterative process of knowledge discovery, or interactive multi-objective optimization that involves trial and error. There are a handful types of clustering, such as strict partitioning clustering, strict partitioning clustering with outliers, hierarchical clustering, overlapping clustering and subspace clustering. Strict partitioning clustering with outliers, which is a type of hard clustering is adopted in this section of our study. These clusters, which are formed based on document co-citation, and namely the formulating stage, accelerating stage and transforming stage, are distinguished by the cluster labels of global BIM research. The cluster labels are used as a proxy to determine the diffusion of innovation or technology adoption stage. For cluster #0,1,2,3,4 and 9, it can be inferred that the research has been expanded and translated to industry practice, ; for cluster #5,6,7and 8, it can be inferred that the research direction is at the accelerate stage, suggested by early to early majority adoption of the knowledge or technology; for cluster #10 and 11, it can be inferred that the research thrust for that cluster is innovative and at a nascent, transforming stage, as illustrated in **Figure.14**.
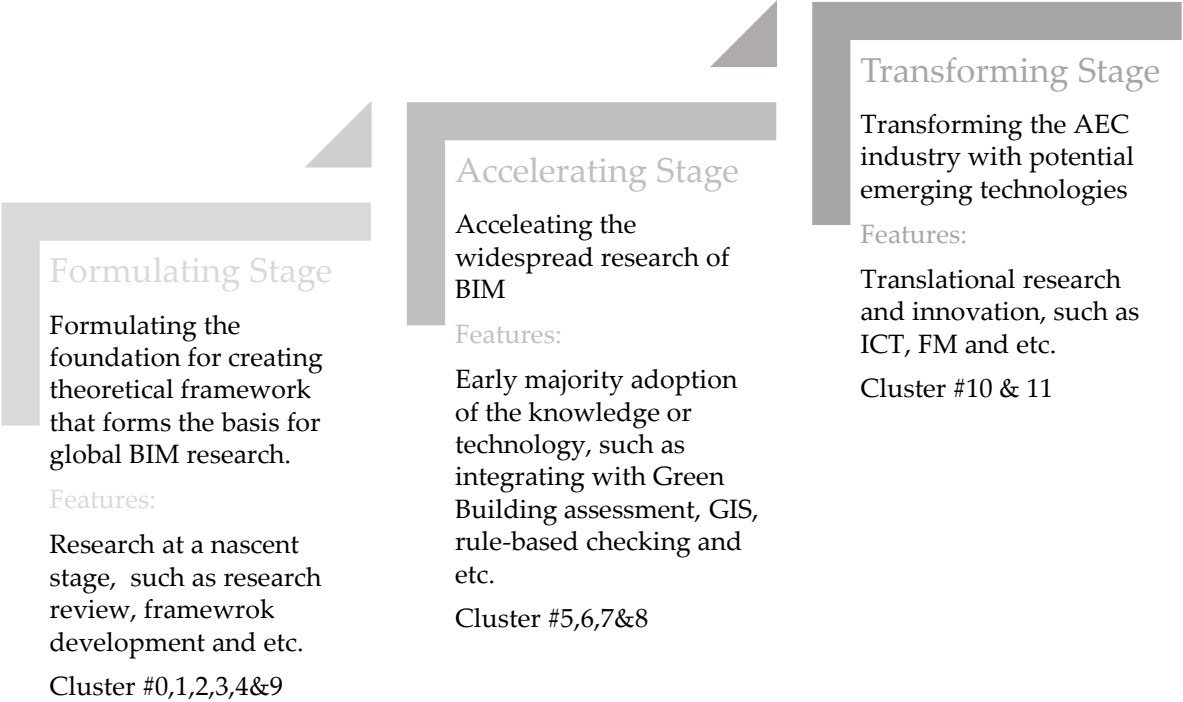
Transforming Stage

Transforming the AEC industry with potential emerging technologies

Features:

Translational research and innovation, such as ICT, FM and etc.

