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6 **Scientometric Analysis of BIM-based Research in Construction**

7 **Engineering and Management**

8 **Abstract**

9 **Purpose**

10 This study aims to summarize the latest research of BIM adoption in Construction
11 Engineering and Management (CEM) and propose research directions for future scholarly
12 work. During the recent decade, Building Information Modelling (BIM) has gained
13 increasing applications and research interest in the construction industry. Although there have
14 been review-based studies that summarized BIM-based research in the overall Architecture,
15 Engineering, and Construction (AEC) area, there is limited review that evaluates the current
16 stage of BIM-based research specifically in the Construction Engineering and Management
17 (CEM) sub-area.

18 **Design/methodology/approach**

19 CEM falls into the scope of AEC. It involves construction-related tasks, activities, and
20 processes (e.g., scheduling and cost estimates), issues (e.g. constructability), as well as
21 human factors (e.g. collaboration). This study adopted a holistic **literature review** approach
22 that incorporates bibliometric search and scientometric analysis. **A total of 276 articles**
23 **related to BIM applied in CEM were selected from Scopus as the literature sample for the**
24 **scientometric analysis.**

25 **Findings**

26 Some key CEM research areas (e.g. CEM pedagogy, integrated project delivery, lean,
27 and off-site construction) were identified and evaluated. Research trends in these areas were

28 identified, and analyses were carried out with regard to how they could be integrated with
29 BIM. For example, BIM, as a data repository for ACE facilities, has substantial potential to
30 be integrated with a variety of other digital technologies, project delivery methods, and
31 innovative construction techniques throughout the whole process of CEM.

32 **Practical implications**

33 As BIM is one of the key technologies and digital platforms to improve the construction
34 productivity and collaboration, it is important for industry practitioners to be updated of the
35 latest movement and progress of the academic research. The industry, academics, and
36 governmental authorities should work with joint effort to fill the gap by firstly recognizing
37 the current needs, limitations, and trends of applying BIM in the construction industry. For
38 example, it needs more understanding about how to address technical interoperability issues
39 and how to introduce the integrated design and construction delivery approach for BIM
40 implementation under the UK BIM Level 2/3 framework.

41 **Originality/value**

42 This study contributed to the body of knowledge in BIM by proposing a framework
43 leading to research directions including the differences of BIM effects between design-bid-
44 build and other fast-track project delivery methods; the integration of BIM with off-site
45 construction; and BIM pedagogy in CEM. It also addressed the need to investigate the
46 similarities and differences between academia and industry towards perceiving the movement
47 of BIM in construction field work.

48 **Keywords:** Building Information Modelling (BIM); Construction engineering and
49 management (CEM); Scientometric analysis; Literature review.

50 **1. Introduction**

51 Building Information Modeling (BIM), as an emerging digital technology in the global
52 Architecture, Engineering and Construction (AEC) industry, enables the creation of accurate

53 information models in a virtual computer environment and supports the **life cycle of a**
54 construction project (Eastman et al., 2011). BIM has been studied in multiple AEC subjects
55 or been linked to various AEC research topics, such as sustainable construction, project
56 management, and data interoperability (Santos et al., 2017). Existing studies in BIM could
57 involve either managerial or technical aspects (Yalcinkaya and Singh, 2015; Oraee et al.,
58 2017), especially in the subject of Construction Engineering and Management (CEM) which
59 generally covers multiple construction-related activities, tasks, processes, issues and human
60 factors such as cost estimate, scheduling, quality control, prefabrication, mass production,
61 constructability, sustainability, etc. In recent years, there have been some emerging
62 contemporary practices or issues in CEM, such as off-site construction, integrated project
63 delivery (IPD), and lean construction. Researchers (e.g., Sacks et al., 2009; Ma et al., 2017;
64 Zhong et al., 2017) have been working on establishing the connections between these
65 contemporary practices in CEM and BIM.

66 The limitations of some existing review-based studies in CEM(e.g., Ke et al., 2009; Tang
67 et al., 2010; Zou, et al., 2017; Martínez-Aires, et al., 2018) include the subjective judgements
68 or limited journals selected for literature search, which might cause biased findings (Song et
69 al., 2016; Hosseini et al., 2018). To reduce the subjectivity in literature review, several
70 studies (e.g., Zhao, 2017; Hosseini et al., 2018) introduced the scientometric analysis in
71 CEM-related review. **By adopting** the consistent scientometric approach, this study provided
72 a more in-depth discussion of existing research in CEM with references to BIM-based topics.

73 **Although there have been a number of recently published BIM-based review articles**
74 **(e.g., He et al., 2017; Oraee et al., 2017), very few of them have specifically focused on CEM.**
75 **BIM has been linked to multiple construction-related activities such as health, safety, and**
76 **risks (Zou et al., 2017). However, there has been insufficient overview of BIM-based studies**
77 **in CEM-related activities or practices. Existing review-based studies in BIM for AEC (e.g.,**

78 Zhao, 2017) are limited to scientometric analysis, without sufficiently engaging in-depth
79 discussions to reveal more implications such as the framework for future directions. Aiming
80 to fill these gaps, this study adopted a comprehensive review approach incorporating
81 scientometric analysis by targeting at the following objectives: 1) to identify the current
82 mainstream research topics within BIM-based studies in CEM; 2) to find out the most
83 influential journals and scholarly work in this domain; 3) to propose the research directions
84 for future work of applying BIM in CEM. This review work of BIM in CEM offers the
85 implications for both the academics and practitioners, specifically, how the understanding of
86 BIM-based research benefit the academic community and the practical field, as well as how
87 the findings from this study contribute to the body of knowledge in BIM for CEM.

88 **2. Background**

89 The movement of BIM within the AEC industry towards multi-stakeholder collaboration
90 and minimizing fragmentation requires the standardization and policy development
91 (Binesmael et al., 2018). For example, the BIM Task Group (2011), initiated by the UK
92 government was founded aiming to strengthen the public sector's capacity in BIM
93 implementation towards collaborative BIM towards BIM Level 2. BIM maturity levels (i.e.,
94 Level 0-3 and beyond) are described by the BIM Task Group (2011). For example, Level 2
95 BIM emphasizes the collaborative working by enabling information exchange among various
96 systems and project participants (Scottish Futures Trust, 2018). In recent years, BIM Level 3
97 has been in the agenda to come to practice by mid-2020s (Innovate UK and Infrastructure and
98 Projects Authority, 2017). Level 3 BIM has not been fully defined yet but aims to create an
99 "Open Data" platform for easy sharing of data across the entire market (McPartland, 2018).

100 Currently both BIM Level 2 and Level 3 mainly focus on design, construction, and hand
101 over (Carbonari et al., 2018). The existing studies of BIM in Level 2 or above have been
102 largely focusing on pre-construction stages, such as structural design and analysis (Reed,

103 2017), product manufacturing(Gigante-Barrera et al., 2017), and building performance
104 analysis (Samuel et al., 2017). Existing studies of BIM maturity level (e.g., Level 2) in the
105 construction field could be found in areas related to: BIM education to raise awareness and
106 understanding of BIM (Gledson et al., 2016); BIM adoption among small and medium-sized
107 enterprises (Hosseini et al., 2016); and stakeholder involvement such as client requirements
108 (Eadie et al., 2015).

109 The information exchange required in Level 2 to enhance multi-party collaboration in
110 construction projects faces challenges due to the interoperability in BIM. Currently the
111 interoperability is low, and there is a lack of clear guidance on how existing standards such as
112 IFC (Industry Foundation Classes) can be effectively used for performance-based design in
113 the early project stages (Arayici et al., 2018). The interoperability could barricade the
114 implementation of BIM Level 2, which should allow information sharing and exchange of
115 information crossing different stages of a construction project as indicated by Alazmeh et al.
116 (2018).Kumar and Hayne (2017) stated that wide scale adoption of BIM has been largely
117 limited to the design stage.

