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Transformation from IT-based knowledge management into BIM-supported knowledge management: A literature review

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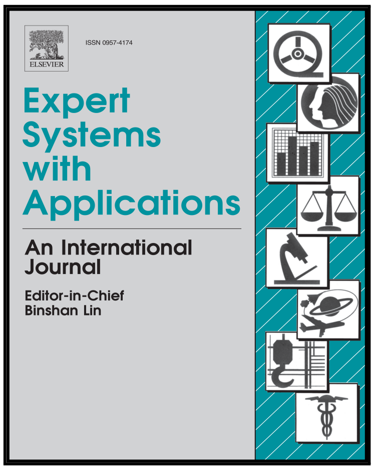

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Highlights

- The construction industry is knowledge intensive and relies on effective KM.
- There are various weaknesses within existing IT-based KM tools or systems.
- BIM has distinctive features to support KM in construction projects.
- BIM-supported KM is advantageous over IT-based KM.
- BIM-supported KM is just emerging and therefore needs future development.

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Transformation from IT-based knowledge management into BIM-supported knowledge management: a literature review

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Abstract

Construction is a knowledge-intensive industry, in which organizations are known for the delivery of products and services, relying on different types of knowledge. To manage knowledge effectively, various information technology (IT) models and systems have been developed for knowledge management (KM) in the construction industry over the years. As the next generation of IT application in construction, building information modeling (BIM) is increasingly used today to aid KM. Compared to generic IT tools, BIM has some distinctive features, such as parametric modeling, virtual visualization and centralized platform. However, how to apply these features of BIM to better serve KM has not yet been well summarized and analyzed. In this research, 115 papers on IT-based KM and 73 papers on BIM-supported KM are reviewed, based on which an integrated framework is developed to describe the current status and future directions for KM in IT-generic and BIM-specific contexts. It is followed by a conceptual model of BIM-supported KM which shows the possible KM factors and their relationships in the BIM environment. This research highlights the transformation from IT-based KM into BIM-supported KM. It contributes to the identification of remaining challenges to BIM-supported KM and the elaboration of BIM-supported KM in construction research and practice.

Keywords: Construction industry; Building information modeling; Knowledge management

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Abstract

Construction is a knowledge-intensive industry, in which organizations are known for the delivery of products and services, relying on different types of knowledge. To manage knowledge effectively, various information technology (IT) models and systems have been developed for knowledge management (KM) in the construction industry over the years. As the next generation of IT application in construction, building information modeling (BIM) is increasingly used today to aid KM. Compared to generic IT tools, BIM has some distinctive features, such as parametric modeling, virtual visualization and centralized platform. However, how to apply these features of BIM to better serve KM has not yet been well summarized and analyzed. In this research, 115 papers on IT-based KM and 73 papers on BIM-supported KM are reviewed, based on which an integrated framework is developed to describe the current status and future directions for KM in IT-generic and BIM-specific contexts. It is followed by a conceptual model of BIM-supported KM which shows the possible KM factors and their relationships in the BIM environment. This research highlights the transformation from IT-based KM into BIM-supported KM. It contributes to the identification of remaining challenges to BIM-supported KM and the elaboration of BIM-supported KM in construction research and practice.

Keywords: Construction industry; Building information modeling; Knowledge management

1. Introduction

Knowledge is one of the most important resources in any organizations (Alavi & Leidner, 2001; Ofek & Sarvary, 2001). Nonaka (1994) defined knowledge as justified personal beliefs that enable individuals to take effective actions. Dretske (1983) and Quigley & Debons (1999) distinguished knowledge from data and information. Dretske (1983) perceived that data are raw numbers and symbols while information is a sequence of meaningful symbols and messages. Quigley & Debons (1999) indicated that information is essential for answering ‘who’, ‘when’, ‘what’, and ‘where’ questions while knowledge answers ‘how’ and ‘why’ questions. For this reason, data, information and knowledge can be placed at three different levels: low, medium and high. Construction organizations are project-based. In construction projects, knowledge is widely recognized as a critical factor to overcome time delays (Alaghbari et al., 2007; Song, Mohamed, & Abourizk, 2009), cost overruns (Baloi & Price, 2003; Iyer & Jha, 2005), quality defects (Josephson & Hammarlund, 1999; Chong & Low, 2005), and safety accidents (Goh & Chua, 2010; Hallowell, 2011). Undoubtedly, close attention should be paid to KM in construction projects.

KM refers to the application of collective knowledge to achieve the goals and objectives of an organization. It is a process that involves different activities, such as knowledge capture, sharing, storage, retrieval and reuse (Wiig, 1997; Alavi & Leidner, 2001; Gold, Malhotra, & Segars, 2001). Compared to projects in other industries, construction projects are heterogeneous, fragmented and diverse (Anumba, Egbu, & Carrillo, 2008). In a construction project, different parties, such as client, architect, engineer, contractor and facility management (FM) team that deliver operation, maintenance and services, have various backgrounds, use diverse terminologies, and undertake different tasks (Baiden, Price, & Dainty, 2006). For this reason, managing knowledge collaboratively is a challenge. On the other hand, a construction project usually contains different structural elements with different building materials (Anumba, Egbu, & Carrillo, 2008). Obviously, construction projects require massive and sophisticated knowledge that is difficult to manage. In addition, the required knowledge often changes during different project phases across the project lifecycle (Kamara et al., 2002).

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Various IT tools have been developed over the years to aid KM in construction projects. For example, Kivrak et al. (2008) developed a web-based system to facilitate knowledge capture. Chen (2012) established an integrated model for knowledge sharing based on the interpretation of rules. El-Diraby & Zhang (2006) used ontology in a corporate memory system to improve knowledge storage. Ontology was applied in the system developed by Park et al. (2013c) to suggest keywords during the search process, which made knowledge retrieval easy. However, there are still gaps within existing studies on IT-based KM. For example, existing IT tools fail to consider the combination of knowledge with its related building objects and the relationship between building objects that are affected by knowledge (Motawa & Almarshad, 2013). On the other hand, knowledge sharing using existing IT tools mainly promotes the exchange of knowledge but fails to achieve the mutual understanding of knowledge between project parties (Ho, Tserng, & Jan, 2013). Furthermore, collaborative KM using existing IT tools usually lacks the direct interaction with building models (Lin, 2014). In addition, knowledge in existing IT systems is generally scattered across different documents, such as value engineering proposal, change orders and post project review, which makes KM difficult (Deshpande, Azhar, & Amireddy, 2014). It is also difficult to exchange and retain knowledge through different phases of a construction project in the generic IT context (Anumba, Egbu, & Carrillo, 2008; Dave & Koskela, 2009).

BIM is one of the most promising developments in today’s construction industry. It is viewed as the next generation of IT application in construction (Azhar, 2011). According to the National Institute of Building Sciences (2015), BIM can be defined as a digital representation of physical and functional characteristics of a facility. A BIM model digitally contains geometric and non-geometric information to describe building elements (Eastman et al., 2011). Given that the complete 3D building model and its relevant information are all included in a single model, BIM enables exchange and sharing of building information between project parties (Fu et al., 2006). BIM also refers to digital visualization and repository of building information, which is collected, utilized and updated across the lifecycle of a project, from design through construction to FM (Taylor & Bernstein, 2009). The information in the BIM model can be used for a wide range of purposes, such as code checking, clash detection, construction planning simulation, and energy performance analysis (Lin, 2014).

A number of studies have started to introduce BIM into KM in construction projects. Some of them use customized parameters of BIM to capture and retain knowledge during a project (Meadati & Irizarry, 2010; Motawa & Almarshad, 2013; Deshpande, Azhar, & Amireddy, 2014). Others highlight the importance of BIM visualization to KM (Lin, 2014). According to such studies as Grover & Froese (2016), knowledge can be collaboratively managed in the BIM environment based on a central platform. Compared to IT-based KM that has been long studied, BIM-supported KM is relatively new. Unlike numerous studies on IT-based KM, research work investigating BIM-supported KM is still limited and therefore demands more efforts. Although many review works have been done in different BIM research areas, such as BIM for existing buildings (Volk, Stengel, & Schultmann, 2014), BIM for sustainability (Wong & Zhou, 2015), BIM for risk management (Zou, Kiviniemi & Jones, 2017), and BIM for FM (Pärn, Edwards, & Sing, 2017), there is a lack of a systematic review to explore BIM-supported KM. As a result, it is difficult to take full advantage of the distinctive features of BIM to improve the effectiveness of KM in construction. It is widely recognized that BIM brings a revolution to the construction industry. However, BIM is still mainly used today to deal with information. Moving from the information level to the knowledge level will maximize the benefits of introducing BIM into the construction industry.

