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Scientometric Analysis of BIM-based Research in Construction Engineering and Management

Abstract

Purpose

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

Design/methodology/approach

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

Findings

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

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

Practical implications

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

Originality/value

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

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

1. Introduction

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

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

Although there have been a number of recently published BIM-based review articles (e.g., He et al., 2017; Oraee et al., 2017), very few of them have specifically focused on CEM. BIM has been linked to multiple construction-related activities such as health, safety, and risks (Zou et al., 2017). However, there has been insufficient overview of BIM-based studies in CEM-related activities or practices. Existing review-based studies in BIM for AEC (e.g., Zhao, 2017) are limited to scientometric analysis, without sufficiently engaging in-depth discussions to reveal more implications such as the framework for future directions. Aiming to fill theses gaps, this study adopted a comprehensive review approach incorporating scientometric analysis by targeting at the following objectives: 1) to identify the current mainstream research topics within BIM-based studies in CEM; 2) to find out the most influential journals and scholarly work in this domain; 3) to propose the research directions for future work of applying BIM in CEM. This review work of BIM in CEM offers the implications for both the academics and practitioners, specifically, how the understanding of BIM-based research benefit the academic community and the practical field, as well as how the findings from this study contribute to the body of knowledge in BIM for CEM.

2. Background

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

Currently both BIM Level 2 and Level 3 mainly focus on design, construction, and hand over (Carbonari et al., 2018). The existing studies of BIM in Level 2 or above have been largely focusing on pre-construction stages, such as structural design and analysis (Reed, 2017), product manufacturing(Gigante-Barrera et al., 2017), and building performance analysis (Samuel et al., 2017). Existing studies of BIM maturity level (e.g., Level 2) in the construction field could be found in areas related to: BIM education to raise awareness and understanding of BIM (Gledson et al., 2016); BIM adoption among small and medium-sized enterprises (Hosseini et al., 2016); and stakeholder involvement such as client requirements (Eadie et al., 2015).

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

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

3. Methodology

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

<Insert Fig.1 here>

Step 1: Defining the scope of bibliometric research

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

Step 2: Bibliometric search

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

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

Step 3: Science mapping

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

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

Step 4: Trend analysis

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

4. Results of Scientometric Analysis

By inputting these pre-defined keywords in *Scopus*, originally *1003* publications were found. By limiting the type of documents to journal articles and excluding conference proceedings, *352* articles were shortlisted. As seen in Fig.1, further screenings of the shortlisted*352* articles were performed in order to narrow down articles within the scope of BIM-based research or practice in CEM-related activities, tasks and processes, or issue, or human factors. For example, studies such as Lopez and Love (2012) that include BIM in the abstract but did not focus on BIM application were removed. Other studies such as those of Penttilä (2006) and Rekola et al. (2010) that focused on the ICT (i.e., Information and Communication Technology) in architectural design, design management, design coordination, were also excluded in the literature sample because they did not have any particular reference to the construction stage. Studies like Eastman et al. (2010) and Steel et al. (2012) were also removed as they focused on the development of standards for information management without specific focus on CEM. Articles such as Kubicki et al. (2009) and Neff et al. (2010) that have integrated AEC practices were included. Others such as Wong et al. (2011), where BIM was studied in its application in CEM, building technology and quantity surveying were also included. Interdisciplinary studies such as Boton, et al. (2013) and Karan and Irizarry (2015) that involves CEM focusing on BIM in pre-construction or design stages, particularly those with contractors or construction personnel involved, were all included. At the end, a total of *276* articles remained for the later scientometric analysis.

4.1.An overview of the literature sample

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

<Insert Fig.2 here>

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

4.2.*Science mapping of journal sources*

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

<Insert Fig.3 here>

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

<Insert Table 1 here>

Five major measurement indicators are listed in Table 1, namely total link strength, number of published articles, total citation number, the average citation per publication, and the average normalized citation. The relationship between each pair of the indicators is presented in Table 2 based on the Pearson correlation analysis with 5% level of significance. It is seen that the former three measurements are generally highly correlated to each other with correlation coefficients over 0.900 and corresponding p values equal to 0.000. *AiC, JCEM*, and *IJPM* are the top three journals in terms of their quantity of publications, total citations, and total link strength. However, the average normalized citation, which measures the research significance or influence of a given journal, are found not significantly related to its total publications or citations. For example, these journals could be considered with higher impacts compared to others listed in Table 1: *IJPM* and *Safety Science,* based on that fact they have higher average normalized citations.