118 Despite of these challenges encountered during BIM implementation, BIM is being
119 integrated to other digital technologies or concepts, such as: Internet of Things or IoT
120 (Kirstein and Ruiz-Zafra, 2018) in the Level 2, GIS or Geographic Information System
121 (Bansal, 2011), and Virtual Reality (Xie et al., 2011). As indicated by Yalcinkaya and Singh
122 (2015) and Oraee et al. (2017), a successful BIM implementation should involve both
123 technical aspects and managerial part. For example, BIM-based platform could potentially
124 enhance the performance of project adopting the integrated project delivery (IPD) system
125 (Ma and Ma, 2017). BIM integrated with IPD could also enhance the project collaborative
126 management and reduce wastes of resources (Mei et al., 2017).

127 **3. Methodology**

128 This study adopts a holistic approach to investigate existing BIM literature related to
129 CEM activities. The four-step workflow of literature reviewed in this study is illustrated in
130 Fig.1 and discussed below:

131 <Insert Fig.1 here>

132 *Step 1: Defining the scope of bibliometric research*

133 The aim of the first step was to define the scope of the literature review. BIM is an
134 interdisciplinary digital tool that has been studied in various AEC areas, such as: project
135 management (Cao et al., 2018), construction automation (Mangal and Cheng, 2018), building
136 performance analysis (Pinheiro et al., 2018), structural analysis (Ramaji and Memari, 2018),
137 facility management (Rodrigues et al., 2018), as well as BIM integrated with other emerging
138 technologies such as laser scanning (Santos et al., 2017). This study was about BIM-based
139 research that focused on CEM activities, tasks, processes, issues, or human factors such as
140 construction planning and constructability evaluation (Nascimento et al., 2017). The field of
141 CEM covers topics related to construction scheduling, cost estimate, construction simulation,
142 health and safety, site logistics, constructability review, and project delivery method (Tan,
143 1997; Abudayyeh et al., 2000; Sacks and Pikas, 2013). Construction, as one of the main
144 stages within a project life cycle, is closely related to its preceding stages (e.g., design) and
145 follow-up phases (e.g., operation). It is not uncommon to find studies focusing on integrated
146 design and construction (e.g., Badi and Diamantidou, 2017; Kapogiannis and Sherratt, 2018;
147 Said and Reginato, 2018) using fast-track project delivery approach such as Design-Build
148 (DB) (Bogus et al., 2013). Modern procurement options could integrate construction
149 activities, tasks and processes, or issues, or professionals (e.g., contractors) with those beyond
150 the construction phase (e.g., Park et al., 2017). The scope of the study includes pre-
151 construction, construction and post-construction phases but with a particular reference to

152 construction stage activities, processes, issues and human factors. It excluded topics which
153 did not focus on CEM, such as design coordination, business feasibility, and facility
154 management.

155 *Step 2: Bibliometric search*

156 The bibliometric search of publications of BIM applied in CEM was performed in
157 *Scopus*, one of the main search engines for academic research outputs. *Scopus* covers more
158 journals and more recent publications than other sources such as *Web of Science*
159 (AghaeiChadegani et al., 2013). Keywords were input in *Scopus* using the **TITLE-ABS-**
160 **KEY** as follows: (BIM OR "building information modeling" OR "building information
161 modelling") AND ("construction management" OR "construction projects" OR "construction
162 engineering").

163 Following the keyword input, the publication source was limited to journals, and the
164 language of publication was English. Conference papers were excluded in the literature
165 sample as they did not provide as much information as journal articles did (Butler and Visser,
166 2006). After the initial selection of journal articles, two more steps, science mapping and
167 trend analysis, were performed to screen out articles that did not focus on BIM or CEM fields.

168 *Step 3: Science mapping*

169 Science mapping could form part of the scientometric analysis approach (Xu et al, 2018).
170 It evaluates research policies and processes large bibliometric data (Tijssen and Van Raan,
171 1994). It also displays the dynamic and structural aspects of a research domain as described
172 by Cobo et al. (2011). Specifically, science mapping illustrates the relationships among
173 disciplines, fields, and individual publications in a spatial approach (Small, 1999).In this
174 study, *VOSViewer*, the science mapping tool developed by Van Eck and Waltman (2010),
175 was adopted for the science mapping purpose. Other science mapping tools such as *CiteSpace*
176 (Chen, 2016) and *Gephi* (Bastian et al., 2009) could also be used in the literature review.

177 Compared to these tools, *VOSViewer* has been established by Van Eck and Waltman (2014) to
178 be more suitable for visualizing larger networks and it has its special text-mining features. It
179 provides distance-based visualizations of bibliometric networks, and distance between two
180 visualized nodes indicates their inter-relatedness (Van Eck and Waltman, 2014). Adopting
181 *VOSViewer* in scientometric analysis can be found in other review-based studies in
182 construction project management fields, such as managerial studies of BIM (Oraee et al.,
183 2017), public-private-partnership (Song et al., 2016), and off-site construction (Hosseini et al.
184 2018). In this study, *VOSViewer* was used to perform the following sub-steps: 1) transporting
185 the finalized literature sample from *Scopus*; 2) visualizing, computing, and analysing the
186 influence of journals and articles in the BIM-based CEM research; and 3) analysing the
187 mainstream keywords and their inter-relatedness.

188 *Step 4: Trend analysis*

189 Trend analysis was the last step following the scientometric study. Generally, review-
190 based studies would propose framework or suggest directions for scholars in this domain, for
191 example, the domain of construction and demolition waste management (Yuan and Shen
192 2011), and public-private-partnership (Ke et al., 2009). Using the same approach for this
193 study, the potential research directions and emerging topics for near-future research work
194 were proposed in BIM-based research in CEM.

195 **4. Results of Scientometric Analysis**

196 By inputting these pre-defined keywords in *Scopus*, originally 1003 publications were
197 found. By limiting the type of documents to journal articles and excluding conference
198 proceedings, 352 articles were shortlisted. As seen in Fig.1, further screenings of the
199 shortlisted 352 articles were performed in order to narrow down articles within the scope of
200 BIM-based research or practice in CEM-related activities, tasks and processes, or issue, or
201 human factors. For example, studies such as Lopez and Love (2012) that include BIM in the

202 abstract but did not focus on BIM application were removed. Other studies such as those of
203 Penttilä (2006) and Rekola et al. (2010) that focused on the ICT (i.e., Information and
204 Communication Technology) in architectural design, design management, design
205 coordination, were also excluded in the literature sample because they did not have any
206 particular reference to the construction stage. Studies like Eastman et al. (2010) and Steel et
207 al. (2012) were also removed as they focused on the development of standards for
208 information management without specific focus on CEM. Articles such as Kubicki et al.
209 (2009) and Neff et al. (2010) that have integrated AEC practices were included. Others such
210 as Wong et al. (2011), where BIM was studied in its application in CEM, building technology
211 and quantity surveying were also included. Interdisciplinary studies such as Boton, et al.
212 (2013) and Karan and Irizarry (2015) that involves CEM focusing on BIM in pre-
213 construction or design stages, particularly those with contractors or construction personnel
214 involved, were all included. At the end, a total of 276 articles remained for the later
215 scientometric analysis.

216 ***4.1.An overview of the literature sample***

217 The whole literature sample is divided according to the year of publication. Fig.2
218 displays the number of yearly publications.

219 <Insert Fig.2 here>

220 The first Scopus-indexed journal article adopting BIM in CEM research was found in
221 2008. Only two journal articles were published in 2008 from the literature sample, but since
222 then more publications were found especially after 2011, when more than 10 articles were
223 found yearly. A significant increase of BIM-based research in CEM can be found after 2015.
224 Since then more than 40 articles can be found annually. This may suggest that the trend of
225 increased research outputs in this domain can be expected in the follow-up years.

226 ***4.2.Science mapping of journal sources***

227 Journal sources that publish BIM-based research in CEM were identified through
228 scientometric analysis. Setting the minimum number of documents and minimum citation
229 number of a journal to be 3 and 20 respectively, a total of 16 out of 90 journals met the
230 threshold. Fig.3 displays the nodes of these journals and their inter-relations using connection
231 lines.