This research performs a systematic review of relevant literature. It aims to bridge the research gap within existing studies. The objectives of this research include: (1) summarizing the studies on IT-based KM and BIM-supported KM; (2) identifying the difficulties encountered by IT-based KM; (3) confirming the potential of BIM to support KM; (4) examining the use of BIM to overcome the difficulties of IT-based KM; and (5) outlining the possible directions for BIM-related research to facilitate effective KM. The rest of this paper is presented as follows. Section 2 illustrates research methods used in this research. An overview of IT and BIM-related publications on KM is given in Section 3. Section 4 provides a discussion about IT-based KM and BIM-supported KM in different KM activities, based on which an integrated framework is developed to show current and future

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trends for relevant research. Subsequent to the development of the integrated framework, a conceptual model is proposed to describe the possible KM factors and their relationships in the BIM environment. Section 5 summarizes the findings and implications of this research.

2. Methodology

2.1. Overview of literature review methods

A systematic review is adopted to achieve the objectives of this research. A literature review can provide an up-to-date understanding of a subject, identify significant issues for the existing body of knowledge, and develop a knowledge basis for further research (Gray, 2014). In this research, relevant literature is reviewed, including existing studies on IT-based KM and BIM-supported KM. According to Jesson, Matheson, & Lacey (2011), a systematic review requires transparent process, rigorous search, screening protocol, rational analysis, and evidence synthesis. This research includes four main stages shown in Figure 1. In this research, the information of selected publications (journal/conference title, paper title, and publication year), focused project phase (design, construction, FM and project lifecycle) and targeted KM activities (capture, sharing, storage, retrieval and reuse) is extracted manually. To avoid any possible author bias, the databases and keywords were identified based on the discussion between two authors. Then, the first author of this study selected the papers, and extracted information independently, which was followed by double-check of the second author based on the same criteria. The disagreements were resolved through discussion to reach a consensus. All extracted information is sorted out and descriptive statistical analysis is conducted to provide an overview of IT and BIM-related publications.

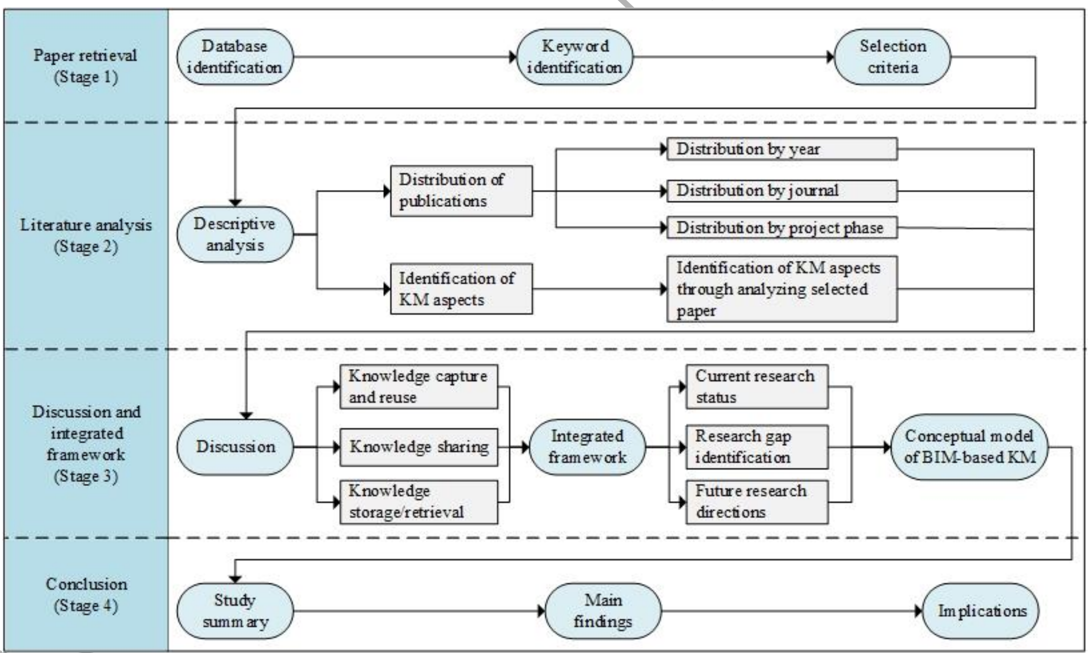

Fig. 1. Flow chart of research methods.

KM aspects and KM during project phases are two focuses of this study. According to Anumba, Egbu, & Carrillo (2008), knowledge is required during different project phases (design, construction and FM) or throughout the project lifecycle. In this study, both deductive and inductive approaches are adopted for content analysis, in which categories can be determined based on pre-existing theory and collected information (Neuendorf, 2016). KM is an integrated process that includes knowledge capture, sharing, storage, retrieval and reuse (Wiig, 1997; Alavi & Leidner, 2001; Gold, Malhotra, & Segars, 2001). Accordingly, these KM aspects were confirmed as initial categories through deductive reasoning. As the literature review continued, several new KM aspects, such as knowledge classification, representation and visualization, were identified in the way of inductive coding. After examining the relationships between initial categories and new KM aspects, the latters were considered as sub-categories of the formers. In this study, Section 3.3 describes the distribution of publications during different project phases while Section 3.4 presents the distribution of publications in different KM aspects, through which it is possible to analyze the degree of concentration, or the level of intensity, during each project phase and in each KM aspect, respectively. All these provide a basis for exploring the current research status and future research directions of IT-based KM and BIM-supported KM.

2.2. Paper retrieval

The paper was retrieved in November 2018. The paper retrieval process in this research is divided into two parts. The first part focuses on the publications on IT-based KM. The second part concerns the publications on BIM-supported KM. Four databases are chosen for paper retrieval, namely Web of Science, Scopus, ScienceDirect and American Society of Civil Engineers (ASCE) Library, among which Web of Science is the core collection. The four databases are chosen in this research due to their comprehensive coverage of engineering management, construction management and construction IT. However, minor variations exist between the four databases in terms of their focus areas. The variations are important because they can reduce the possibility of missing any useful or important publications for the literature review.

This research considers the intersection of IT tools and KM and the intersection of BIM and KM. To retrieve the literature on IT-based KM, the following search schemes are applied to verify a paper's Title, Abstract and Keywords (Topic instead in Web of Science and Anywhere instead in ASCE Library): 'Knowledge management' AND 'Construction project' OR 'Construction project management' OR 'Civil engineering management' OR 'Engineering project'. To search the literature on BIM-supported KM, the following search schemes are devised: 'Knowledge management' AND 'Building information modeling' OR 'Building information modelling' OR 'Building information model' OR 'BIM'. Literature search is not limited to a certain date range. The search results are screened by limiting the search to the following subject categories: 'Engineering' (Scopus); 'Engineering and civil' and 'Construction building technology' (Web of Science); and 'Construction management', 'Information management' and 'Building information modeling' (ASCE Library). Since ScienceDirect does not allow users to set any subject category, the literature from ScienceDirect that does fall into engineering and construction-related subject categories is removed manually. Given that a significant number of existing studies have investigated IT-based KM, this research only includes papers published in peer-reviewed academic journals. In contrast, BIM is an emerging subject and there are only a small number of journal publications on BIM-supported KM. Therefore, both journal and conference papers on BIM-supported KM are retrieved in this research. For both IT-based KM and BIM-supported KM, literature search is only limited to the papers written in English. The literature search results in each database and the total number of search results for IT-based KM and BIM-supported KM are shown in Table 1.

Table 1
Literature search results.