Cluster #10 & 11

Accelerating Stage

Acceleating the widespread research of BIM

Features:

Early majority adoption of the knowledge or technology, such as integrating with Green Building assessment, GIS, rule-based checking and etc.

Cluster #5,6,7&8

Formulating Stage

Formulating the foundation for creating theoretical framework that forms the basis for global BIM research.

Features:

Research at a nascent stage, such as research review, framewrok development and etc.

Cluster #0,1,2,3,4&9

Figure.14: Evolution of global BIM research

5.2 Formulating stage

Formulating stage means formulate the foundation for creating theoretical framework that forms the basis for global BIM research. At this stage, research themes are summarized in the following aspects: 1) Research review in BIM; 2) Conceptual BIM framework; and; 3) Building BIM capability.

5.2.1 Formulating stage – Research Review

There were 40 members in Cluster #1 "Research Review". The top three representative articles were published by Carrie S. Dossick [40], Rafael Sacks [41] and Timo Hartmann [27], all of which were published on the "Journal of Construction Engineering and Management". Carrie S. Dossick et al. [40] (frequency = 46) reviewed related work on what caused successful technology adoption both in the AEC industry and in general. The application of BIM technology in MEP coordination as well as how the cooperation and communication are affected by introduction of BIM were also studied by them. Their findings show that the BIM-enable projects are often technically coupled but with organizational differences. It also suggests that organization power and structure should be considered for the successful performance of BIM. Rafael Sacks et al. [41] (frequency = 39) reviewed different concepts and BIM of lean construction in the life cycle of the whole projects. On this basis, an analytical framework or classification was established to evaluate the interrelationship between lean construction and BIM. Timo Hartmann et al. [27] (frequency = 27) qualitatively summarized and reviewed the results of 26 case studies applying 3D/4D models to construction projects, showing researchers and practitioners the challenges of applying 3D/4D model to projects. The challenges faced by 3D/4D models in test cases by practitioners were elaborated by them as well. The main analytical results show that project practitioners in most of the test cases use the model only in one application domain. In this article, it suggests that further research is needed on how to integrate 3D/4D model technology into the work and business processes conducted by project teams, thereby making wider use of the 3D/4D models throughout the life cycle of the project.

640   There were 33 members in Cluster #2 "literature review". The top three representative articles
641 were published by Rebekka Volk [25], David Bryde [42] and Ning Gu [43]. Rebekka Volk et al. [25]
642 (frequency = 27) reviewed more than 180 articles on BIM for existing buildings. The results show that
643 the lack of implementation of BIM for existing buildings is caused by the following factors: (1) high
644 modeling/transformation efforts from captured building data to semantic BIM objects, (2) the
645 information update in BIM, (3) handling of uncertain data, objects and relationships in BIM of existing
646 buildings. David Bryde et al.   [42] carried out literature review on BIM, collected information of 35
647 building projects using BIM, and explored the benefit degree of BIM application to a cross-section of
648 the construction projects. The study also provided a set of criteria for project success, using analysis
649 to determine the degree of compliance of each project to the criteria. The study also pointed out that
650 the most frequently reported benefits were related to cost reduction and control in the life cycle of
651 projects, and that negative benefits were mainly concentrated on the use of BIM software.
652 Cost/benefit analysis, awareness improvement, education and training are key responses to the
653 challenge of BIM use. Ning Gu et al. [43] (frequency = 90) did a literature review for BIM-related
654 academic publications, white paper, technical reports from major technology providers, guidelines,
655 online newsletters and government reports. They analyzed the present situation of BIM in the AEC
656 industry and reevaluated its role and potential contribution in the future. This paper analyzes the
657 preparation in (1) products, (2) processes and (3) personnel in the industry in order to locate the
658 adoption of BIM according to the cross-domain status quo and expectation. Through the study of this
659 paper, it suggests that there are many factors that may affect the adoption of BIM, of which the
660 functional requirements of technical tools and non-technical strategic issues are two primary factors.