232 <Insert Fig.3 here>

233 According to the node and font sizes displayed in Fig.3, *Automation in Construction*, and
234 *Journal of Construction Engineering and Management* were among the most influential
235 journals that had been contributing to the research community of BIM application in CEM.
236 The connection lines and clusters in Fig.3 indicate the mutual citations among these journals.
237 The mutual citation shows the interrelatedness between a pair of journals, indicating the
238 likelihood for one journal to disseminate research outputs in BIM-based CEM studies based
239 on the relevant findings from the other journal. For example, *Automation in Construction*
240 (*AiC*) is strongly connected to *International Journal of Project Management (IJPM)*, and
241 *Journal of Civil Engineering and Management (JCEM)*. More quantitative measurements of
242 these journals' contributions are provided in Table 1.

243 <Insert Table 1 here>

244 Five major measurement indicators are listed in Table 1, namely total link strength,
245 number of published articles, total citation number, the average citation per publication, and
246 the average normalized citation. The relationship between each pair of the indicators is
247 presented in Table 2 based on the Pearson correlation analysis with 5% level of significance.
248 It is seen that the former three measurements are generally highly correlated to each other
249 with correlation coefficients over 0.900 and corresponding p values equal to 0.000. *AiC*,
250 *JCEM*, and *IJPM* are the top three journals in terms of their quantity of publications, total
251 citations, and total link strength. However, the average normalized citation, which measures
252

253 the research significance or influence of a given journal, are found not significantly related to
254 its total publications or citations. For example, these journals could be considered with higher
255 impacts compared to others listed in Table 1: *IJPM* and *Safety Science*, based on that fact
256 they have higher average normalized citations.

257 ***4.3.Co-occurrence of keywords***

258 Keywords are considered one major means of clear and concise descriptions of research
259 contents (Su and Lee, 2010; He et al., 2017). A network of keywords depicts the knowledge
260 among their relationships and intellectual organization of research topics (Van Eck and
261 Waltman, 2014). Following the suggestions of Oraee et al. (2017) and Hosseini et al. (2018),
262 “Author Keywords” and “Fractional Counting” were adopted in *VOSViewer* for keyword
263 filtering. These keywords came from the literature sample that is shown in Fig.1. Setting the
264 minimum occurrence of keywords at 3, initially 68 keywords met the threshold. These
265 initially filtered keywords needed further refinement. General keywords such as “BIM”,
266 “construction management”, and “construction projects” were removed. Other keywords such
267 as “IFC” and “Industry Foundation Class” which had the same semantic meanings, were
268 combined into one. By rerunning the keyword analysis, a total of 35 keywords were selected
269 as shown in Fig.4 and Table 3.

270 <Insert Fig.4 here>

271
272 These frequently studied keywords with strong connections to others can be identified
273 according to node sizes, distance among nodes, and connection lines among keywords as
274 shown in Fig.4. They include collaboration, visualization, interoperability, lean, planning and
275 design, and education/pedagogy. Various colors in Fig.4 represent different clusters, meaning
276 that keywords within the same cluster are more closely linked to each other. As shown in

277 Fig.4, there are 6 main categories (colour clusters) within BIM-based CEM research and
278 these can be defined as follows:

- 279 • *Education/pedagogy*, although with longer distance with other clusters in Fig.4, is one of
280 the key research areas in CEM. Multiple studies (e.g., Lee et al., 2013; Pikaset al., 2013;
281 Hallowell et al., 2014; Solnosky et al., 2014; Ghosh et al., 2015; Bozoglu, 2016) have
282 focused on the curriculum update and teaching effectiveness of BIM in CEM education.
283 AEC students and college graduates are the future employees of the industry (Zou et al.,
284 2018). The institutional education plays a key role in BIM transition (Solnosky and Parfitt,
285 2015; Jävājā and Salin, 2016). Educators (e.g., Gerber et al., 2013; Sacks and Pikas, 2013)
286 have suggested the importance of updating BIM education to meet the industry
287 requirements. Multiple studies (e.g., Solnosky et al., 2014; Wu et al., 2015; Lucas, 2017)
288 have proposed the strategies to bridge the gaps between institutional education and
289 industry requirements, such as interdisciplinary teaching adopting project-based learning
290 approach (Jin et al., 2018a);
- 291 • *Collaboration, cloud computing, and interoperability* happened to be in the same cluster,
292 inferring their close internal relationships. Collaboration has been identified as the key for
293 successful BIM implementation from multiple previous studies (e.g., Eadie et al., 2013;
294 Hadzamanet al., 2016; Jin et al., 2017a; Jin et al. 2017b). Cloud computing has been
295 recently adopted as a digital technology integrated with BIM in enhancing the efficiency
296 of construction delivery and reducing human errors. For example, Chen et al.
297 (2018) incorporated cloud computing and BIM to enable the real-time collection,
298 communication, and visualisation of information across the processes of production,
299 transportation, and on-site assembly for prefabricated construction;
- 300 • *Planning and design* can be highly integrated with the construction phase through BIM
301 adoption, especially in IPD. Keywords including *communication, optimization, algorithm,*

302 *and constructability* were found highly connected to planning and design, indicating that
303 BIM had large potential in assisting project planning, optimize construction activities, as
304 well as enhancing the communication among project participants (Faghihiet al., 2016;
305 Jian, 2017);

- 306 • Keywords including *visualization, construction safety, scheduling, 4D, and construction*
307 *planning* were found strongly connected to each other within the same cluster. The term
308 4D in BIM generally refers to adding the time or scheduling into 3D (Zhou et al. 2015;
309 Park et al., 2018). Through visualization, BIM could be adopted as a more effective tool
310 in safety training to site employees. BIM was further believed to reduce site accidents
311 (Sadeghi et al., 2016). The 4D augmented-reality could be further adopted for integrated
312 visualization of as-built and as-planned models in construction monitoring (Golparvar-
313 Fardet al. 2011);
- 314 • The cluster consisting of *IFC, cost estimate, database, and ontology* shows the research
315 movement of data storage, sharing, and application when implementing BIM in
316 construction practice. The data inconsistency or the interoperability problem (Parket al.
317 2017) continues to be studied when applying BIM in certain construction tasks (e.g., cost
318 estimate or bills of quantities). The semantic interoperability and ontology have been the
319 more recently studied topics in BIM (Parket al. 2017). The importance of data
320 consistency to enable multi-party collaboration in BIM-driven projects was addressed by
321 Niknam and Karshenas(2015) in the cost estimate and quantity take-off;
- 322 • *Lean and sustainability* form part of BIM-related studies in CEM. Lean principle has
323 been studied in its effectiveness to enable BIM adoption (Mahalingam et al., 2015).
324 Although lean construction and BIM are different initiatives, there is a synergy between
325 them to improve construction processes (Sacks et al. 2010). Case studies have been
326 adopted in multiple studies (e.g., Wen, 2014; Mahalingam et al., 2015) to combine BIM

327 and lean practice during design and construction. Multiple studies (e.g., Harper and
328 Hazleton, 2014; Lee and Kim, 2017; Marzouk et al., 2017) addressed the role of BIM in
329 improving construction sustainability.

330 More quantitative measurements of keywords are summarized in Table 3.

331 <Insert Table 3 here>

332
333 Consistent to the science mapping in Fig.4, most frequently studied keywords in BIM-
334 based CEM include education/pedagogy, lean, planning and design, as well as collaboration.
335 The Pearson correlation analysis is provided in Table 4 to evaluate the relationships between
336 each pair of these four major indicators (i.e., total link strength, occurrence, average citation,
337 and average normalized citation). It can be seen that average citation and average normalized
338 citation, which measure the influence of a keyword in the BIM application in CEM, are
339 independent of their frequencies of being studied. These two citation-based measurements are
340 found not significantly correlated to each other, with a p value at 0.279. Keywords receiving
341 the highest average citations, however, differ from these which have highest
342 occurrences. CAD (i.e., Computer-Aided-Design) had significantly higher average citation
343 compared to other keywords. The transition from traditional 2D CAD to BIM had raised a
344 wide concern in the AEC industry. Cultural resistance to a new digital technology and new
345 management mode could become a barrier in promoting BIM (Denzer and Hedges, 2008;
346 Dawood and Iqbal, 2010). Other keywords receiving high average citations include 3D,
347 communication, and lean. The reason that these keywords had higher average citations could
348 be partly due to that they had been studied in earlier years according to their average years of
349 publication shown in Table 3. Some more recent emerging keywords, although currently with
350 lower average citation, may be studied more in the future, for example, cloud computing,
351 algorithm (e.g., generic algorithm), IOT (i.e., Internet of Things), and integration. Cloud
352 computing, with the average normalized citation of 3.9 which is significantly higher than that

353 of any other keywords listed in Table 3, could be one of the emerging research topics to be
354 integrated with BIM for CEM activities. Other topics especially IOT, database,
355 interoperability, and construction safety are also gaining the momentum in BIM-related CEM
356 research.