	Web of Science	Scopus	ScienceDirect	ASCE Library	Total (before removing duplications)	Total (after removing duplications)
IT-based KM	489	880	160	247	1776	1179
BIM-supported KM	176	412	90	923	1601	1399

2.3. Paper selection

Selection criteria are developed in Table 2 to screen the publications that have no relevance to IT-based KM or BIM-supported KM in construction. The selection process consists of two steps: (1)

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selection through scanning the title, abstract and keywords of a paper; and (2) selection through scanning the full text of the paper. Based on the title, abstract and keywords, any paper rated 1 or 2 is removed without scanning the full text. For any paper rated 3 or 4, in addition to the title, abstract and keywords, the full text must be scanned to determine whether the paper can be included in the literature review. On the other hand, any paper rated 5 is evidently suitable for the literature review and therefore it is unnecessary to extend scanning from the title, abstract and keywords to the full text. As a result of screening irrelevant publications, the number of selected papers at each level of selection criteria is shown in the Table 2.

Table 2
Literature selection criteria and results.

Level	IT-based KM	Number of selected papers	BIM-supported KM	Number of selected papers
5	A paper is highly consistent with IT-based KM in construction and engineering project management (CEPM).	37	A paper is highly consistent with BIM-supported KM in CEPM.	25
4	Although a few IT techniques and KM are mentioned in the title, abstract and/or keywords of a paper, IT for KM is not specified in the abstract.	32	BIM for KM is not emphasized in the abstract although the title, abstract and/or keywords of a paper contain the terminologies about KM and BIM.	15
3	Although a paper focuses on KM, the title, abstract and/or keywords of the paper do not mention the adoption of IT tools, failing to confirm in the title, abstract and/or keywords that the paper targets IT-based KM.	41	Although a paper is related to BIM and the title, abstract and/or keywords of the paper contain a few terminologies about KM, whether a paper targets BIM-supported KM cannot be confirmed in the title, abstract and/or keywords.	29
2	A paper is related to IT application in CEPM but does not concern KM issues.	0	A paper is related to BIM application in CEPM but does not investigate KM.	0
1	A paper on IT does not have any relevance to KM because IT is used for other purposes.	0	A paper on BIM does not have any relevance to KM because BIM is used for other purposes.	0

Based on the screening of irrelevant publications, 110 and 69 papers are left for IT-based KM and BIM-supported KM, respectively. A snowball technique is then used to reduce the possibility of missing any relevant publications. Snowballing refers to using the reference list of a paper or the citation list of a paper to identify additional papers (Booth, Sutton, & Papaioannou, 2016). The same criteria shown in Table 2 are adopted in this research for snowballing. This leads to the identification of five additional papers on IT-based KM and four additional papers on BIM-supported KM, which are added to the paper collection. Finally, 115 papers on IT-based KM and 73 papers on BIM-supported KM are selected in this research for the literature review.

2.4 Analysis tools

OriginPro is a software package that analyzes and visualizes the data inputted (OriginLab, 2018). This study applied OrginPro 9 to visualize the information about KM activities according to the publication years of related papers. The visualization results can be shown as contour maps. On the other hand, Unified Modeling Language (UML) provides a standard way to visualize the design of use case diagram (Dennis, Wixom, & Tegarden, 2015). Use cases represent the functional requirements of a system. Use case diagram is a simplified and graphical representation of how the system is designed. It can provide a high-level view of the system. UML is employed in this study to develop a conceptual model to show the possible factors of KM (namely use cases) and the relationship between them in a BIM-supported KM system.

3. Analysis of IT and BIM-related publications

In Section 3, studies on IT-based KM and BIM-supported KM are quantitatively analyzed to reveal research trends.

3.1. Overall distribution of publications

Table 3 summarizes the distribution of 115 articles on IT-based KM and 73 articles on BIM-supported KM. Articles on IT-based KM are all journal papers. On the other hand, 40 journal papers and 33 conference papers are selected in this research for BIM-supported KM. Most of the journals and conference proceedings have engineering and construction backgrounds. As shown in Table 3, the top five journals are *Automation in Construction*, *Journal of Computing in Civil Engineering*, *Journal of Construction Engineering and Management*, *Journal of Information Technology in Construction*, and *Journal of Civil Engineering and Management*. They are often viewed as the influential journals in the research field of engineering and construction management and meanwhile have relevance to construction IT and/or BIM (Wing, 1997; Xue et al., 2012). Except for *Journal of Information Technology in Construction*, they are all included in the Science Citation Index (SCI). In addition to construction-specific journals, BIM-supported KM has also attracted research attention from non-construction journals, such as *Expert Systems with Applications*, *Journal of Knowledge Management* and *Scientific World Journal*, which indicates wider popularity and recognition of BIM in today's research and practice.

Table 3
Number of papers by journal and conference.

No.	Journal title	Number of papers
1	Automation in Construction	38
2	Journal of Computing in Civil Engineering	15
3	Journal of Construction Engineering and Management	11
4	Journal of Information Technology in Construction	10
5	Journal of Civil Engineering and Management	6
6	Journal of Management in Engineering	5
7	Advanced Engineering Informatics	4
8	Safety Science	4
9	Canadian Journal of Civil Engineering	3
10	Construction Innovation	3
11	Expert Systems with Applications	3
12	Journal of Knowledge Management	3
13	KSCE Journal of Civil Engineering	3
14	Scientific World Journal	3
15	Artificial Intelligence for Engineering Design, Analysis and Manufacturing	2
16	Computer-Aided Design	2
17	Computers in Industry	2
18	Journal of Information and Knowledge Management	2
19	Facilities	2
20	Other journals	34
21	Conference paper	33
Total		188

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3.2. Distribution of publications by year

Figure 2 shows the distribution of relevant publications by year. IT-based KM has been studied since the late 1980s. For example, Paulson Jr et al. (1989) proposed the potential of using intelligent machines for KM in construction projects. Adams (1993) explored the application of relational databases for knowledge representation and processing. Despite abnormalities in 2008 and 2010, Figure 2 describes a steady increase in the number of studies on IT-based KM from 2004 to 2012. However, this number has dramatically decreased since 2012. The concept of BIM-supported KM was firstly proposed by Lee, Sacks, & Eastman (2006). BIM-supported KM has become an emerging area since 2009. Interestingly, the volume of BIM-related research on KM grew from 2012 to 2014 while the volume of IT-related research on KM sharply declined since 2012. This finding implies the transformation of research focus in construction from IT-based KM to BIM-supported KM as a new approach. Compared to IT-based KM, BIM-supported KM has drawn more research attention in recent six years although the volume of BIM-related research on KM stopped growing between 2015 and 2017.

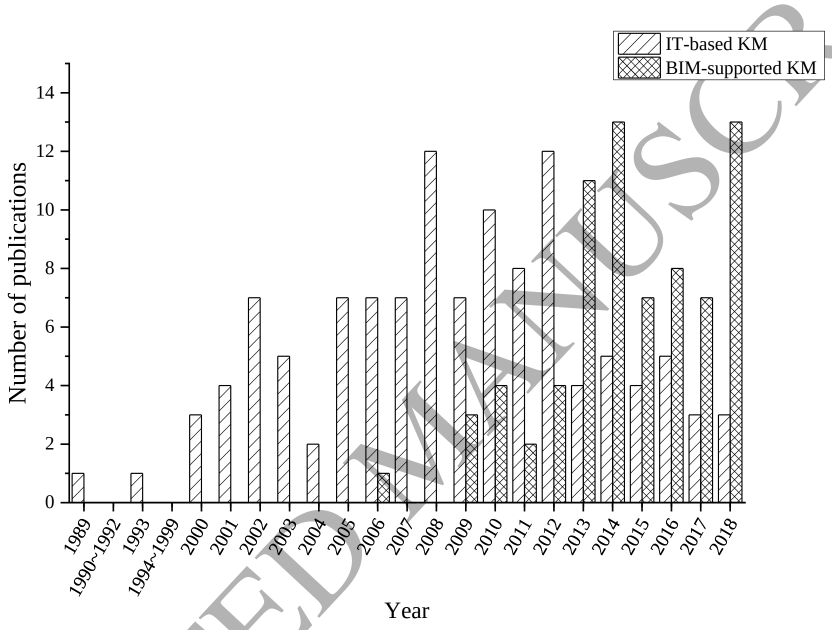

Fig. 2. Distribution of publications by year.