4.3.Co-occurrence of keywords

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

<Insert Fig.4 here>

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

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

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

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

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

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

More quantitative measurements of keywords are summarized in Table 3.

<Insert Table 3 here>

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

4.4.Citation of articles

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

<Insert Table 5 here>

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

The study of Bryde et al. (2013) received the highest citation as well as the average normalized citation, indicating its high influence in the academic field of BIM for CEM. The study of Sacks et al. (2010) focusing on lean in BIM received the second highest total citation number. However, the study of Lee et al. (2014) integrating ontology in BIM received second highest average normalized citation. Consistent with Table 3, ontology is one of the keywords with high influence. It can be found from Table 5 that most influential studies generally involve these topics suggested by Table 3 and Fig.4, including lean construction, ontology, integration and collaboration among project team members, BIM integration with other digital technologies (e.g., GIS or Geographic Information System), as well as interoperability issues in BIM practice involving IFC standard.

5. In-depth Discussions

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

<Insert Fig.5 here>

Fig.5 highlights the differences between traditional project delivery method (e.g., DBB) and fast-track in terms of their interactions with BIM. It also shows that BIM serves as a tool that facilitates multi-disciplinary collaboration and supports dynamic construction processes. Due to the fragmented practice of the construction industry (Arashpouret al. 2018), so far more BIM-related practice and studies have been conducted in the design or pre-construction stage than in CEM and facility management. The research of applying BIM in CEM remains a relatively new theme with the first two *Scopus*-indexed journal articles published in 2008. But since then this research domain has gained a significant increase, from below *10* journal articles published yearly before 2010, slightly more than *10* after 2011, to over *40* articles published annually after 2015. The increasing trend of BIM-based research in CEM can be expected in the follow-up years. BIM is envisioned to play an important role to integrate design, construction and facility management stages through coordinated changes in the project life cycle (Pilehchian et al., 2015). Based on these existing BIM-based studies that focus on the construction stage or integrated design and construction, a few specific directions for the near-future research are proposed in terms of project delivery system, technological integration, non-traditional construction technique, and continued BIM pedagogy in CEM.

5.1.Fast-track project delivery and BIM

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

5.2.Integration of digital technologies and methods in construction

BIM has been tried in its integration with other digital construction technologies, such as Virtual Reality (Xieet al. 2011). Fang et al. (2016) adopted BIM and cloud-enabled radio-frequency identification (RFID) inconstruction site tests and showed that BIM and cloud-enabled RFID has a promising potential in practical applications such as site security control, safety management, asset management, and productivity monitoring. The study of Fang et al. (2016) served as an example of integrating the passive localization system in RFID, the visualization system in BIM, and the cloud computing system. RFID integration with BIM can be found in multiple other studies (e.g., Ikonen et al., 2013 ;Costin et al. 2015) to enhance the security, safety, quality control, worker logistics, and maintain local ordinances of construction projects. Other technologies, such as GIS, havedisplayed their potential to work with BIM in construction projects. The integration of BIM and geospatial analyses can enhance managing the planning process during the design and pre-construction stages (Karan and Irizarry, 2015). A few studies (e.g., Bansal 2011a; Bansal 2011b; Elbeltagi and Dawood 2011; Karan and Irizarry, 2015) worked on integrating GIS and BIM to enhance site collaboration and construction information sharing through the visualization and modelling functions of BIM and the spatial planning feature in GIS. GIS can use the details of building components provided by BIM in preconstruction planning, and BIM can then visualize the GIS analyses outcomes in a virtual world (Irizarry and Karan, 2012).A main challenge of promoting the application of multiple BIM tools and their integration with other digital technologies (e.g., GIS and RFID) is the lack of interoperability (Gökçe et al., 2013; Ciribini et al., 2016; Petriet al., 2017), involving issues related to data storage, sharing, semantics, and ontology (Lee et al. 2014; Nepal and Staub-French, 2016; Hamledari et al., 2018). For example, Karan and Irizarry (2015) identified one of the main interoperability gaps between BIM and GIS in the semantic level, which required more future work to develop the interoperable framework as well as the IFC-compatible standard. The lack of automated information transformation within BIM to support construction site visualization and decision making was also reported in more recent research such as Li and Lu (2018), who recommended the future integration of 4D BIM to enable the automated generation of site animation. The interoperability-focused research in BIM implementation is an ongoing mainstream research theme.