357

358 ***4.4.Citation of articles***

359 Journal articles with the highest citations were identified in *VOSViewer*. Setting the
360 minimum number of citation set at 50, a total of 15 articles met the threshold. Table 5 lists
361 details of the selected articles.

362 <Insert Table 5 here>

363 Based on a Personal correlation coefficient of 0.452 and the corresponding p value at
364 0.091 between the total citation and normalized citation, it is indicated that these two citation-
365 based measurements for articles are not significantly related to each other. In another word,
366 an article which has gained the highest citation number might not be the same one that has
367 received the highest average citation. Therefore, a more comprehensive evaluation of an
368 article's influence in the academic field is necessary.

369

370 The study of Bryde et al. (2013) received the highest citation as well as the average
371 normalized citation, indicating its high influence in the academic field of BIM for CEM. The
372 study of Sacks et al. (2010) focusing on lean in BIM received the second highest total citation
373 number. However, the study of Lee et al. (2014) integrating ontology in BIM received second
374 highest average normalized citation. Consistent with Table 3, ontology is one of the
375 keywords with high influence. It can be found from Table 5 that most influential studies
376 generally involve these topics suggested by Table 3 and Fig.4, including lean construction,
377 ontology, integration and collaboration among project team members, BIM integration with

378 other digital technologies (e.g., GIS or Geographic Information System), as well as
379 interoperability issues in BIM practice involving IFC standard.

380 **5. In-depth Discussions**

381 BIM encourages the interdisciplinary collaboration among project team members
382 through visualization and information sharing. IPD, as an innovative project delivery method
383 to the conventional design-bid-build (DBB) approach, seeks to improve project performance
384 through a more collaborative approach of early involvement of all parties, and a multiparty
385 agreement of sharing benefits and risks (Kent and Becerik-Gerber, 2010). Inherently, IPD or
386 other project delivery methods permitting fast-track could be more integrated with BIM to
387 enhance its effect across the project life cycle. Fig.5 illustrates the inter-relationship between
388 BIM and multiple project stages with corresponding AEC practitioners. The review scope of
389 this study was set limited to CEM. There were two main types of articles selected from the
390 literature sample: 1) BIM implementation in the construction stage or where contractors were
391 involved (e.g., pre-construction review) (e.g., Choi et al., 2014; Ghosh et al., 2015); and 2)
392 BIM application in integrated design and construction (e.g., Cao et al., 2015; Merschbrock
393 and Munkvold, 2015). The former type of articles covered multiple CEM related activities, or
394 issues, such as cost estimate (Niknam and Karshenas, 2015) and safety management (Zhanget
395 al., 2015). The latter type of articles emphasized the collaboration among multiple project
396 parties in BIM environment, especially the integrated design and construction.

397 <Insert Fig.5 here>

398 Fig.5 highlights the differences between traditional project delivery method (e.g., DBB)
399 and fast-track in terms of their interactions with BIM. It also shows that BIM serves as a tool
400 that facilitates multi-disciplinary collaboration and supports dynamic construction processes.
401 Due to the fragmented practice of the construction industry (Arashpouret al. 2018), so far
402 more BIM-related practice and studies have been conducted in the design or pre-construction

403 stage than in CEM and facility management. The research of applying BIM in CEM remains
404 a relatively new theme with the first two *Scopus*-indexed journal articles published in 2008.
405 But since then this research domain has gained a significant increase, from below 10 journal
406 articles published yearly before 2010, slightly more than 10 after 2011, to over 40 articles
407 published annually after 2015. The increasing trend of BIM-based research in CEM can be
408 expected in the follow-up years. BIM is envisioned to play an important role to integrate
409 design, construction and facility management stages through coordinated changes in the
410 project life cycle (Pilehchian et al., 2015). Based on these existing BIM-based studies that
411 focus on the construction stage or integrated design and construction, a few specific
412 directions for the near-future research are proposed in terms of project delivery system,
413 technological integration, non-traditional construction technique, and continued BIM
414 pedagogy in CEM.

415 ***5.1.Fast-track project delivery and BIM***

416 There have been so far limited number of studies focusing on how project delivery
417 methods would impact BIM adoption in construction projects. Fig.6lists fast-track as one of
418 the non-traditional project delivery approach compared to the conventional DBB. Konchar
419 and Sanvido (1998) conducted the performance comparison for projects adopting DBB, DB,
420 and construction management at risk (CMAR). The study of Konchar and Sanvido (1998) can
421 be extended comparing the performance of BIM and non-BIM construction projects
422 implementing different delivery methods. Existing studies (e.g., Jones, 2014; Ma et al., 2018)
423 on developing BIM-based collaborative platform for IPD are still limited to developing a
424 prototype or framework, lacking the applications or validations in the real-world scenario.
425 Empirical studies of applying BIM in IPD and case studies can be more performed to analyse
426 how IPD and BIM could benefit each other for improved project performance through shared
427 information, project objectives, and higher work efficiency.

428 *5.2.Integration of digital technologies and methods in construction*

429 BIM has been tried in its integration with other digital construction technologies, such as
430 Virtual Reality (Xie et al. 2011). Fang et al. (2016) adopted BIM and cloud-enabled radio-
431 frequency identification (RFID) in construction site tests and showed that BIM and cloud-
432 enabled RFID has a promising potential in practical applications such as site security control,
433 safety management, asset management, and productivity monitoring. The study of Fang et al.
434 (2016) served as an example of integrating the passive localization system in RFID, the
435 visualization system in BIM, and the cloud computing system. RFID integration with BIM
436 can be found in multiple other studies (e.g., Ikonen et al., 2013 ;Costin et al. 2015) to enhance
437 the security, safety, quality control, worker logistics, and maintain local ordinances of
438 construction projects. Other technologies, such as GIS, have displayed their potential to work
439 with BIM in construction projects. The integration of BIM and geospatial analyses can
440 enhance managing the planning process during the design and pre-construction stages (Karan
441 and Irizarry, 2015). A few studies (e.g., Bansal 2011a; Bansal 2011b; Elbeltagi and Dawood
442 2011; Karan and Irizarry, 2015) worked on integrating GIS and BIM to enhance site
443 collaboration and construction information sharing through the visualization and modelling
444 functions of BIM and the spatial planning feature in GIS. GIS can use the details of building
445 components provided by BIM in preconstruction planning, and BIM can then visualize the
446 GIS analyses outcomes in a virtual world (Irizarry and Karan, 2012). A main challenge of
447 promoting the application of multiple BIM tools and their integration with other digital
448 technologies (e.g., GIS and RFID) is the lack of interoperability (Gökçe et al., 2013; Ciribini
449 et al., 2016; Petriet al., 2017), involving issues related to data storage, sharing, semantics, and
450 ontology (Lee et al. 2014; Nepal and Staub-French, 2016; Hamledari et al., 2018). For
451 example, Karan and Irizarry (2015) identified one of the main interoperability gaps between
452 BIM and GIS in the semantic level, which required more future work to develop the

453 interoperable framework as well as the IFC-compatible standard. The lack of automated
454 information transformation within BIM to support construction site visualization and decision
455 making was also reported in more recent research such as Li and Lu (2018), who
456 recommended the future integration of 4D BIM to enable the automated generation of site
457 animation. The interoperability-focused research in BIM implementation is an ongoing
458 mainstream research theme.

459 ***5.3. Integration of innovative construction techniques and BIM***

460 According to the prior scientometric analysis of research keywords as shown in Table 3,
461 lean and sustainability are frequently studied topics in BIM for CEM. Lean, sustainability,
462 and BIM are inherently inter-connected concepts to be more integrated (Eastman et al., 2011).
463 For example, there is a need to develop a technological BIM information system for lean
464 management in construction (Guerriero et al., 2017), and also the need to map lean principles
465 into BIM (Zhang et al., 2018b). Deeper exploration to integrate BIM, lean, and green
466 paradigm utilizing practical evidences is recommended by Saieg et al. (2018), who further
467 suggested developing a sustainability indicator system by using the automatic extraction of
468 model data starting from early project stages.