A considerable proportion of studies on BIM-supported KM combine BIM and some traditional KM techniques to aid KM. These traditional KM techniques mainly include ontology and case-based reasoning (CBR). The features of BIM and the capabilities of traditional KM techniques are mutually beneficial. In the early stage, the combination of BIM and traditional KM techniques provided a big research space, which led to explosive growth of relevant research in the short term. As time goes on, the potential of the combination has been largely exploited. To a certain extent, this explains why the number of papers on BIM-supported KM decreased to seven or eight per year between 2015 and 2017. Recently, it is identified that some new KM tools, such as semantic-web and spoken dialogue systems, can be involved in the BIM environment to aid KM. It is also identified that BIM-supported KM can be applied to some new areas of project management, such as material control and off-site prefabrication. As a result, a new round of research growth of BIM-supported KM is observed in 2018. It is expected that research interest in BIM-supported KM will continue to rise and become diversified.

3.3. Distribution of publications by project phase

Figure 3 presents the distribution of 188 publications by project phase. Many studies on IT-based KM are related to the construction phase, which is followed by the design phase. Meanwhile, two studies,

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namely Ugwu (2005) and Anumba, Egby, & Carrillo (2008), explore IT-based KM for both design and construction (D&C). Compared to design and construction, FM and project lifecycle draw less research attention from IT-based KM. Among the 115 studies on IT-based KM, only five studies address KM issues during FM. Although many studies highlight the importance of managing a project from the lifecycle perspective, only four studies consider the application of IT for KM throughout the project lifecycle, which include Treloar et al. (2000), Bilec et al. (2006), Boddy et al. (2007), and Guo, Li, & Skitmore (2009). In addition, 42 studies on IT-based KM cannot be classified by project phase.

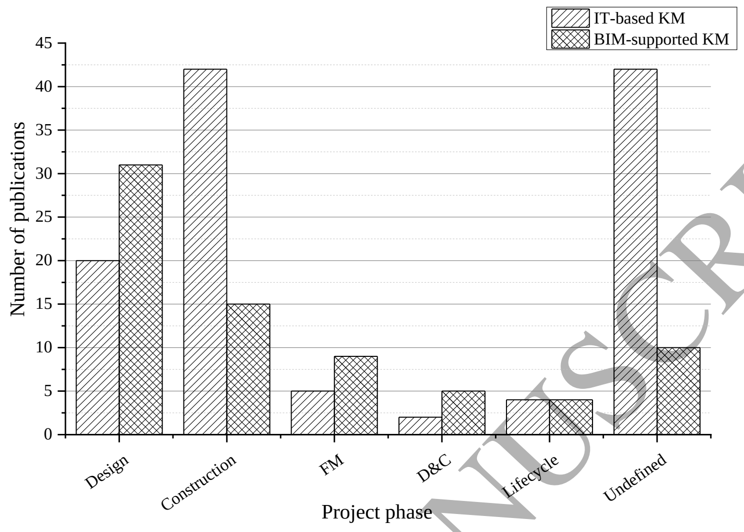

Fig. 3. Distribution of publications by project phase.

A total of 73 papers on BIM-supported KM are selected for the literature review. Nearly 31 papers concern the design phase probably because BIM is often seen as a 3D model for design coordination, design assessment, and design review (Kim & Grobler, 2009; Schlueter & Thesseling, 2009; Gu & London, 2010; Eastman et al., 2011; Lee et al., 2012). Among the 73 papers on BIM-supported KM, 15 papers focus on the construction phase. Five papers cover both design and construction: Jiang, Solnosky, & Leicht (2013), Deshpande, Azhar, & Amireddy (2014), Jiang, Leicht, & Kremer (2014), Jiang & Leicht (2015), and Zhang et al. (2015). Nine papers show research interest in BIM for KM during FM, which are a little more than those on IT for KM during FM. Similar to IT-based KM, only four papers look into BIM-supported KM throughout the project lifecycle, including Konukcu & Koseoglu (2012), Kivits & Furneaux (2013), Liu & Issa (2016), and Nývlt & Prušková (2017). For both IT-based KM and BIM-supported KM, there is a research gap from the perspective of project lifecycle. In addition, ten papers on BIM-supported KM cannot be classified by project phase.

3.4. Publications in different aspects of KM

KM activities, or KM aspects, include knowledge capture, classification, sharing, storage, representation, retrieval, reuse and visualization. Table 4 provides a comparative summary of IT and BIM-related publications in different KM aspects. This research employs OriginPro 9 to develop Figures 4 and 5 as two contour maps. Based on time scale and KM aspects, the two figures describe the distribution and concentration of studies on IT-based KM and BIM-supported KM, respectively. Studies referring to each KM aspect are described by the contours in different colors. Each contour map changes color from cool tone to warm tone to show research intensity from low to high. A warm color generally indicates that studies are dedicated intensively or actively. A red area generally shows a very intensive research concentration in a specific KM aspect during a particular period of time. On the contrary, research inactivity is generally presented in blue.

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Table 4
Comparative summary of IT and BIM-related research in different KM aspects.