5.3. Integration of innovative construction techniques and BIM

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

So far BIM has been more widely applied in conventional construction, and has not been fully utilized to assist off-site construction (Abanda et al., 2017). The integration of BIM has not been achieved from the practical aspect (Goulding et al., 2015). Off-site construction provides an alternative approach by shifting the building construction process away from sites to a controllable factory environment (Jiang et al., 2018). Off-site construction, through a cleaner construction method (Mao et al., 2016; Hwang et al., 2018), provides a sustainable and integrated platform. BIM is inherently connected to off-site construction (Babič et al., 2010; Abanda et al., 2017; Mann, 2017). For example, Zhonget al. (2017) introduced a multi-dimensional BIM platform involving RFID to achieve the real-time visibility and traceability in prefabricated construction. Liet al. (2016) adopted the BIM-centered strategy to facilitate stakeholder communication aiming to mitigate schedule risks in off-site construction projects. Nevertheless, the internal relationship between BIM and off-site construction have still not been sufficiently studied (Hosseini et al. 2018) as expected. However, applying BIM in the project delivery process of off-site constructionis becoming critical to improve the productivity of the construction industry (Abanda et al., 2017; Jin et al., 2018b), for example,the implementation of BIM Level 2 for off-site construction project delivery described by Nicola Scammell (2018) to assist just-in-time deliveries.

5.4.BIM pedagogy in CEM curriculum

It is seen in Table 3 that pedagogy and education is the mostly widely studied topic in BIM for CEM. This is consistent with previous BIM-based studies in CEM (e.g., Kim, 2012; Lee et al., 2013; Ghosh et al., 2015; Zhang et al., 2016). The concern of lack of sufficient BIM education has been raised on addressing the gap between academia and industry. A growing number of AEC programs have begun to incorporate BIM contents in their curriculum (Bozoglu 2016). Recent pedagogical studies such as Zhang et al. (2018a) adopted project-based teamwork stressing the project delivery process in BIM education. Interdisciplinary BIM pedagogy (e.g., Solnosky et al., 2014; Jin et al., 2018a) is becoming a commonly adopted teaching strategy to encourage students' cross-disciplinary teamwork. More pedagogical studies could continue the interdisciplinary education motivating students from different AEC subjects to work in a project-based or problem-based approach (Jin et al., 2016). Existing BIM pedagogical studies (e.g., Tang et al., 2015; Zhao et al., 2015) have more focused on students' perceptions or feedback right after the learning cycle. The effect of certain teaching and learning strategy in students' longer-term career development can be traced as suggested by Li et al. (2018a). According to the BIM learning and practice framework proposed by Zou et al. (2018), several human factors in BIM practice, such as perceptions, understanding, expectations, and behaviours, could be further investigated and compared between college graduates and AEC professionals. As suggested by Zou et al. (2018), students could gain certain consistent perceptions towards BIM implementation in the construction industry as industry professionals do. However, limited studies have been performed investigating the learning and practical cycle of BIM learners and practitioners, specifically, how gaining practical experience would affect individuals' perceptions of BIM, and how the multiple factors (e.g., local BIM culture and climate) would affect BIM learners' perceptions.

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

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

<Insert Fig.6 here>

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

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

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

7. Conclusion

This study adopted a holistic review approach to evaluate BIM-based research in construction engineering and management (CEM). It aimed to fill the gap of previous BIM-review-based studies by focusing on CEM-related technological or managerial aspects, such as cost estimate, constructability review, and integrated design and construction. Following the defined scope of literature review, a bibliometric search of journal articles, scientometric analysis, and qualitative discussion were performed to deliver the comprehensive review.

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

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

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

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

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

This review work offers the implications for both academics and practitioners in the CEM fields in terms that: (1) the understanding of the latest research topics (e.g., collaborative BIM, interoperability, etc.) provides the insights for practitioners regarding what are key issues in implementing BIM in the construction industry; (2) the current study focuses existing BIM-based work in CEM and foresees that BIM adoption in being extended from pre-construction to construction stages; (3) the summaries and recommended directions for future study address the joint needs for both academic research and industry practice such as BIM integrated with off-site construction; and (4) this study provides the hints on why BIM-based research is critical for improving the construction performance (e.g., sustainability) and how BIM can be effectively adopted to improve the construction productivity. Specifically, BIM, due to its collaborative nature, could be utilized to more efficiently handle the fragmented construction activities. The application of BIM, as the digital platform to improve the construction project delivery efficiency does not only ask technical advancement (e.g., enhanced interoperability between different software platforms), but also the integrated project delivery approach. Finally, the governmental authority, academics, and industry practitioners should develop a consistent view on the movement, needs, limitations, and actions to promote the transformation of the construction industry towards higher efficiency assisted by digital technologies and connected multi-stakeholder platform.