661   Observation 1: At formulating stage, many authors conduct research review in BIM, theoretical
662 exploration of BIM origins, foundations, relevant theories and emerging scenarios to lay the
663 foundation of the BIM development, such as Cluster #1 and Cluster #2.

664 *5.2.2Formulating stage – Conceptual BIM framework*

665   There were 36 members in Cluster #0 "Building Information Model". The top three
666 representative articles were published by Succar Bilal [24], Rob Howard [30] and James D. Goedert
667 [38] and Dana K. Smith [39]. Succar Bilal [24] (frequency = 130) explored a number of open BIM
668 international guidelines and developed the BIM framework. Rob Howard et al. [30]   (frequency =
669 51) discussed BIM and IFC and proposed a framework for a preliminary outline that should be
670 developed into a precise tool with the function of case comparison. James D. Goedert et al. [38]
671 (frequency = 29) created a 3D completion model and a 4D completion model, and they attached
672 construction process information to the models so that the owners can use them after construction.
673 The research results show that BIM program and software need to be modified in order to obtain the
674 construction process documents. Dana K. Smith et al. [39]   (frequency = 29) published a book based
675 on strategic thinking which could help readers to understand the whole situation and refine the BIM
676 workflow, thus showing the potential of BIM construction by all participants in the industry.

677   There were 31 members in Cluster #3 "Construction Project". The top three representative articles
678 were published by Salman Azhar [44], Youngsoo Jung [45] and Pingbo Tang [46]. Salman Azhar et
679 al. [44] (frequency = 134) mentioned that BIM could simulate construction project in a virtual
680 environment. The prospect of BIM was also discussed by them, showing that the future of BIM was
681 exciting and challenging. It was expected that an increasing number of BIM applications may help to
682 strengthen the collaboration of AEC industry, reduce fragmentation, ultimately improve
683 performance and reduce project costs. Youngsoo Jung et al. [45] (frequency = 59) proposed a
684 comprehensive BIM framework to evaluate promising areas and to identify driving factors for
685 practical applications in real-world construction projects. Pingbo Tang et al.   [46] (frequency = 54)
686 presented an approach that can be used to automately create the process of as-built BIMs for
687 construction projects.

688 Cluster #9 "Project Information Management Framework" contained 18 members. The top three
689 representative articles were published by Charles M. Eastman [47], M. Venugopal [23], Jim Steel [59].
690 Charles M. Eastman et al. [47] (frequency = 266) published the 2nd Edition, 2011 version of BIM
691 Handbook. M. Venugopal et al.   [23] (frequency = 21) proposed to use model view definition (MVD)
692 concept as an object-oriented and modular mechanism, so as to embed semantic meaning in model
693 views. The conclusion of the paper is that Industry Foundation Classes (IFC) model lacks a formal
694 definition of entities, attributes and relationships despite of the rich expression of the IFC product
695 model. It suggests that the modularization and logical framework of formal specifications based on
696 IFC concepts should be further studied to achieve standardized and reusable model views. Jim Steel
697 et al. [59](frequency = 14) presented experiences with issues of model-based interoperability in
698 exchanging building information models between various tools, particularly using the industry
699 standard IFC data modelling format. Fernanda Leite et al. [66](frequency=14) evaluated the modeling
700 work related to different levels of detail generation in BIM and the role levels of development (LoD)
701 played in supporting the design coordination of mechanical, electricity and plumbing (MEP). The
702 results show that the total modeling time from one LoD to another increases, from doubling of the
703 modeling work to 11 times of folding. The research shows that additional modeling work can
704 contribute to more comprehensive analysis and better decision support in the process of design and
705 construction.