KM aspect	IT-based KM	BIM-supported KM
Knowledge capture	Soibelman et al. (2003); Tserng & Lin (2004); Hari, Egbu, & Kumar (2005); Ugwu, Anumba, & Thorpe (2005); Lin, Wang, & Tserng (2006); Tan et al. (2006); Lee & Egbu (2007); Tan et al. (2007); Ahmad & An (2008); Kivrak et al. (2008); Udeaja et al. (2008); Fong & Wong (2009); Lin (2009); Zhang, Mao, & Abourizk (2009); Kamardeen (2011); Lin & Lee (2012); Wu, Weng, & Weng (2017)	Lee, Sacks, & Eastman (2006); Fruchter, Schrotenboer, & Luth (2009); Meadati & Irizarry (2010); Ho, Tserng, & Jan (2013); Jiang, Solnosky, & Leicht (2013); Motawa & Almarshad (2013); Park et al. (2013a); Wang & Leite (2013); Deshpande, Azhar, & Amireddy (2014); Jiang, Leicht, & Kremer (2014); Lin (2014); Motawa, Janarthanam, & Almarshad (2014); Motawa & Almarshad (2015); Ding et al. (2016); Grover & Froese (2016); Liu & Issa (2016); Wang & Leite (2016); Motawa (2017)
Knowledge reuse	Fruchter & Demian (2002); Soibelman et al. (2003); Tserng & Lin (2004); Woo et al. (2004); Demian & Fruchter (2006); Lin, Wang, & Tserng (2006); Tan et al. (2007); Kivrak et al. (2008); Lin (2008); Udeaja et al. (2008); Goh & Chua (2009); Tserng et al. (2009); Goh & Chua (2010); Zhong et al. (2015); Yeung et al. (2016)	Lee, Sacks, & Eastman (2006); Fruchter, Schrotenboer, & Luth (2009); Motawa & Almarshad (2013); Kadolsky, Baumgärtel, & Scherer (2014); Zhang, Boukamp, & Teizer (2015); Ding et al. (2016); Oti, Tah, & Abanda (2018)
Knowledge sharing	Paulson Jr et al. (1989); Hew, Fisher, & Awbi (2001); Tah & Carr (2001); Li et al. (2002); Hameri & Puittinen (2003); Tserng & Lin (2004); El-Diraby & Bricenov (2005); Lima, El-Diraby, & Stephens (2005); El-Diraby (2006); Lin, Wang, & Tserng (2006); Boddy et al. (2007); Lee & Egbu (2007); Wetherill et al. (2007); Issa & Haddad (2008); Lin (2008); Dave & Koskela (2009); Fong & Wong (2009); Lin (2009); Zhang, Mao, & Abourizk (2009); Kamardeen (2011); Chen (2012); El-Ghazali, Lefebvre, & Lefebvre (2012); Lee & Jeong (2012); Lin & Lee (2012); Zhang & El-Diraby (2012); Park et al. (2013b); Bashouri & Duncan (2014); Kamsu-Foguem & Abanda (2015); Li et al. (2017); Wu, Weng, & Weng (2017)	Lee, Sacks, & Eastman (2006); Ho, Tserng, & Jan (2013); Jan, Ho, & Tserng (2013); Kim, Coffeen, & Sanguinetti (2013); Motawa & Almarshad (2013); Deshpande, Azhar, & Amireddy (2014); Forgues & Chiocchio (2014); Johansson, Linderoth, & Granth (2014); Kadolsky, Baumgärtel, & Scherer (2014); Grover & Froese (2016); Liu & Issa (2016); Zhong et al. (2017); Jung, Häkkinen, & Rekola (2018); Nývlt (2018); Tan, Zaman, & Sutrisna (2018); Wang, Meng, & McGetrick (2018a); Wang, Meng, & McGetrick (2018b); Wang, Meng, & McGetrick (2018c)
Knowledge storage/retrieval	Adams (1993); Fruchter & Demian (2002); Soibelman & Kim (2002); Pályi (2003); El-Diraby, Lima & Feis (2005); El-Diraby & Briceno (2005); Lima, El-Diraby, & Stephens (2005); van den Berg & Popescu (2005); Demian & Fruchter (2006); El-Diraby & Zhang (2006); Rezgui (2006); Lin & Soibelman (2007); Lee, Hsueh, & Tseng (2008); Liao & Perng (2008); Tserng & Chang (2008); Goh & Chua (2009); Lin & Soibelman (2009); Zhang, Mao, & Abourizk (2009); Goh & Chua (2010); Li, Cao, & Dong (2012); Lin, Chi, & Hsieh (2012); Zhang & El-Diraby (2012); Park et al. (2013c); Chi, Lin, & Hsieh (2014); Hu et al. (2016); Yeung et al. (2016); Ding et al. (2017); Goh & Guo (2018)	Aksamija et al. (2010); Meadati & Irizarry (2010); Mikulakova et al. (2010); Motawa & Almarshad (2013); Park et al. (2013a); Zhang et al. (2013); Deshpande, Azhar, & Amireddy (2014); Jiang, Leicht, & Kremer (2014); Jiang & Leicht (2015); Gómez-Romero et al. (2015); Motawa & Almarshad, (2015); Zhang, Boukamp, & Teizer (2015); Ding et al. (2016); Nepal & Staub-French (2016); Zhang et al. (2016); Hossain et al. (2018); Oti, Tah, & Abanda (2018)
Knowledge representation	Hew, Fisher, & Awbi (2001); Tah & Carr (2001); Lima, Stephens, & Böhms (2003); Woo et al. (2004); Lima, El-Diraby, & Stephens (2005); Ugwu, Anumba, & Thorpe (2005); El-Diraby & Zhang (2006); Lin, Wang, & Tserng (2006); Yang (2007); Anumba et al. (2008); Goh & Chua (2009); El-Gohary & El-Diraby (2010); Tan, Hammad, & Fazio (2010); Yu et al. (2010); El-Diraby & Osman (2011); Wang & Boukamp (2011); Wang, Boukamp, & Elghamrawy (2011); Lee & Jeong (2012); Lin & Lee (2012); Wu et al. (2012); Zhang & El-Diraby (2012); El-Diraby (2013); Park et al. (2013c); Yeung et al. (2014); Kamsu-Foguem & Abanda (2015); Zhong et al. (2015); Dimyadi et al. (2016)	Lee, Sacks & Eastman (2006); Gursel et al. (2009); Kim & Grobler (2009); Aksamija et al. (2010); Tang et al. (2010); Nawari (2012); Krystallis, Demian, & Price (2013); Aram, Eastman, & Sacks (2014); Charlesraj (2014); Lin (2014); Motamedi, Hammad, & Asen (2014); Gómez-Romero et al. (2015); Zhang, Boukamp, & Teizer (2015); Amann & Borrmann (2016); Ding et al. (2016); Nepal & Staub-French (2016) Wang & Leite (2016); Niknam & Karshenas (2017); Quattrini, Pierdicca, & Morbidoni (2017); Singh, Sawhney, & Borrmann (2017); Chen, Chen, & Cheng (2018); Hamid, Tolba, & El-Antably (2018); Nývlt (2018)
Knowledge classification	van den Berg & Popescu (2005); El-Diraby & Zhang (2006); Chen (2008); Yin, Tserng, & Tsai (2008); Yu et al. (2010); Wang & Boukamp (2011); Wang, Boukamp, & Elghamrawy (2011); Ur-Rahman & Harding (2012); Wu et al. (2012); El-Diraby (2013); Chi, Lin, & Hsieh (2014); Hoła, Sawicki, & Skibniewski (2015); Chang & Yu (2016); Guaglianone, Aracri, & Oliveri (2018)	Deshpande, Azhar, & Amireddy (2014); Quattrini, Pierdicca, & Morbidoni (2017)
Knowledge visualization	Udaipurwala & Russell (2002); Kanapeckiene et al. (2010); Moodi (2010); Tan, Hammad, & Fazio (2010); Chi, Lin, & Hsieh (2014); Kamsu-Foguem & Abanda (2015)	Qi et al. (2011); Ho, Tserng, & Jan (2013); Jan, Ho, & Tserng (2013); Lin (2014); Motamedi, Hammad, & Asen (2014); Zhang, Boukamp, & Teizer (2015); Grover & Froese (2016)

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As shown in Figure 4, existing studies on IT-based KM have spanned many years and covered all KM aspects to varying extents. Figure 4 shows a red area for knowledge storage/retrieval in 2005 and a red area for knowledge representation in 2012. On the other hand, two red areas are observed in Figure 4 for knowledge sharing: one in 2009 and the other in 2012. Compared to other KM aspects, knowledge sharing is the most research intensive. Although knowledge capture, classification and reuse are not marked in red at any time, these KM aspects still attract considerable research attention. On the other hand, knowledge visualization is mainly characterized by cool tone colors. Among all aspects of KM, research on IT-based knowledge visualization is the most inactive. The finding demonstrates the weakness of existing IT tools for KM visualization. In other words, IT-based KM is not advantageous in terms of knowledge visualization.

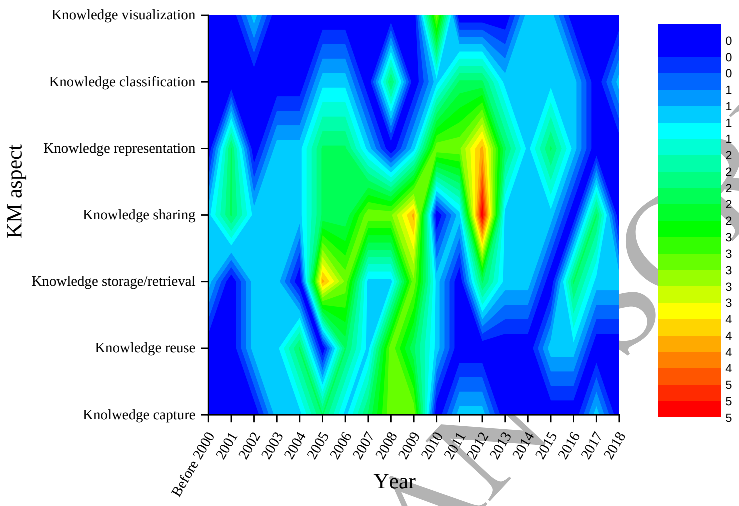

Fig. 4. Distribution and concentration of studies on IT-based KM.

Figure 5 maps the distribution and concentration of emerging studies on BIM-supported KM. Such studies first emerged in 2006. They were evident during 2009-2010 for knowledge representation and knowledge storage/retrieval. They have become available in many KM aspects since 2012. Figure 5 shows two red areas between 2013 and 2014: one for knowledge capture and the other for knowledge sharing. This means that relevant studies in the two KM aspects were active during 2013-2014. Figure 5 exhibits the third red area in 2015 for knowledge storage/retrieval, the fourth red area in 2014 for knowledge representation, the fifth red area in 2016 for knowledge representation, and the sixth red area in 2018 for knowledge sharing. On the other hand, knowledge classification, reuse and visualization are mainly presented in cool tone colors, indicating underexplored research areas.

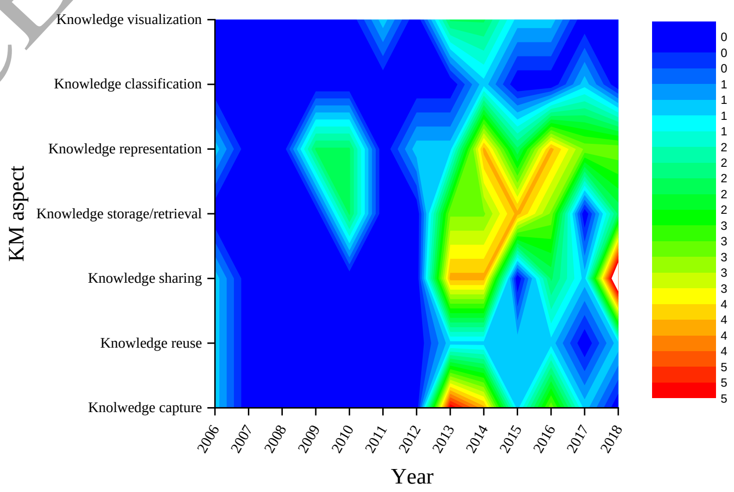

Fig. 5. Distribution and concentration of studies on BIM-supported KM.