The literature sample adopted in this review-based study linking BIM into CEM was limited to journal articles emphasizing academic research, without sufficiently addressing the practical concerns from the industry perspective. It remains unclear of the similarities and differences between academia and industry in perceiving the movement of BIM in being applied in construction field work. As a recommendation for further study, it would be interesting to establish the degree of comparative significance between the six proposed directions for future scholarly work in the perspectives of both academics and practitioners. The perceptions between academics and industry practitioners towards these identified research gaps and directions can be further compared. It would also be necessary to provide further details or breakdown of each of the six proposed directions in order to define key 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]
Automation in Construction (AiC)	84	40	1066	26.7	2.0
Journal of Construction Engineering and Management (JCEM)	59	26	735	28.3	1.1
International Journal of Project Management (IJPM)	49	10	320	32	3.7
Journal of Information Technology in Construction	27	12	42	3.5	0.4
Journal of Civil Engineering and Management	26	8	48	6	0.9
Electronic Journal of Information Technology in Construction	17	10	250	25	1.1
Engineering, Construction and Architectural Management	12	7	25	3.6	0.4
Construction Management and Economics	12	4	67	16.8	1.3
Journal of Professional Issues in Engineering Education and Practice	8	7	102	14.6	0.8
Advanced Engineering Informatics	8	5	152	30.4	1.6
Journal of Computing in Civil Engineering	7	10	117	11.7	0.9
Construction Innovation	7	9	35	3.9	0.3
Journal of Management in Engineering	7	6	55	9.2	1.3
Safety Science	4	3	84	28	3.1
Malaysian Construction Research Journal	2	3	21	7	0.5
International Journal of Construction Education and Research	1	5	30	6	0.4

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

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

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	*r*		0.912	0.914	0.482	0.375
	p value		0.000	0.000	0.059	0.153
Number of publications	*r*			0.949	0.351	0.131
	p value			0.000	0.183	0.630
Total citation	*r*				0.598	0.339
	p value				0.014	0.199
Average citation	*r*					0.787
	p value					0.000

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

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

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	*r*		0.857	0.083	-0.022
	p value		0.000	0.645	0.905
Occurrence	*r*			-0.044	0.028
	p value			0.807	0.877
Average citation	*r*				0.194
	p value				0.279