706 Observation 2: Conceptual BIM framework, to develop BIM framework to satisfy the niche BIM-
707 based application

708 *5.2.3 Formulating stage – Building BIM capability*

709 There were 28 members in Cluster #4 "Integral Part", 1st alternative label "Civil engineering
710 education" and 2nd alternative label "Teaching Building Information Modeling" The top three
711 representative articles were published by Charles M. Eastman [47], Vishal Singh [48] and Tomo
712 Cerovsek [49]. Charles M. Eastman et al. [47] (frequency = 143) published a BIM Handbook (2008)
713 which brought together information about current BIM, history and potential future in a convenient
714 location. It can be used as a convenient reference book or a technical support for buildings involved
715 in design, construction and operation. Vishal Singh et al. [48] (frequency = 73) developed a BIM-server
716 based multi-disciplinary integrated collaboration platform. Tomo Cerovsek [49] (frequency = 45)
717 proposed an improved method, framework and schemata of integrated BIM tools and patterns
718 through the critical review of Building product modelling, including the development of
719 communication standards and the characteristics of more than 150 AEC/O (building, engineering,
720 construction and operations) tools and digital models.

721 Observation 3: Building BIM capability, by developing educational curriculum structure around
722 BIMs use-case, such as Cluster 4.

723 *5.3 Accelerating stage*

724 The theoretical foundation developed under formulating stage forms the knowledge based for
725 BIM research during the accelerating stage. Accelerating stage means accelerating the widespread
726 research of BIM and kicking-start the transition from traditional 2D based workflow to an object-
727 orientated workflow. At this stage, research focuses on the integration of BIM and other related
728 technologies such as GIS, energy calculation, rule-based checking and the development of BIM
729 application.

730 There were 27 members in Cluster #5 "building information modelling". The first three
731 representative articles were published by Salman Azhar [50] , Arno Schlueter [51] and Burcin Becerik-
732 Gerber [52]. Salman Azhar et al. [50] (frequency = 56) demonstrated the application of BIM in
733 sustainable design and LEED® certification with real cases. The results of this study show that the
734 documents supporting LEED credits can be compiled directly or indirectly using the results of BIM-
735 based sustainable analysis software. Compared with traditional methods, this process simplifies the

LEED® certification process and saves a lot of time and resources. Arno Schlueter et al. [51] (frequency = 39) developed a BIM-based prototypical tool to support graphical visualization of instantaneous energy, energy calculations and result performance metrics. Burcin Becerik-Gerber et al.[52] (frequency = 36) reviewed extensive cases and provided an anecdotal evidence to support the view that the use of BIM could make the construction process more efficient. They also presented the results of an industry-wide online survey. The aim of their study was to understand the perceived value of BIM in the American construction industry, with particular attention paid to the actual benefits and costs associated with the use of BIM at the project level.

There were 24 members in Cluster #6 "inspecting post-construction energy efficiency". The top three representative articles were published by Alan Redmond [53], Lieyun Ding [54] and Johnny Kwok Wai Wong [55]. Alan Redmond et al. [53] (frequency = 36) put forward an integrated platform of cloud BIM using the cloud calculation as BIM application based on the semi-structured interview for 11 expert interviewees. The platform also includes applications like energy performance analysis, which was designed to identify the energy use and energy needs of HVAC partitions in the early design phase as well as BIM applications, so as to take advantage of the corresponding 3D, 4D, and 5D features. Lieyun Ding et al.[54] (frequency = 27) developed a BIM application framework to outline BIM applications in the construction industry, such as project quality, safety and environmental management. The expansion process from 3D to computable nD model, especially the method of integrating safety, quality and carbon emission variables into BIM was described and analyzed as well. Johnny Kwok Wai Wong et al. [55] (Frequency=23) reviewed and compared 84 Green-BIM-related documents, of which 44 were in the design stage, 25 in the construction stage, 8 in the maintenance and retrofitting stage and 12 in the demolition stage. The authors also suggested that the use of "one-stop" BIM technology should be promoted for environmental sustainability monitoring and management throughout the life cycle of buildings in future studies. Meanwhile, the use of cloud-based BIM technology should be considered, thereby using "big data" to manage the sustainability of buildings.