469 So far BIM has been more widely applied in conventional construction, and has not been
470 fully utilized to assist off-site construction (Abanda et al., 2017). The integration of BIM has
471 not been achieved from the practical aspect (Goulding et al., 2015). Off-site construction
472 provides an alternative approach by shifting the building construction process away from
473 sites to a controllable factory environment (Jiang et al., 2018). Off-site construction, through
474 a cleaner construction method (Mao et al., 2016; Hwang et al., 2018), provides a sustainable
475 and integrated platform. BIM is inherently connected to off-site construction (Babič et al.,
476 2010; Abanda et al., 2017; Mann, 2017). For example, Zhong et al. (2017) introduced a multi-
477 dimensional BIM platform involving RFID to achieve the real-time visibility and traceability

478 in prefabricated construction. Liet al. (2016) adopted the BIM-centered strategy to facilitate
479 stakeholder communication aiming to mitigate schedule risks in off-site construction projects.
480 Nevertheless, the internal relationship between BIM and off-site construction have still not
481 been sufficiently studied (Hosseini et al. 2018) as expected. However, applying BIM in the
482 project delivery process of off-site construction is becoming critical to improve the
483 productivity of the construction industry (Abanda et al., 2017; Jin et al., 2018b), for
484 example, the implementation of BIM Level 2 for off-site construction project delivery
485 described by Nicola Scammell (2018) to assist just-in-time deliveries.

486 ***5.4. BIM pedagogy in CEM curriculum***

487 It is seen in Table 3 that pedagogy and education is the mostly widely studied topic in
488 BIM for CEM. This is consistent with previous BIM-based studies in CEM (e.g., Kim, 2012;
489 Lee et al., 2013; Ghosh et al., 2015; Zhang et al., 2016). The concern of lack of sufficient
490 BIM education has been raised on addressing the gap between academia and industry. A
491 growing number of AEC programs have begun to incorporate BIM contents in their
492 curriculum (Bozoglu 2016). Recent pedagogical studies such as Zhang et al. (2018a) adopted
493 project-based teamwork stressing the project delivery process in BIM education.
494 Interdisciplinary BIM pedagogy (e.g., Solnosky et al., 2014; Jin et al., 2018a) is becoming a
495 commonly adopted teaching strategy to encourage students' cross-disciplinary teamwork.
496 More pedagogical studies could continue the interdisciplinary education motivating students
497 from different AEC subjects to work in a project-based or problem-based approach (Jin et al.,
498 2016). Existing BIM pedagogical studies (e.g., Tang et al., 2015; Zhao et al., 2015) have
499 more focused on students' perceptions or feedback right after the learning cycle. The effect of
500 certain teaching and learning strategy in students' longer-term career development can be
501 traced as suggested by Li et al. (2018a). According to the BIM learning and practice
502 framework proposed by Zou et al. (2018), several human factors in BIM practice, such as

503 perceptions, understanding, expectations, and behaviours, could be further investigated and
504 compared between college graduates and AEC professionals. As suggested by Zou et al.
505 (2018), students could gain certain consistent perceptions towards BIM implementation in the
506 construction industry as industry professionals do. However, limited studies have been
507 performed investigating the learning and practical cycle of BIM learners and practitioners,
508 specifically, how gaining practical experience would affect individuals' perceptions of BIM,
509 and how the multiple factors (e.g., local BIM culture and climate) would affect BIM learners'
510 perceptions.

511 **6. Recommended research directions of applying BIM in CEM**

512 Based on the scientometric analysis and the qualitative analysis of current mainstream
513 topics within BIM-based CEM research, a framework is proposed in Fig.6 to link the current
514 research problems to recommended future directions.

515 <Insert Fig.6 here>

516 According to Fig.6, the limitations of existing studies could be categorized into five
517 major themes within the BIM-based CEM research leading to corresponding future research
518 directions, specifically:

- 519 • Collaboration-based BIM, either managerial (Jin et al., 2017a) or technological
520 (Hamledari et al., 2018) can be further developed. According to Post (2018), although
521 IPD is supposed to enable multi-party collaboration and sharing of risks without fear of
522 lawsuits, in reality it is still far from enhancing collaboration. Therefore, differences of
523 the benefits and barriers of applying BIM between fast-track projects and traditional DBB
524 projects can be further explored. The information workflow and interoperability to
525 integrate design and construction can be better developed, such as developing the BIM-
526 based system in construction waste reduction (Won and Cheng, 2017);

- 527 • BIM can be linked to other existing digital technologies (e.g., GIS and RFID) in being
528 applied in construction field work, such as BIM-based virtual reality for monitoring the
529 construction process of off-site construction (Li et al., 2018b). **Technical issues such as**
530 **interoperability between different BIM tools and among these digital technologies remain**
531 **to be addressed;**
- 532 • BIM has been identified with inherent connection to off-site construction according to
533 both academic studies (e.g., Abanda et al., 2017) and practical report (e.g., Gowan, 2018).
534 However, more empirical studies are needed to showcase or demonstrate the impacts of
535 BIM on off-site construction projects (Abanda et al., 2017);
- 536 • Current research has not sufficiently addressed the inherent connections among BIM, off-
537 site construction, and lean construction (Hosseini et al., 2018). There is a need to connect
538 BIM to lean principles as recommended by Saieg et al. (2018) and Zhang et al. (2018b),
539 and to further utilize BIM to support decision making in integrated design and
540 construction (Saieg et al., 2018);
- 541 • BIM pedagogy-based research can be shared among the academic community to keep the
542 BIM education updated. More alternative pedagogical practices (e.g., Jin et al., 2018a)
543 can be explored to bridge the gap between institutional education and industry needs. **It is**
544 **also suggested to investigate the effects internal and external factors (e.g., practical**
545 **experience and local BIM culture) on individuals' perceptions of BIM.**

546 **7. Conclusion**

547 This study adopted a holistic review approach to evaluate BIM-based research in
548 construction engineering and management (CEM). It aimed to fill the gap of previous BIM-
549 review-based studies by focusing on CEM-related technological or managerial aspects, such
550 as cost estimate, constructability review, and integrated design and construction. Following

551 the defined scope of literature review, a bibliometric search of journal articles, scientometric
552 analysis, and qualitative discussion were performed to deliver the comprehensive review.

553 Since 2008, research outputs had been gaining a significant increase in adopting BIM for
554 CEM. The continued growth of BIM-based research in CEM topics can be expected in the
555 follow-up years. Journals that have more significantly contributed to the dissemination of
556 relevant research findings included *Automation in Construction*, and *Journal of Construction*
557 *Engineering and Management*.

558 There has been much emphasis in the pedagogy-based research in addressing the
559 importance of college education in BIM transition, especially the benefits of implementing
560 interdisciplinary BIM education. It is expected that more pedagogical studies in BIM for
561 CEM will be published in the future. Other popular and influential research topics included
562 lean construction, 4D BIM, interoperability, ontology, planning and design adopting BIM for
563 CEM (e.g., safety). These keywords have been gaining the momentum in being integrated
564 with BIM in CEM research, including cloud computing, database, Internet of Things, and
565 construction safety.

566 Following the scientometric analysis, the qualitative analysis summarized several
567 mainstream research topics, including but not limited to BIM applied in fast-track project
568 delivery methods, BIM integrated with other digital technologies (e.g., GIS), BIM impacts on
569 off-site construction, and innovative BIM pedagogy. A further framework was finally
570 proposed by linking these existing research topics to future research directions. For example,
571 there could be a comparison of BIM benefits and barriers between fast-tracking and
572 traditional Design-Bid-Build project delivery methods. More specifically, these directions
573 could be summarized as:

- 574 • The mutual impact between BIM and integrated project delivery system, as compared to
575 how BIM works in the traditional design-bid-build project;

- 576 • Integration of BIM with other digital technologies, such as RFID and GIS;
- 577 • The interoperability issue involving data sharing, semantics, and ontology;
- 578 • BIM, as an interdisciplinary tool, has more potential to be integrated with alternative
579 digital technologies, project delivery methods, and innovative construction techniques
580 (e.g., off-site construction). More studies are needed to expand the current research
581 progress of BIM applied in off-site construction, through more cases, empirical data, and
582 qualitative analysis;
- 583 • Development of prototypes with more case studies addressing the role of BIM in
584 enhancing lean construction and sustainable practice;
- 585 • Continued BIM pedagogical studies to address the gap between CEM education and
586 industry practice, through more innovative teaching strategies such as interdisciplinary
587 project-based teamwork.