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4. Discussion and framework development

The literature on IT-based KM and BIM-supported KM is further discussed in Section 4, which are grouped into three categories: (1) knowledge capture and reuse; (2) knowledge sharing; and (3) knowledge storage and retrieval. Based on the discussion, it is possible to clearly identify some obvious advantages of BIM-supported KM over IT-based KM.

4.1. Knowledge capture and reuse

KM generally starts with knowledge capture. Knowledge capture means capturing the answers of 'know-how' questions to address similar problems in the future (Hari, Egbu, & Kumar, 2005). It often represents a process that transfers personal knowledge to organizational knowledge. The transferred knowledge can then be shared and reused to enhance the competitiveness of a construction organization and improve the performance of its projects. Project knowledge and best practice experience are generally captured and validated for reuse (Demian & Fruchter, 2006). Therefore, Section 4.1 covers both capture and reuse of knowledge.

4.1.1. IT-based knowledge capture and reuse

In the construction industry, the simplest way to capture knowledge is to record it in the form of written documents, such as specifications, design and construction rules, and textbooks (Rezgui, 2001; Kasvi, Vartiainen, & Hailikari, 2003). However, these knowledge capture approaches are not only time and labor consuming but also vulnerable to errors. In addition to written documents, audio diary can also be used to capture knowledge generated in construction projects (Hari, Egbu, & Kumar, 2005). Although it simplifies the knowledge capture process to a certain extent, knowledge captured in this way often brings difficulties to knowledge retrieval when knowledge is reused. Following the development of Internet and Web 2.0, some web-based KM models or tools have been developed to facilitate knowledge capture, making knowledge reuse easy (Kivrak et al., 2008; Udeaja et al., 2008; Lin & Lee, 2012).

Design review is generally used in construction projects to identify design errors and conflicts. Prior to the emergence of BIM, the design review process was complex and heavily relied on manual techniques. Computer-aided design (CAD) makes it possible to compare and check design drawings on computers (Eastman et al., 2011). A traditional KM-enabled CAD system refers to the use of separate CAD tools with hard-coded knowledge. Some of these systems integrate with object-oriented CAD, by which knowledge is linked to related objects. Since the traditional object-oriented CAD is not parameter driven, however, it cannot impose and maintain the constraints between different objects. If captured knowledge about a certain object is changed, its related objects are not adjusted accordingly in an automatic way (Lee, Sacks & Eastman, 2006). To improve knowledge capture activities during design, Soibelman et al. (2003) developed a design review checking system to capture personal experience and lessons learned from projects and transfer them into the organization level. However, this system is based on moving the traditional design review process to the online network. Although this system facilitates interactive communication between design experts, it relies on manual detection of design errors. Consequently, knowledge capture in the design review process is still not effective.

Knowledge can be classified into explicit and tacit types (Smith, 2001). Explicit knowledge is easily codified, articulated and communicated in natural language or symbolic form while tacit knowledge is judgmental and context-specific (Alavi & Leidner, 2001). During a project, solutions to problems and answers of 'know-how' are retained in the head of experienced project participants. Such knowledge is viewed as tacit knowledge (Kazi, 2005). Some studies on IT-based KM are dedicated to tacit knowledge capture during the construction phase of a project (Ugwu, Anumba, & Thorpe, 2005; Lin, Wang, & Tserng, 2006; Kivrak et al., 2008; Lin & Lee, 2012). For example, Ugwu, Anumba, & Thorpe (2005) introduced ontological techniques to support knowledge capture, representation and reuse for constructability assessment. It demonstrated that ontological techniques can capture domain

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knowledge and have a potential to convert captured tacit knowledge to explicit knowledge. Unfortunately, follow-up studies to explore ontology-based tacit knowledge capture are not available. Lin, Wang, & Tserng (2006) presented a network knowledge map for capturing construction knowledge. This map is different from other knowledge maps because it not only presents the location of captured knowledge but also illustrates the relationship between different knowledge. It aids project participants to easily review available knowledge and identify missing knowledge. In this map-based KM system, tacit knowledge is captured in the form of problems, solutions, process records and expert suggestions. However, storing tacit knowledge and transferring it to other people through recording and writing is difficult without human interaction. As a result, this system is useful for tacit knowledge to a limited degree.

As mentioned above, Section 4.1 covers both capture and reuse of knowledge. Due to time lapse, staff turnover and reassignment, however, sometimes knowledge loss is inevitable (Tan et al., 2006). For example, capturing knowledge through post project review often means missing lessons learned from project implementation. Therefore, proposing a method to capture knowledge during a project is imperative to facilitate knowledge reuse for subsequent tasks of the project or for future projects. A concept of 'live' capture and reuse of project knowledge is proposed, based on which web systems of KM are developed by a number of existing studies, such as Kamara et al. (2003), Tan et al. (2006), Tan et al. (2007), and Udeaja et al. (2008). Although the capability of 'live' knowledge capture and reuse is evaluated in these studies, further exploration is needed, especially for the adaptation of 'live' captured knowledge to its reuse in new situations. The volume growth of captured knowledge may lead to the redundancy and inaccuracy of knowledge retrieval. Existing IT-based knowledge capture methods fail to clarify the knowledge required by different project parties. For these reasons, IT-based knowledge capture is not accurate and efficient enough.

4.1.2. BIM-supported knowledge capture and reuse

The parametric modeling approach makes BIM different from existing IT tools in terms of knowledge capture and reuse (Eastman et al., 2011). In the BIM environment, parametric modeling with 3D graphic presentation provides the opportunity to capture domain knowledge and transfer it to geometric expression. Emerging studies on BIM-supported KM show three possible ways to capture knowledge and lessons learned from project management: the first is recording knowledge using customized parameters in BIM models (Deshpande, Azhar, & Amireddy, 2014); the second is adopting Application Programing Interface (API) provided by software vendors to implement parameters in BIM models through external applications or web-based systems (Wang & Leite, 2016); and the third is capturing knowledge by using other external knowledge capture tools (Fruchter, Schrotenboer, & Luth, 2009; Motawa, Janarthanam, & Almarshad, 2014).

The object-oriented nature of BIM determines the relationship between building objects and expresses the behavior of these objects in the BIM context (Eastman et al., 2011). BIM software vendors provide various basic objects that are defined by some geometric parameters. For example, 'rectangular beam' in AutoDesk Revit Architecture can be defined by two-dimensional parameters, namely width and depth. In addition to geometric parameters, other descriptive object information, such as color and fire rating, can also be added in a BIM model as non-geometric parameters. These default parameters only provide object information rather than knowledge. BIM allows users to create customized parameters to add the knowledge of objects or even projects, making BIM models capable of capturing such knowledge (Meadati & Irizarry, 2010; Motawa & Almarshad, 2013). With regard to AutoDesk Revit Architecture, two types of parameters can be defined, namely project and shared parameters. Only shared parameters can be portioned between different families or projects and exported to external databases using Open Database Connectivity (ODBC). For example, Deshpande, Azhar, & Amireddy (2014) developed a BIM-supported KM system in which various user-defined parameters, such as lessons learned and subject experts involved, can be used to capture the knowledge of objects or even projects.

Many BIM software vendors provide API or ODBC to extend the functions of BIM, making it possible for users to integrate existing knowledge capture applications or systems to BIM models (Lee, Sacks, & Eastman, 2006; Wang & Leite, 2016). Some plug-in or web-based systems are developed for knowledge capture in the BIM environment (Ho, Tserng, & Jan, 2013; Lin, 2014; Ding et al., 2016; Wang & Leite, 2016). These BIM-supported KM systems display knowledge using plug-in or web-based user interfaces. Consequently, user interfaces contribute to knowledge capture. For example, Wang & Leite (2016) developed a KM prototype system, in which knowledge captured during mechanical, electrical and plumbing design coordination meetings is stored in a form of tags. The tags are integrated to the BIM model through API. In the systems proposed by Ho, Tserng & Jan (2013) and Lin (2014), external databases are directly linked to BIM models through ODBC. If there is any change in a BIM model, the change is also reflected in its external database. Conversely, any change made in the external database will be automatically shown in the BIM model.