There were 23 members in Cluster #7 "construction safety planning". The top three representative articles were published by Charles M. Eastman [35] , Javier Irizarry [36] and Umit Isikdag [37]. Charles M. Eastman et al. [35] (frequency = 46) explored a rule checking system which evaluated architectural design according to different criteria, such as Building code and construction safety. It also mentioned that the rule-based checking system was still in an early stage. Javier Irizarry et al. [36] (frequency = 34) integrated BIM and geographic information system (GIS) into a unique system that tracked the status of the supply chain and provided early warning signals to ensure the delivery of materials. The study of Umit Isikdag et al. [37]   (frequency = 13) showed that high-level geometric and semantic information obtained from BIMs can be transferred to the geospatial environment, results of which also suggest that sufficient level and quantity of geometric and semantic information related to buildings are provided by BIMs to achieve seamless automation of data management tasks in the process of location selection and fire response management.

There were 21 members in Cluster #8 "modelling organization". The first three representative articles were published by Rafael Sacks [56], Cabinet Office [57] and Guillermo Aranda-Mena [58]. Rafael Sacks [56] (frequency = 16) carried out an experimental study on BIM and product data exchange in the design and production of the building prefabricated facade. The study also showed that there are no restrictions on the use of existing software to design and refine prefabricated facade. The production of the same set of drawings shows a 57 percent increase in productivity compared to the CAD process. However, the data exchange between the building and the prefabricated engineering system is incomplete and inconsistent, which confirms the necessity of the BIM exchange standard. Current Industry Foundation Classes (IFC version 2x3) model lacks a predefined set of entities and attributes. Cabinet Office [57] (Frequency=11) is a government construction strategy published by the British government in an effort to improve the productivity and save costs in the construction industry. Guillermo Aranda-Mena et al. [58] (frequency = 10) investigated 47 value propositions using BIM through several case studies in Australia and Hong Kong. The focus of the paper was

787 designed on the challenges and benefits for architectural and engineering consultants. In addition,
788 the findings were coded, interpreted and synthesized to identify the challenges and business drivers.
789 The authors also found that the shared understanding of BIM application on business drivers ranged
790 from commercial to high-rise building projects, especially for managing the process of design and
791 construction.

792   Observation 4: At this stage, research on BIM application was revolutionized to incorporated
793 with other technologies such as energy calculation, GIS and rule-based checking.

794 *5.4 Transforming stage*

795   Transforming the AEC industry with protential emerging technologies and getting the
796 stakeholders to use BIM extensively in a streamlined and integrated manner over the building life
797 cycle.

798   There were 14 members in Cluster #10 "automated IFC-based workflow". The top three
799 representative articles were published by Rizal Sebastian [60], Mehmet Yalcinkaya [61] and Heap-
800 Yih Chong [62]. Rizal Sebastian [60] (frequency = 21) proposed five success factors known as
801 "POWER" for integrated collaborative application of BIM based on literature analysis, previous
802 researches and case studies, including: (1) Product information sharing (P), (2) Organisational roles
803 synergy (O), (3) Work processes coordination (W), (4) Environment for teamwork (E) and (5)
804 Reference data consolidation (R). It is also conducive to actually discussing the changes in the roles
805 and processes needed for developing and operating sustainable buildings with the support of
806 integrated ICT framework and tools in science and practice. Mehmet Yalcinkaya et al. [61] (frequency
807 = 17) drew some clear conclusions through the comprehensive annotation of a large number of BIM
808 research literature published from 2004 to 2014. Latent semantic analysis (LSA) was used to analyze
809 the abstracts of 975 academic papers objectively, through which, 12 main research fields were
810 revealed. Various specific research topics related to each of the main areas have been identified. These
811 main research fields and research subjects have reflected the model and trend of BIM research. Heap-
812 Yih Chong et al. [62] (frequency = 16) analyzed the BIM standards, guidelines and peer- reviewed
813 academic publications through retrospective review. The results show that there has been a lot of
814 researches and development in the use of BIM in different stages, but few in refurbishment and
815 demolition, which also reveals some significant insights, including (1) new BIM tools are needed for
816 evaluation of the sustainability criteria, (2) the interoperability between BIM software and energy
817 consumption analysis tools needs to be improved, (3) streamlining the BIM usage into refurbishment
818 and demolition is required, and (4) there is a need for an innovative procurement system to make the
819 society sustainably compliant with the project.