588 This review work offers the implications for both academics and practitioners in the
589 CEM fields in terms that: (1) the understanding of the latest research topics (e.g.,
590 collaborative BIM, interoperability, etc.) provides the insights for practitioners regarding
591 what are key issues in implementing BIM in the construction industry; (2) the current study
592 focuses existing BIM-based work in CEM and foresees that BIM adoption in being extended
593 from pre-construction to construction stages; (3) the summaries and recommended directions
594 for future study address the joint needs for both academic research and industry practice such
595 as BIM integrated with off-site construction; and (4) this study provides the hints on why
596 BIM-based research is critical for improving the construction performance (e.g.,
597 sustainability) and how BIM can be effectively adopted to improve the construction
598 productivity. Specifically, BIM, due to its collaborative nature, could be utilized to more
599 efficiently handle the fragmented construction activities. The application of BIM, as the
600 digital platform to improve the construction project delivery efficiency does not only ask

601 technical advancement (e.g., enhanced interoperability between different software platforms),
602 but also the integrated project delivery approach. Finally, the governmental authority,
603 academics, and industry practitioners should develop a consistent view on the movement,
604 needs, limitations, and actions to promote the transformation of the construction industry
605 towards higher efficiency assisted by digital technologies and connected multi-stakeholder
606 platform.

607 The literature sample adopted in this review-based study linking BIM into CEM was
608 limited to journal articles emphasizing academic research, without sufficiently addressing the
609 practical concerns from the industry perspective. It remains unclear of the similarities and
610 differences between academia and industry in perceiving the movement of BIM in being
611 applied in construction field work. As a recommendation for further study, it would be
612 interesting to establish the degree of comparative significance between the six proposed
613 directions for future scholarly work in the perspectives of both academics and practitioners.
614 The perceptions between academics and industry practitioners towards these identified
615 research gaps and directions can be further compared. It would also be necessary to provide
616 further details or breakdown of each of the six proposed directions in order to define key
617 components for focused in-depth scholarly activity for greater efficiency.

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Table 1. Quantitative measurements of journals publishing research in BIM-based CEM

Source	Total link strength ¹	Number of publications	Total citation	Average citation	Average normalized citation ²
<i>Automation in Construction (AiC)</i>	84	40	1066	26.7	2.0
<i>Journal of Construction Engineering and Management (JCEM)</i>	59	26	735	28.3	1.1
<i>International Journal of Project Management (IJPM)</i>	49	10	320	32	3.7
<i>Journal of Information Technology in Construction</i>	27	12	42	3.5	0.4
<i>Journal of Civil Engineering and Management</i>	26	8	48	6	0.9
<i>Electronic Journal of Information Technology in Construction</i>	17	10	250	25	1.1
<i>Engineering, Construction and Architectural Management</i>	12	7	25	3.6	0.4
<i>Construction Management and Economics</i>	12	4	67	16.8	1.3
<i>Journal of Professional Issues in Engineering Education and Practice</i>	8	7	102	14.6	0.8
<i>Advanced Engineering Informatics</i>	8	5	152	30.4	1.6
<i>Journal of Computing in Civil Engineering</i>	7	10	117	11.7	0.9
<i>Construction Innovation</i>	7	9	35	3.9	0.3
<i>Journal of Management in Engineering</i>	7	6	55	9.2	1.3
<i>Safety Science</i>	4	3	84	28	3.1
<i>Malaysian Construction Research Journal</i>	2	3	21	7	0.5
<i>International Journal of Construction Education and Research</i>	1	5	30	6	0.4

1073 ¹: Total link strength corresponds to Fig.3 and indicates the interrelatedness between the given journal and other
1074 peer sources.

1075 ²: The average normalized citation can measure the citation number of a journal source, a keyword, or an article
1076 by correcting the misinterpretation that an older document has more time to receive citations than more recent
1077 publications (van Eck and Waltman, 2014). It is calculated via dividing the total citation number by the average
1078 number of citation per year. The average normalized citation or normalized citation in the follow-up tables are
1079 calculated in the same approach to measure the influence of BIM-related keywords and articles.

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Table 2. Pearson correlation analysis among the measurement indicators for journal sources

Measurement item	Statistical values*	Total link strength	Number of publications	Total citation	Average citation	Average normalized citation
Total link strength	<i>r</i>		0.912	0.914	0.482	0.375
	<i>p</i> value		0.000	0.000	0.059	0.153
Number of publications	<i>r</i>			0.949	0.351	0.131
	<i>p</i> value			0.000	0.183	0.630
Total citation	<i>r</i>				0.598	0.339
	<i>p</i> value				0.014	0.199
Average citation	<i>r</i>					0.787
	<i>p</i> value					0.000

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Note: the statistical values in the Pearson correlation analysis include *r* value which represents the correlation coefficient between a pair of measurement indicators. Based on the 5% level of significance, there is a *p* value corresponding to each *r* to measure the significance of the correlation. A *p* value lower than 0.05 would indicate that the tested two indicators are with significant correlation with each other. The same statistical values and rules apply to Table 4 for the correlation analysis of keywords

Table 3. Summaries of main keywords in BIM-based CEM research

Keywords Within BIM-based CEM studies	Total Link Strength	Occurrence	Average Year Published	Average Citation	Average normalized citation
Education/Pedagogy	8	17	2014	12.6	0.5
Collaboration	8	14	2015	7.1	1.0
Lean	8	11	2014	33.4	1.2
Planning and Design	4	11	2016	6.9	1.3
4D	5	9	2013	15.6	0.9
Construction Safety	4	9	2014	24.7	1.7
Interoperability	5	9	2014	21.8	1.5
Visualization	8	9	2013	7.2	0.3
IFC (i.e., Industry Foundation Class)	6	8	2015	15.0	1.3
Scheduling	2	7	2015	4.6	0.3
Cloud Computing	2	6	2016	9.8	3.9
Cost Estimate	4	6	2015	16.0	1.3
Communication	3	5	2011	38.2	1.2
GIS (Geographic Information System)	3	5	2012	28.8	1.1
IPD (Integrated Project Delivery)	2	5	2015	6.2	0.6
Ontology	4	5	2015	16.0	1.3
CAD (Computer Aided Design)	3	4	2013	58.8	1.4
Constructability	2	4	2015	28.8	0.7
Construction Planning	3	4	2015	7.5	1.3
Cost Control	1	4	2015	1.8	0.1
Database	2	4	2015	7.3	2.0
Sustainability	1	4	2015	1.3	0.3
3D	2	3	2011	58.7	1.1
Algorithm	1	3	2016	10.7	1.0
Architecture	2	3	2015	13.7	0.7
Benefit	1	3	2017	1.0	0.7
Coordination	3	3	2015	9.0	0.5
Integration	3	3	2016	6.0	0.3
IOT (Internet of Things)	2	3	2016	8.3	1.7
Malaysia	1	3	2015	6.0	0.6
Mobile Computing	1	3	2015	25.7	1.2
Optimization	2	3	2013	13.0	0.7
Standard	2	3	2015	12.0	1.3

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Note: keywords in Table 2 are listed according to their occurrences.