Some researchers have interest in the integration of IT tools or systems and BIM to facilitate knowledge capture. For example, Fruchter, Schrotenboer, & Luth (2009) integrated RECALL and TalkingPaper, two IT solutions of knowledge capture, with BIM. RECALL is used to capture the dialogue between people and index it with the sketch and annotation of drawings. TalkingPaper is the companion application of RECALL, through which audio-sketch objects can be synchronized with relevant documents. Motawa, Janarthanam, & Almarshad (2014) and Motawa (2017) integrated spoken dialogue systems with BIM models to verbally capture knowledge of building energy from energy management experts. When IT tools or systems integrate with BIM, BIM makes knowledge capture easy, in which captured knowledge is related to building objects.

4.2. Knowledge sharing

Knowledge sharing is an important part of KM. It is a process through which knowledge can be disseminated and exchanged between individuals or groups (Alavi & Leidner, 2001). Knowledge sharing supported by IT tools and BIM are discussed in Section 4.2. Knowledge sharing is not only a process that delivers knowledge to those who really demand it but also a means through which those who receive knowledge easily absorb it (Riege, 2005). Therefore, Section 4.2 considers both knowledge delivery and knowledge absorption. Knowledge visualization is also discussed in Section 4.2 because it aids knowledge absorption during knowledge sharing.

4.2.1. IT-based knowledge sharing

A variety of IT tools and IT-based techniques have been applied for knowledge sharing over the years. Before the World Wide Web (WWW) emerged, Intranet was commonly used by organizations to share information and knowledge (Egbu, 2004). Even today, many organizations are still using Intranet to share information and knowledge. Intranet may include Blog and Wiki to encourage the staff of an organization to share information and knowledge. Knowledge sharing between different organizations is difficult because Intranet is a network that can only be accessed by internal staff of an organization (Dave & Koskela, 2009). The WWW was invented in 1989, followed by various web-based technologies. Particularly in the era of Web 2.0, many web-based technologies and techniques are developed to facilitate knowledge sharing between different organizations. KM can gain some benefits from Web 2.0 technologies. For example, Web 2.0 technologies increase the accessibility to knowledge sources (McAfee, 2006).

Knowledge sharing in a collaborative environment is essential for the improvement of project management in construction. For this reason, various information and communication technologies (ICT) and multimedia technologies have been introduced into the construction industry, which may include video conferences, social networks, chat rooms and groupware solutions (Tserng & Lin, 2004; Issa & Haddad, 2008). Communities of practice (CoP) represent a technique that involves a group of experts to share knowledge through their interaction. It is often deemed as an effective tool for tacit knowledge sharing (Lin, 2009). As discussed above, web-based technologies can facilitate collaboration within an organization or between organizations. Consequently, a number of studies integrate CoP with web-based technologies to realize collaborative sharing of tacit knowledge (Lin & Lee, 2012; Zhang & El-Diraby, 2012). Experts easily participate in an online CoP to share their

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knowledge. However, these studies only enhance interaction to facilitate tacit knowledge sharing. There is a lack of studies that contribute to tacit knowledge sharing based on the codification of knowledge and the conversion of tacit knowledge to explicit knowledge. Although traditional ICT tools, such as web-based platform, make collaboration between project parties easier, such collaboration is usually in the form of text communication with the assistance of 2D drawings. With the platform provided by traditional ICT tools, project parties may only share information and knowledge that they are willing to share. ICT-aided platforms lack a shared database to store all information and knowledge in a project.

The involvement of different parties in a project often causes misunderstanding and ambiguity (Tah & Carr, 2001; Anumba et al., 2008). The use of ICT is advocated to encourage knowledge sharing between project parties. However, ICT only facilitates knowledge exchange, but cannot codify knowledge into a shared meaning mutually understandable to different project parties (Bresnen et al., 2003). This problem is especially difficult to overcome in the generic IT context when a project is supported by multiple IT tools or systems that need to interoperate (Anumba et al., 2008). To address this challenge, Anumba et al. (2008) proposed an ontology-based approach for construction concepts to present a common set of unambiguous definitions. However, ontological techniques can only conceptualize and represent the knowledge of a certain domain (Lima, El-Diraby, & Stephens, 2005). It is difficult for them to support knowledge exchange across different domains.

4.2.2. BIM-supported knowledge sharing

As mentioned in Section 4.2.1, web-based technologies are widely utilized in the knowledge sharing process. Some studies on BIM-supported KM combine BIM with software or web-based systems for knowledge sharing (Lee, Sacks, & Eastman, 2006; Ho, Tserng, & Jan, 2013; Grover & Froese, 2016). Systems combining BIM and web-based applications not only make use of source accessibility, search capability and social interaction of web-based technologies but also take advantage of 3D illustration and parametric modeling of BIM. Given that web-based technologies provide interaction opportunities, tacit knowledge can be shared to a certain extent. For example, Grover & Froese (2016) proposed a social platform for users to view a BIM model and interact with each another. The platform based on user interaction contributes to tacit knowledge sharing.

Understanding knowledge is sometimes difficult without a relevant context, especially when knowledge is shared between project parties. To overcome this difficulty, Ho et al. (2013) and Jan, Ho & Tserng (2013) developed a BIM-supported KM system for 3D explanation of experience-based knowledge. This system utilizes AutoDesk Inventor to create BIM-based animations to interpret knowledge in a visualized way, facilitating users to understand and absorb experience-based knowledge. On the other hand, Grover & Froese (2016) developed a BIM system for knowledge sharing that takes advantage of 3D visualization to enhance the mutual understanding of knowledge between project parties. In these KM systems, 3D visualization of BIM can provide a context of understanding knowledge during the sharing process.

To ensure that knowledge is shared without ambiguity and misunderstanding in the BIM environment, Johansson, Linderoth, & Granth (2014) proposed the use of BIM as boundary objects to facilitate knowledge sharing across the boundaries of project parties. Boundary objects can be defined as '*objects which are plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites*' (Star & Griesemer, 1989). They are increasingly used for mutual and reciprocal knowledge sharing (Whyte & Lobo, 2010; Johansson, Linderoth, & Granth, 2014). Although such studies as Johansson, Linderoth, & Granth (2014) identified the potential to use BIM as boundary objects to facilitate knowledge sharing, there are no follow-up studies in this particular research field.

As a centralized platform, BIM integrates project parties into a single model. According to Kivits & Furneaux (2013), BIM provides a collaborative working environment for multi-disciplinary project teams, such as client, designer, contractor and FM provider, to contribute their knowledge and expertise. Since the knowledge is retained in the form of customized parameters of BIM (Deshpande, Azhar & Amireddy, 2014), project parties can share knowledge through parameters when they collaboratively work on the centralized and integrated BIM model. The objects and their relationship in the BIM model are restricted by parameters. If the parameters in any part of the BIM model are changed, all other related parts will be adjusted accordingly. As a result, the impact of knowledge exchange can be immediately evaluated and automatically shown on the BIM model.

4.3. Knowledge storage and retrieval

As discussed in Section 4.2, knowledge is shared between organizational members or more importantly between different organizations. Shared knowledge must be preserved in a repository to allow its retrieval by other people or parties in the future without interaction with the person or the party who possesses such knowledge (Jasimuddin, 2005). Knowledge storage determines the efficiency of knowledge retrieval (Alaci & Leidner, 2001). In other words, knowledge retrieval depends on knowledge storage methods. Therefore, knowledge storage and retrieval are discussed together in Section 4.3. Knowledge representation and classification are two important factors that affect knowledge storage and retrieval. For this reason, they are also discussed in Section 4.3.

4.3.1. IT-based knowledge storage and retrieval

Knowledge is generally stored in the relational database with a high degree of structure, by which knowledge is readily retrievable. This storage approach requires a strictly predefined classification structure from the beginning of the knowledge storage process (Lin & Lee, 2012). However, this approach is labor consuming and subjective to a certain extent. Moreover, some knowledge may have an overlapping knowledge scope in the predefined classification structure. Other knowledge cannot be classified into any category in the predefined classification structure. Therefore, an automatic knowledge classifier is needed to deal with this issue. Chi, Lin, & Hsieh (2014) developed an ontology-based KM system in which textual knowledge can be automatically classified to reduce human efforts for knowledge labeling. However, the ontology-based textual classification method requires sufficient training for the classifier in a knowledge domain.