820   There were 5 members in Cluster #11 "total construction as-built documentation". The top three
821 representative articles were published by Burcin Becerik-Gerber [63], Dongping Cao [64] and Ibrahim
822 Motawa[65]. Burcin Becerik-Gerber et al. [63] (frequency = 77) explored how BIM can be a useful
823 platform to complement FM practices. Through online survey and face-to-face interview, the
824 application status, potential application prospect and people's interest in application of BIM in FM
825 were evaluated. The interaction between BIM and FM was defined by illustrating application areas
826 and data requirements for FM practices that support BIM. The synergistic effect between the two
827 aspects is emphasized in this paper to help professionals to identify potential areas where BIM may
828 be useful in FM practice. Dongping Cao et al. [64] (frequency = 27) analyzed the current BIM practice
829 in China and evaluated how such practices change their effectiveness based on the investigation of
830 106 projects using BIM. The results also prove that the project characteristics have a significant impact
831 on the success of BIM use. However, the more important factors affecting the effectiveness of BIM
832 are the degree of comprehensive use and customer/owner support. The results show that the current
833 BIM practice involves both technical and organizational issues which also provides a reference for
834 developing the potential of BIM in the industry. Ibrahim Motawa et al. [65] (frequency=19) developed
835 a knowledge-based BIM system for building maintenance, so that maintenance teams can learn from

836 past experience and trace the complete history of building elements and all affected elements through
837 previous maintenance operations. The results show that the knowledge-based BIM integrated system
838 can provide advanced and useful functions for construction operations. On the other hand, the
839 knowledge management principle embedded in the system is combined with the information
840 management principle embedded in the BIM system, which suggests a direction for the transition
841 from "building information modelling" to "Building Knowledge Modelling".

842 Observation 5: At the transforming stage, research on BIM application was revolutionized to
843 integrated with emerging technologies, such as ICT, FM and etc.