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

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

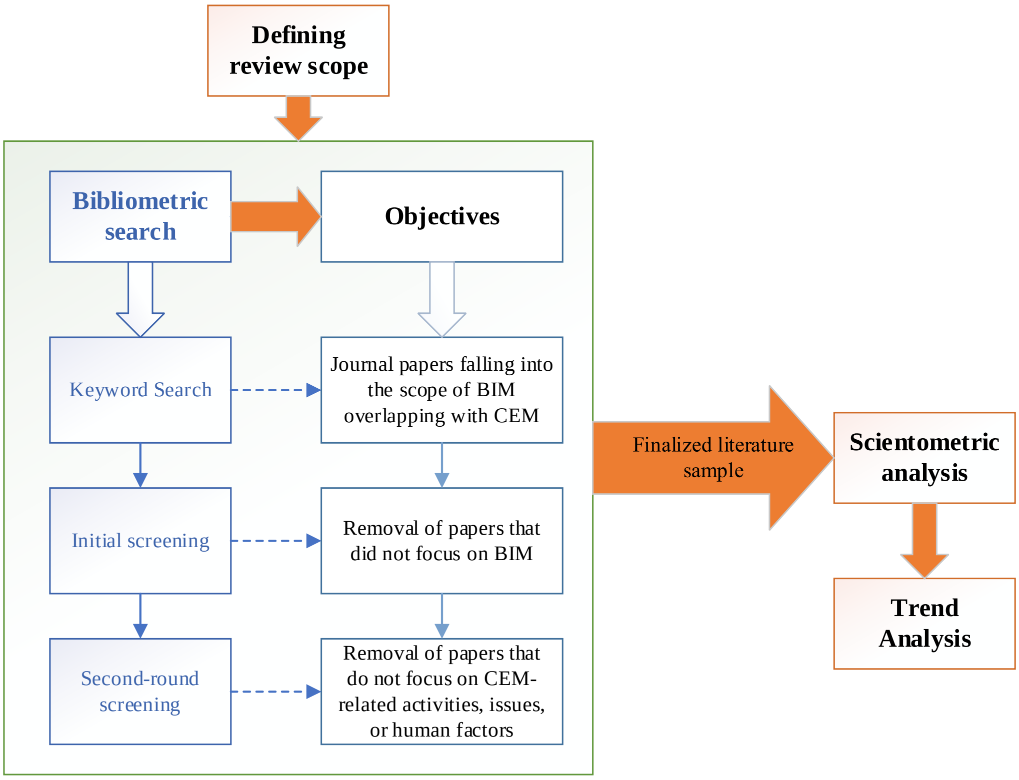
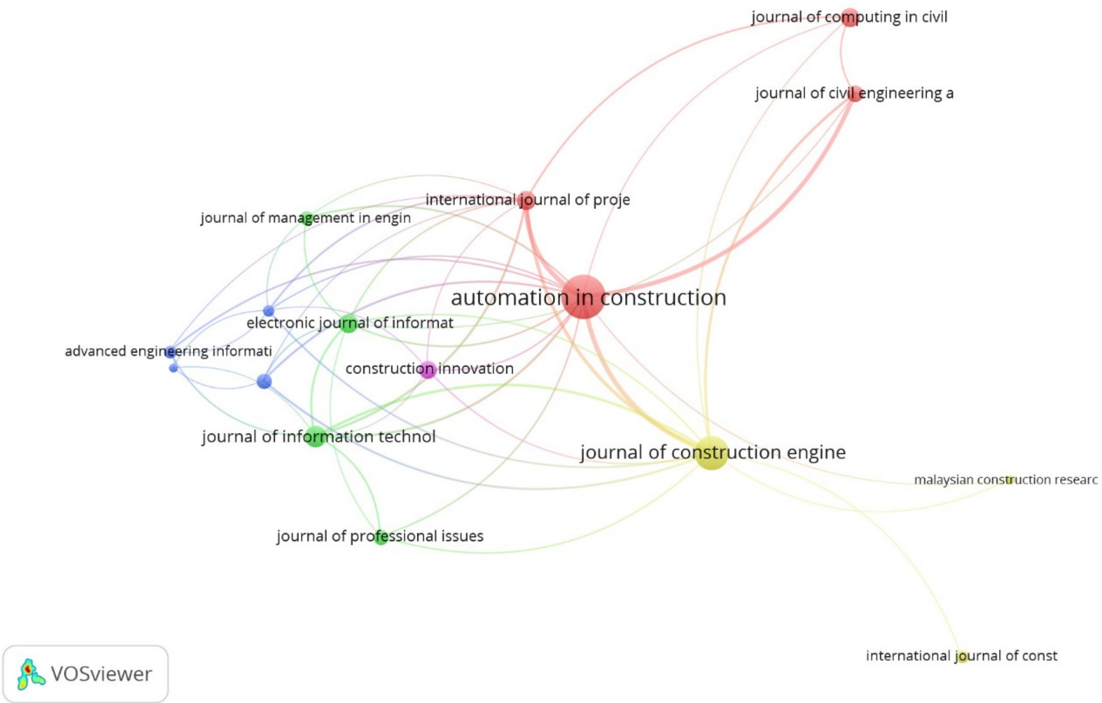


Fig.1. Description of the four-step workflow in the review of BIM-based research in CEM