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Table 4. Pearson correlation analysis among the measurement indicators for journal sources

Measurement item	Statistical values*	Total link strength	Occurrence	Average citation	Average normalized citation
Total link strength	<i>r</i>		0.857	0.083	-0.022
	<i>p</i> value		0.000	0.645	0.905
Occurrence	<i>r</i>			-0.044	0.028
	<i>p</i> value			0.807	0.877
Average citation	<i>r</i>				0.194
	<i>p</i> value				0.279

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Table 5. List of publications with highest impact in BIM-based CEM research

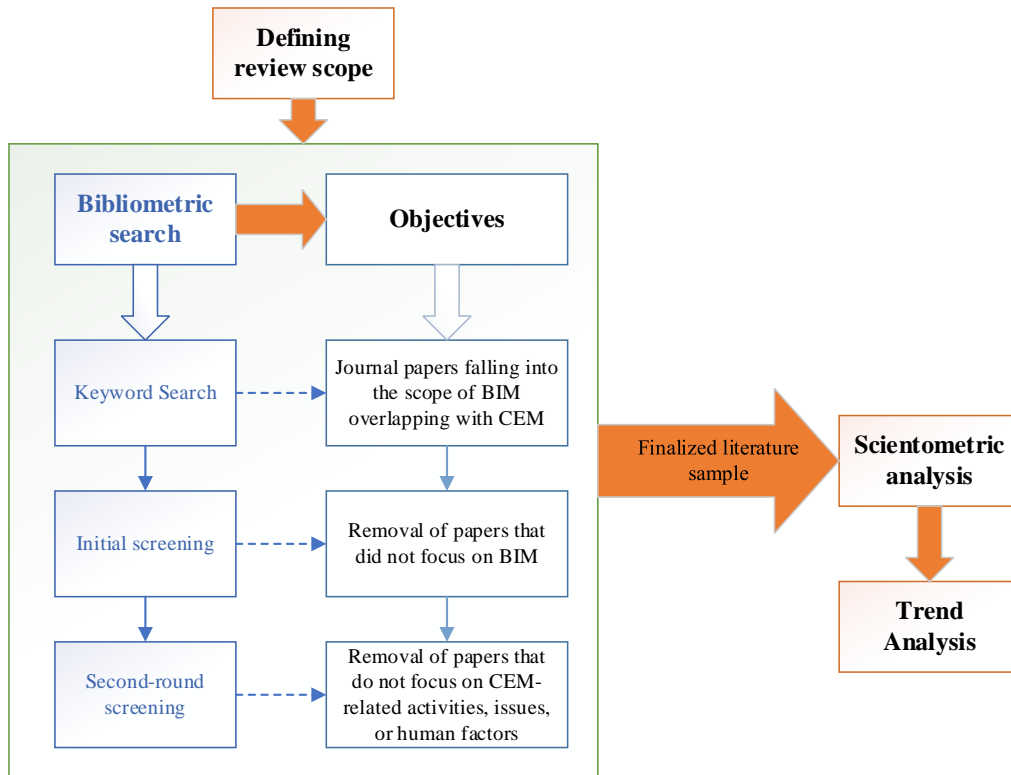
Article	Title	Citation	Normalized citation
Bryde et al. (2013)	The project benefits of building information modelling (BIM)	190	6.5
Sacks et al.(2010)	Interaction of lean and building information modeling in construction	152	2.0
Goedert and Meadati (2008)	Integrating construction process documentation into building information modeling	127	1.6
Dossick and Neff(2010)	Organizational divisions in BIM-enabled commercial construction	113	1.5
Porwal and Hewage(2013)	Building Information Modeling (BIM) partnering framework for public construction projects	105	3.6
Sacks et al. (2010)	Requirements for building information modeling based lean production management systems for construction	103	1.3
Hu and Zhang (2011)	BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials	101	2.9
Eadie et al. (2013)	BIM implementation throughout the UK construction project lifecycle: An analysis	88	3.0
Sacks et al. (2009)	Visualization of work flow to support lean construction	69	2.6
Golparvar-Fardet al. (2011)	Integrated sequential as-built and as-planned representation with D 4AR tools in support of decision-making tasks in the AEC/FM industry	65	1.8
Linderoth(2010)	Understanding adoption and use of BIM as the creation of actor networks	61	0.8
Davies and Harty, (2013)	Implementing 'site BIM': A case study of ICT innovation on a large hospital project	57	1.9
Bansal and Pal (2011)	Construction projects scheduling using GIS tools	56	1.6
Lee et al. (2014)	BIM and ontology-based approach for building cost estimation	51	4.0
Laakso and Kiviniemi (2012)	The IFC standard - A review of history, development, and standardization	51	2.7

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Note: the articles in Table 4 are listed according to the number of citations

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1197 **Fig.1.** Description of the four-step workflow in the review of BIM-based research in CEM

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1207 Note: the number of journal papers in 2018 is incomplete as the articles selected in 2018 was up to the end of
1208 February 2018.

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1210 **Fig.2.** Yearly publications from 2009 to 2018

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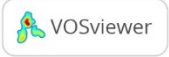
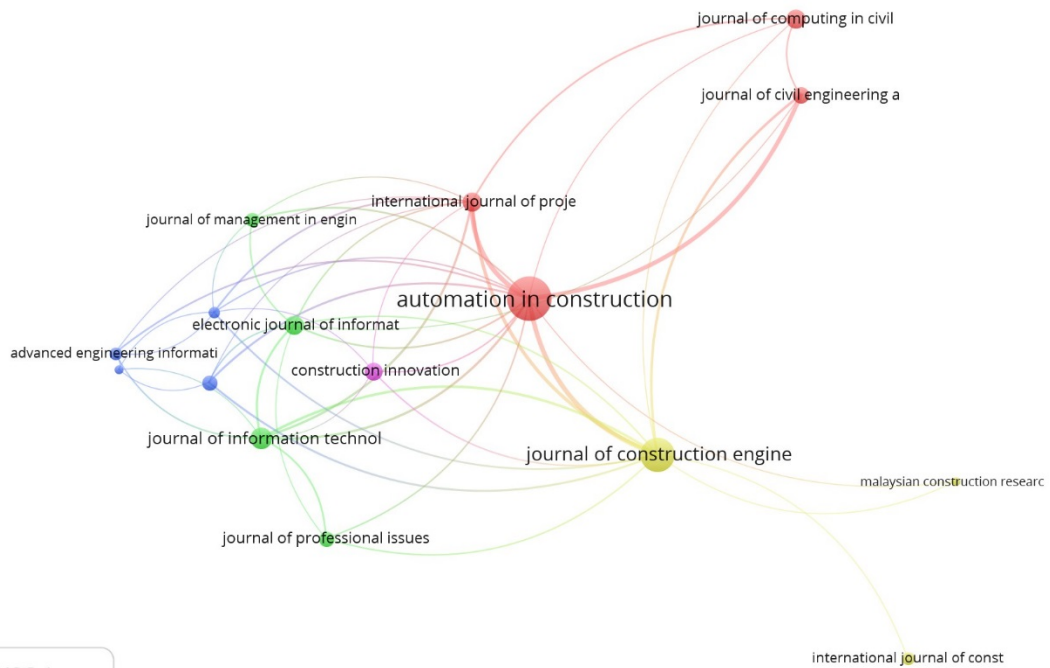
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1218 Note: Journal names may not be fully presented in VOSviewer. The full name of journals are listed in Table 1.

1219 **Fig.3.** Mapping mainstream journals in the domain of BIM-based CEM research