844 *5.4 Co -Research direction and policy implication*

845 Reflecting on the research in the previous three stage, various government and national bodies
846 across globe started to formulate the national BIM implementation polices and strategies to ease BIM
847 adoption such as evolution of BIM policy in Singapore from BIM to Virtual Design Construction
848 (VDC) and to Integrated Digital Delivery (IDD). In Singapore, Building and Construction Authority
849 (BCA) is the driving agency for BIM, VDC and and IDD adoption. In Nov 2010, the 1st BIM roadmap
850 was formulated to steer the construction industry leverage on BIM technology as a mean to enable
851 building professional to deliver their building in more sustainable and effective manner. BIM was
852 identified as one of the key drivers to improve productivity and integration across various
853 disciplines. The 1st BIM roadmap aimed to realize the version of a highly integrated and
854 technologically advanced construction sector by 2020. In 2015, The 2nd Roadmap was rolled out with
855 the goal of catalyzing the construction industry to extensively use BIM in a streamlined project
856 delivery process and integrated work environment over the building lifecycle. The 2nd BIM roadmap
857 focused on the following 5 key strategies, as illustrated in **Figure.15**. Building on the momentum of
858 the previous two Roadmaps, BCA come out the IDD plan to enlarging the digitalization and
859 transforming the AEC industry with potential emerging technologies in year 2017. IDD aims to
860 achieve timely, cost effectively, productive and high-quality project delivery through 4 stages,
861 namely, design, manufacturing, fabrication and asset delivery. This made possible with the help of
862 BIM, VDC and suitable digital solutions to convey relevant, accurate and timely digital information
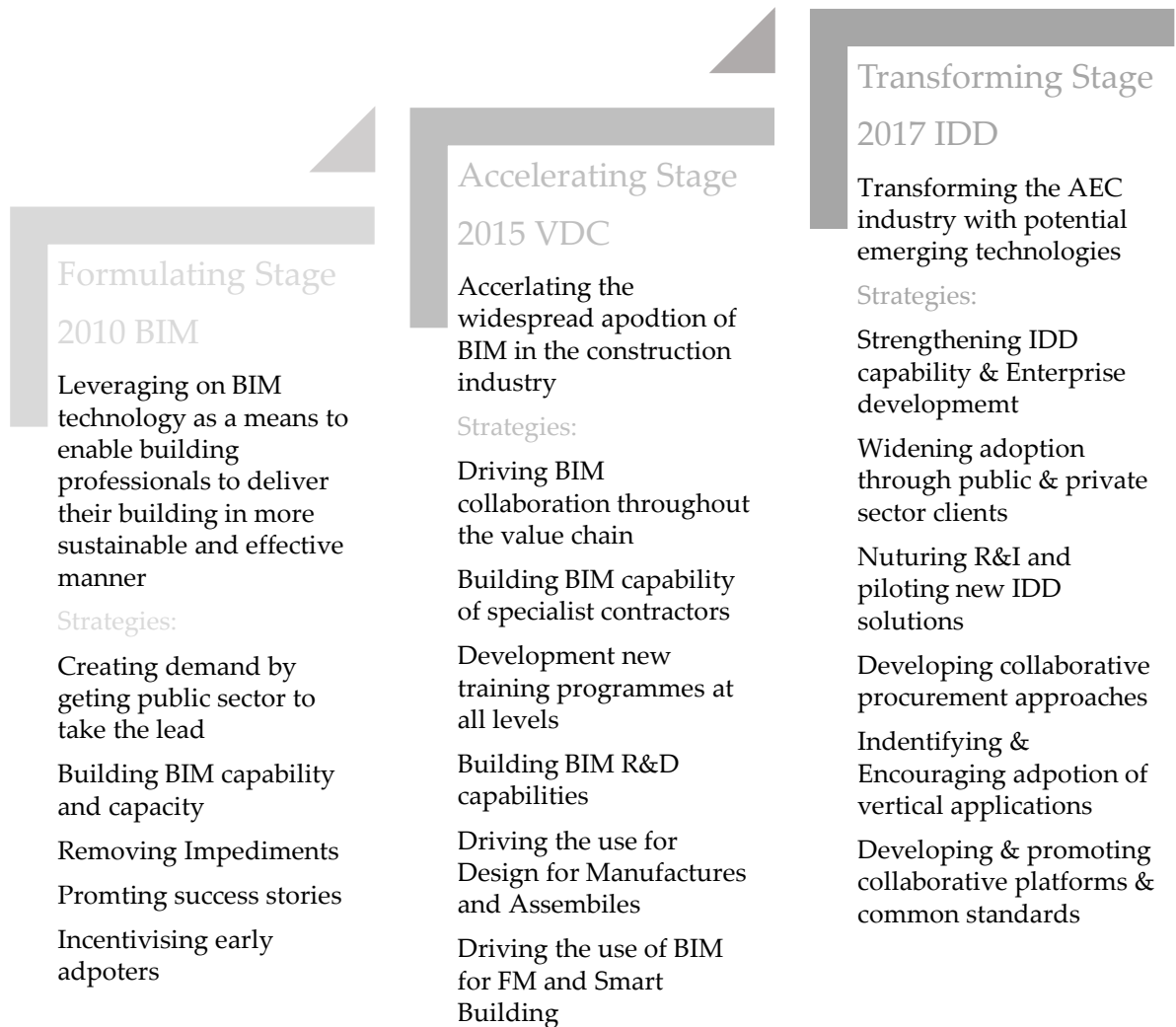863 across the whole life cycle.