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

Fig.2. Yearly publications from 2009 to 2018



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

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

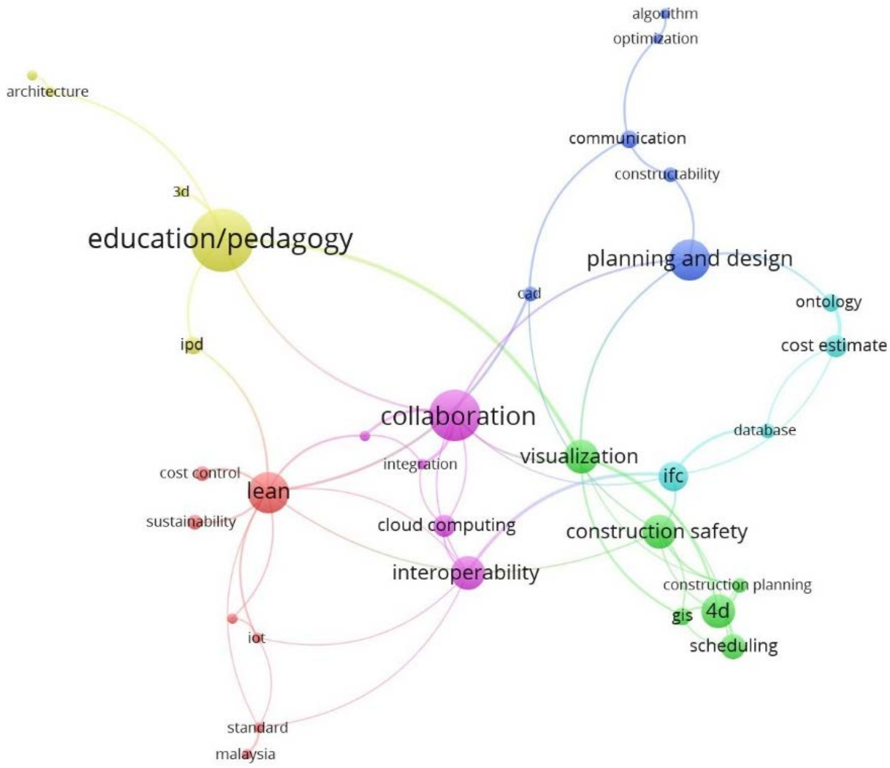
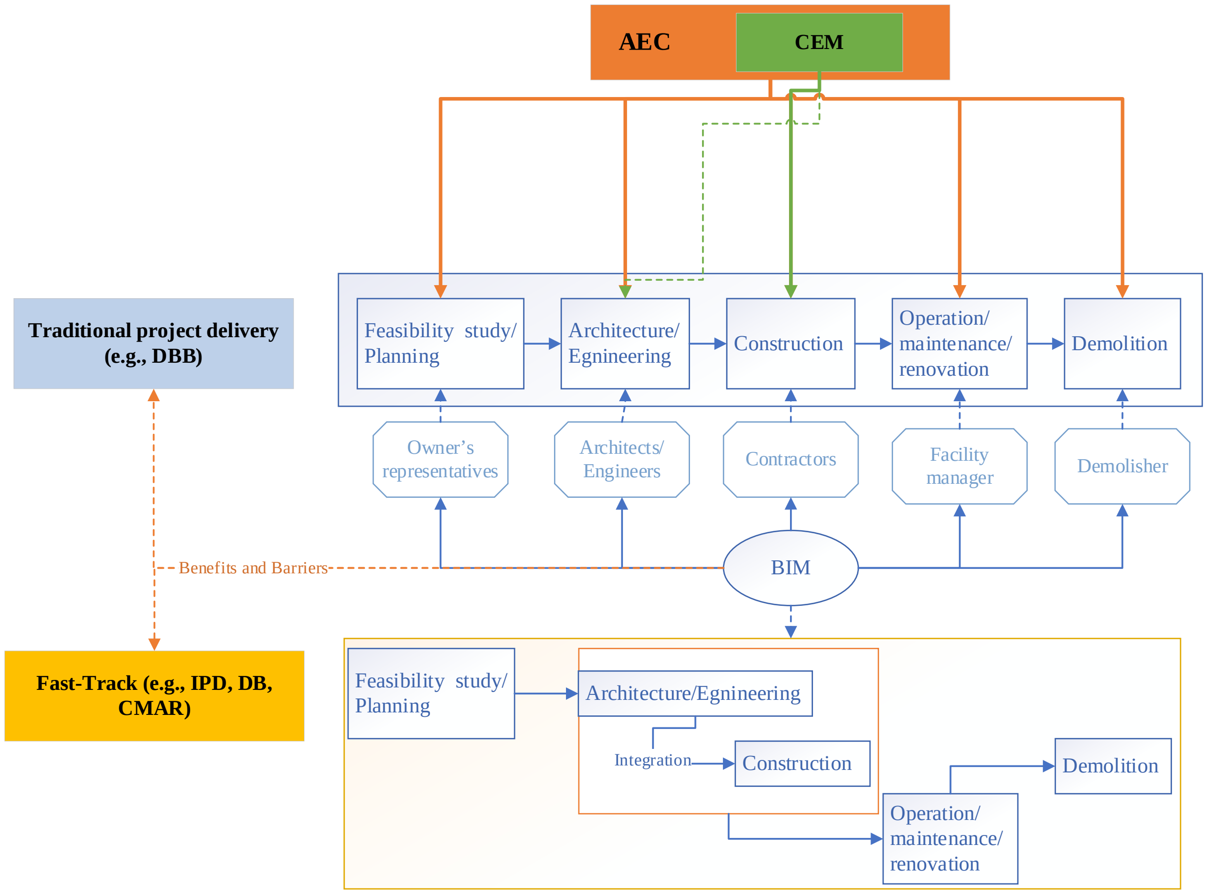