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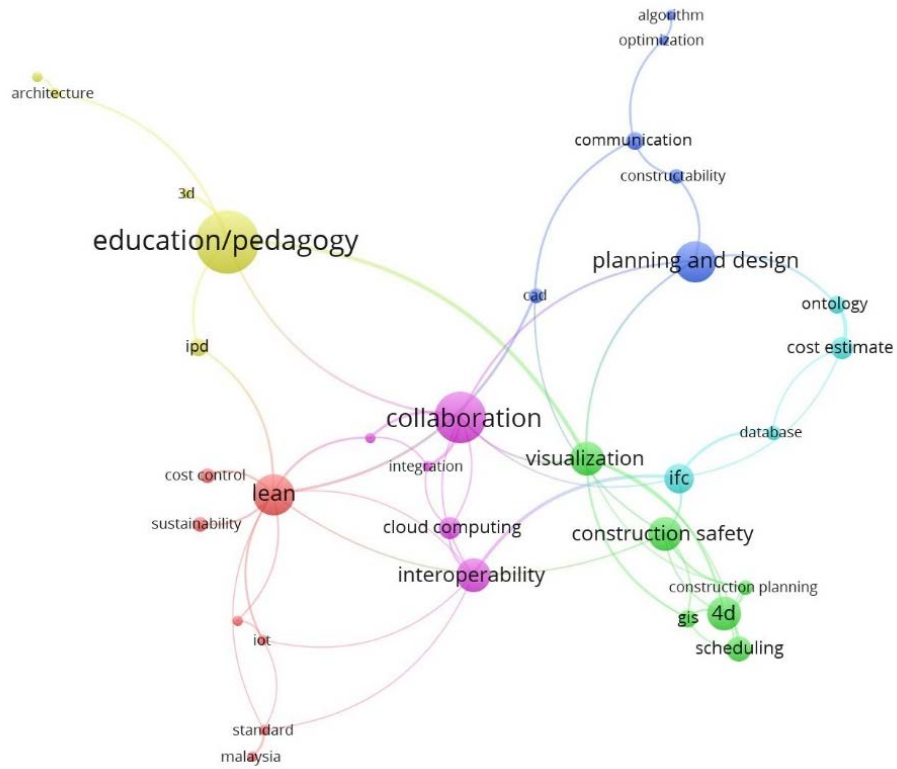
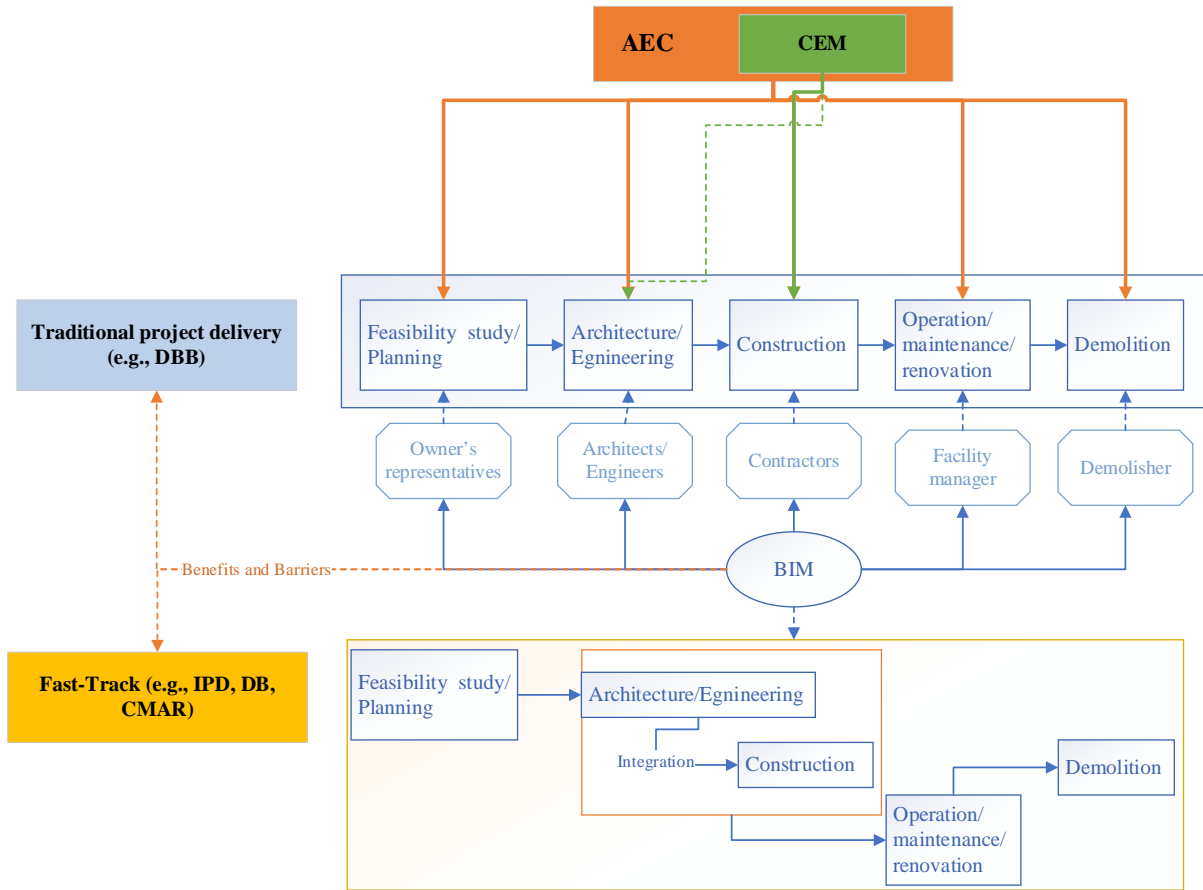


Fig.4. Co-occurrence of keywords in the research of BIM in CEM

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Note: DB and CMAR stand for design-build and construction management at risk respectively.

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Fig.5. Illustration of this review-based study capturing BIM-based CEM research in the

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context of project delivery methods and project phases

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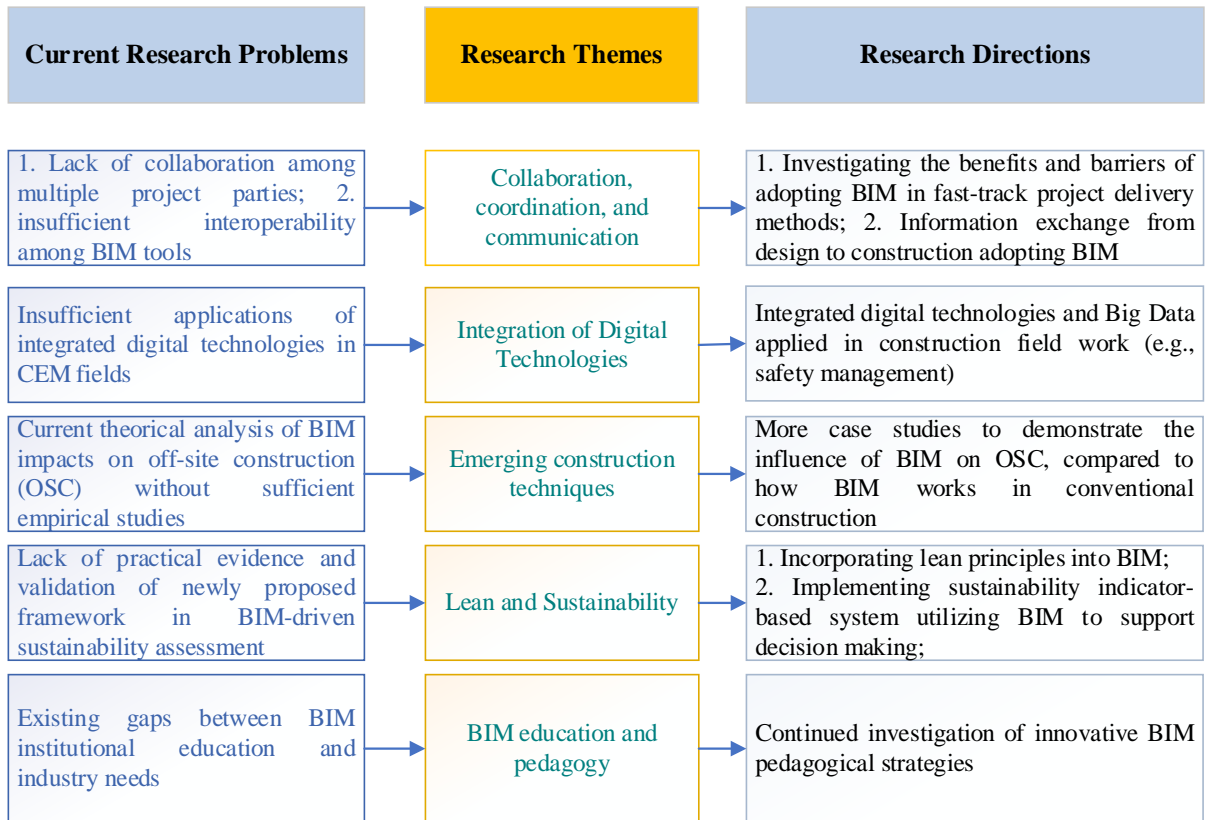


Fig.6. Framework proposing directions in BIM-based CEM research

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