864

Formulating Stage
2010 BIM

Leveraging on BIM technology as a means to enable building professionals to deliver their building in more sustainable and effective manner

Strategies:

Creating demand by geting public sector to take the lead

Building BIM capability and capacity

Removing Impediments

Promting success stories

Incentivising early adpoters

Accelerating Stage
2015 VDC

Accerlating the widespread apodtion of BIM in the construction industry

Strategies:

Driving BIM collaboration throughout the value chain

Building BIM capability of specialist contractors

Development new training programmes at all levels

Building BIM R&D capabilities

Driving the use for Design for Manufactures and Assembiles

Driving the use of BIM for FM and Smart Building

Transforming Stage
2017 IDD

Transforming the AEC industry with potential emerging technologies

Strategies:

Strengthening IDD capability & Enterprise developmemt

Widening adoption through public & private sector clients

Nuturing R&I and piloting new IDD solutions

Developing collaborative procurement approaches

Indentifying & Encouraging adpotion of vertical applications

Developing & promoting collaborative platforms & common standards

865

866   **Figure.15:** Evolution of BIM policy in Singapore

867

868   Observed from **Figure 15** and **Figure 14** , there is a co-production relationship between evolution
869   of BIM policy and global BIM research, both go through three stages, formulating stage, accelerating
870   stage and transforming stage.

871   **6. Conclusions and prospects**

872   In the recent decade, the research in the field of BIM has been developing continuously, which
873   has completely subverted the traditional operation mode of AEC industry and attracted more and
874   more researchers' attention at the same time. An overall, systematic and comprehensive qualitative
875   and quantitative review of the existing global research status of BIM was given through the
876   application of scientific metrology technology in this paper, in an effort to explore the global trend of
877   BIM research. After removing duplicate literature in the core database of WoS, a total of 1,455 BIM
878   records were obtained from bibliographic records. CiteSpace version 5.3.R4 was used to perform co-
879   authorship network analysis (authors, research institutes and countries), co-occurring network
880   analysis (keywords and categories) and co-citation network analysis (authors, journals and
881   documents), so as to identify and visualize the status quo and trend of BIM.

Through the quantitative and qualitative analysis of global BIM research, the contributions and influence of main researchers were identified. In the field of BIM research, Xiangyu Wang, Rafael Sacks and Jack C.P. Cheng were the top three productive authors, while Charles M. Eastman, Salman Azhar and Rafael Sacks were the top three authors with high frequency of citations. In terms of the distribution of journal articles, most of the BIM articles sourced from the United States, China and the United Kingdom. In addition, Curtin University, Georgia Institute of Technology and Hong Kong Poly University were recognized as the most productive research institutes in the field of BIM. These countries and research institutes played an important role in linking research activities between different countries and institutes.

As for the classification of research disciplines, the number of published records of BIM was the most in the following three subjects, namely, Engineering, Engineering Civil and Construction & Building Technology. However, it's also worth mentioning that a large number of scholars have been attracted by subjects like Green & Sustainable Science and Technology in recent year. The high-frequency keywords include construction, design, system, management, model, framework, project, industry and performance. In BIM keyword analysis, the related high-frequency keywords include construction, design, system, management, model, framework, project, industry and performance. The frequency of BIM research co-citation journals is mainly concentrated in journals like Automation in construction, Journal of Information Technology in Construction, Journal of computing in civil engineering and etc. Over the past decade, the co-citation frequency and citation frequency of these journals was also very high, suggesting that they had a strong and sustained impact on BIM research.

This paper provided valuable information for researchers and practitioners by applying visualization technology to visualize the current situation in the research field of BIM. Key scholars, institutions, regions/countries and core articles were identified with the elaboration of the current situation of the research field and the hotspots of BIM research. In addition, it laid the knowledge foundation for the future research.

Data used for this paper was originated from the Web of Science Core Collection. There's certain limitations to the research data with the lack of integration with literature from other academic databases (e.g. EI retrieval and Scopus). Future research could consider to integrated with other academic databases.

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