Fig.4. Co-occurrence of keywords in the research of BIM in CEM



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

Fig.5. Illustration of this review-based study capturing BIM-based CEM research in the context of project delivery methods and project phases

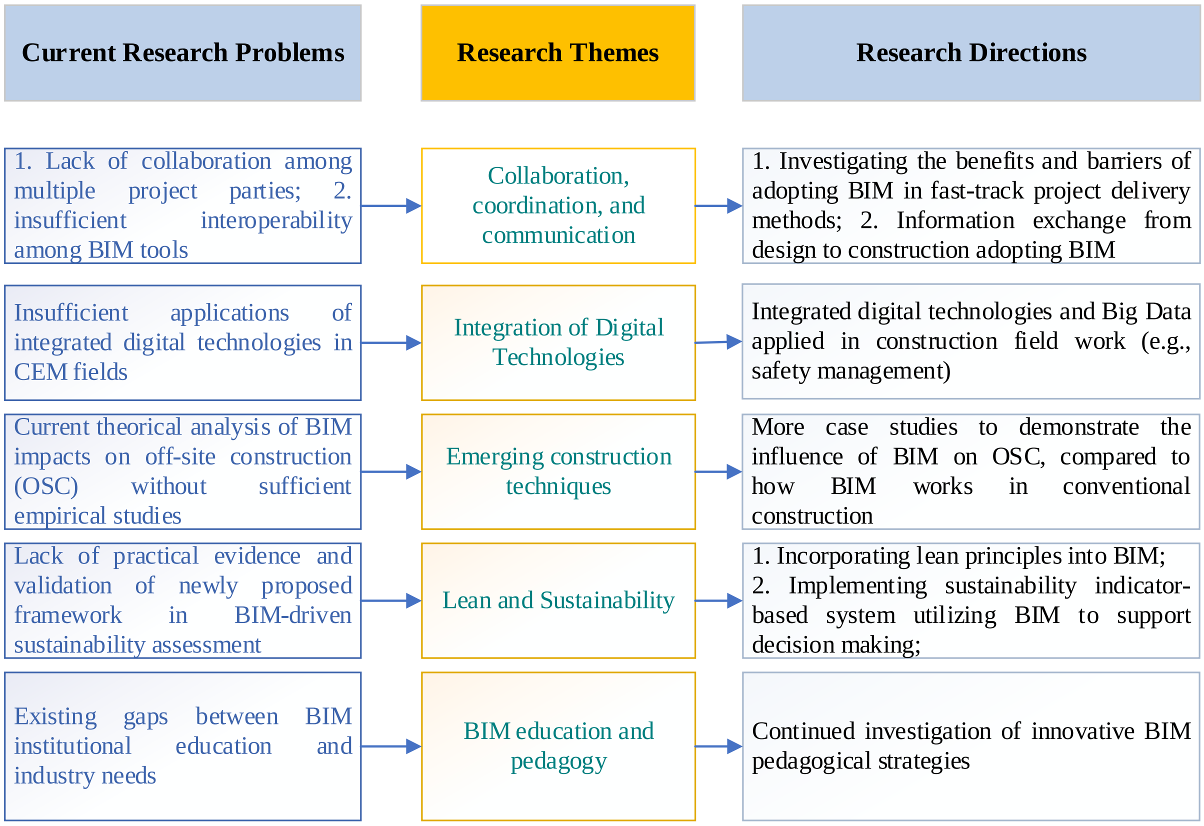


Fig.6. Framework proposing directions in BIM-based CEM research