At the early stage of KM, knowledge retrieval was mainly based on keyword search queries and most of the knowledge retrieval approaches used vector spaces and Boolean models, which required keywords to exactly match those presented in knowledge sources (El-Diraby & Zhang, 2006; Zhang & El-Diraby, 2012). If users retrieved the knowledge with which they were unfamiliar, it would be difficult to apply precise keywords for knowledge search and evaluate search results. Ontology is generally viewed as an explicit specification of shared conceptualization (Gruber, 1993). It is helpful for facilitating knowledge retrieval with the potential to reflect people’s intention. The precision rate of knowledge retrieval results is improved due to the use of ontological techniques. This explains why Park et al. (2013c) developed an ontology-based knowledge retrieval system, suggesting related search keywords during the knowledge search process and achieving precise knowledge retrieval results. Ontology-based techniques are also useful for textual classification to support the knowledge retrieval process (Chi, Lin, & Hsieh, 2014). Although ontological techniques relieve the challenge of knowledge retrieval in the text form, knowledge-related building objects and their relationship with surrounding objects are not considered when using ontological techniques.

Knowledge can be stored and retrieved easily only if it is represented appropriately. In other words, the way to represent knowledge affects its storage and retrieval. Ontology is often used for knowledge representation. It conceptualizes knowledge using a shared format in a certain domain (Lima, El-Diraby, & Stephens, 2005). However, it cannot support knowledge exchange across different domains. A combination of semantic and ontological techniques makes knowledge representation in a certain domain meaningful for other domains and meanwhile avoids misunderstanding. In the KM model developed by Lee & Jeong (2012), for example, the semantic-based mechanism can convert a neutral representation that links with different knowledge domains to a semantic domain-specific format. Conversely, it can translate a semantic domain-specific format into a neutral representation. Even in the same knowledge domain, the specification of ontologies is also heterogeneous (Abanda, Tah, &

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Keivani, 2013). As an innovative semantic web technology, Linked Data can be used to link knowledge in different ontologies (O'Donnell *et al.*, 2013). In addition to Linked Data, Martínez-Rojas, Marín, & Miranda (2016) applied a fuzzy multi-criteria aggregation-based model to identify the relationship between knowledge in different ontologies.

Data mining is a process of sorting through large data sets to identify patterns. This technique is often utilized to aid knowledge retrieval in construction projects. For example, Lee, Hsueh, & Tseng (2008) discovered knowledge retained in organizational performance records using data mining. Liao & Perng (2008) highlighted the potential of data mining for the conversion of raw data to valuable information and knowledge. On the other hand, text mining is useful for discovering understandable knowledge patterns from unstructured text data sources (Ur-Rahman & Harding, 2012). However, the number of studies on data mining or text mining for KM is still limited. Using data mining or text mining to help knowledge retrieval requires a large amount of data to pre-train the classifier.

CBR and rule-based reasoning (RBR) are two mature tools that are widely used for retrieving knowledge represented in the form of cases or rules (Goh & Chua, 2009; Goh & Chua, 2010; Wang & Boukamp, 2011; Wang, Boukamp, & Elghamrawy, 2011). CBR addresses current new problems based on the solutions to similar problems in the past while RBR provides a guide to decision making using a set of predefined rules. Although CBR and RBR have been applied in many instances, such as case-based safety planning and rule-based constructability checking. The solutions reasoned by CBR are often related to a certain situation, but difficult to suit other situations (Hu et al, 2016). On the other hand, knowledge presented in the form of rules is generalized knowledge. For this reason, knowledge reasoned by RBR can be used to complement the reasoning results of CBR. Some KM systems adopt the combination of CBR and RBR to improve the performance of knowledge retrieval. For example, Goh & Guo (2018) developed a system that combines CBR and RBR to avoid safety accidents. Although existing systems can reason possible solutions, it is difficult for them to evaluate the effect of possible solutions.

4.3.2. BIM-supported knowledge storage and retrieval

According to Meadati & Irizarry (2010), BIM can be regarded as a repository of knowledge. However, the knowledge stored in a BIM model is only specific to a particular project, which is difficult to be used for other projects. To address this challenge, some studies attempt to establish a separate knowledge base linked with BIM models to store knowledge. As a result, knowledge can be collected from different projects and meanwhile the knowledge collected from one project can be used for other projects. For example, Motawa & Almarshad (2013) developed a system in which a knowledge base is separate from the BIM model. The knowledge base can exchange knowledge with the BIM model through IFC standards. Similarly, Ding et al. (2016) presented a system in which a separate knowledge base is connected to the BIM model, allowing users to collect knowledge from different projects and use knowledge in different projects.

Ontology-based knowledge representation has been introduced by several studies to facilitate the knowledge retrieval process in the BIM environment (Park et al., 2013a; Ding et al., 2016). For example, ontology was used by Park et al. (2013a) to represent the knowledge of construction defect management in the BIM environment. Ding et al. (2016) represented the knowledge of construction risk management through BIM using ontology and web technologies. As mentioned in Section 4.3.1, ontology can only be used to reflect domain-specific knowledge as a set of concepts and the relationship between these concepts in a knowledge domain. For this reason, Niknam & Karshenas (2017) developed a shared ontology that includes concepts common to different knowledge domains in the BIM environment. Consequently, all domains can create their own ontologies based on the shared ontology. In this case, the shared ontology acts as a semantic mediator in the domain ontology alignment process. The principle to achieve the semantic interoperability between ontologies in different knowledge domains is similar in both IT and BIM contexts, which means that a common semantic mechanism is first established and ontology in each knowledge domain is then developed. Linked Data is applied to integrate knowledge between different ontologies in the BIM environment (Curry et al., 2013). As a result, the interoperability between different ontologies is achieved.

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CBR and RBR can be used for BIM-supported knowledge retrieval (Mikulakova et al., 2010; Motawa & Almarshad, 2013; Jiang & Leicht, 2015; Zhang et al., 2015). Mikulakova et al. (2010) proposed a KM system for schedule generation and evaluation using CBR in the BIM environment. Motawa & Almarshad (2013) developed a BIM-supported KM system with the help of CBR to support building maintenance. In these two systems, BIM is regarded as a carrier of model parameters that are provided to CBR based on IFC standards. IFC serves as a media for the exchange of information and knowledge between a BIM model and a case base. On the other hand, Jiang & Leicht (2015) presented a constructability checking system that introduces RBR into BIM. Zhang et al. (2015) established a rule-based safety checking system in the BIM context. In these two systems, the contents of BIM models are checked according to predefined rules and meanwhile the optimized options for constructability and safety can be evaluated and reported automatically, continuously and proactively. These two systems also apply BIM visualization to display the checking results that contribute to decision making. Furthermore, Zhang et al. (2016) demonstrated a possibility to combine CBR and RBR for a BIM-supported KM system that serves safety risk identification. This system takes advantage of both CBR-BIM and RBR-BIM.

4.4. Integrated framework

Based on the discussion in Sections 4.1-4.3, an integrated framework is proposed in Section 4.4 to provide the state of the art of IT-based KM and BIM-supported KM (see Figure 6). The development of future research is also prospected in the framework. Since BIM-supported KM is advantageous over IT-based KM, more emphasis is placed on BIM-supported KM for future research.

4.4.1. Current research status and gaps

The discussion in Sections 4.1-4.3 reveals the current research status of IT-based KM and BIM-supported KM. Various applications of IT-based KM and BIM-supported KM are presented in Sections 4.1-4.3 in terms of knowledge capture and reuse, knowledge sharing, and knowledge storage and retrieval. Based on the discussion in Sections 4.1-4.3, research gaps are also identified, especially for IT-based KM. Compared to ITs for KM, BIM has some distinctive features to support KM. For example, parametric and object-oriented modeling characterizes BIM. Knowledge and lessons learned can be easily captured through customized parameters created in BIM models. The relationship between knowledge and its related building objects can be automatically and constantly maintained based on the constraints imposed by BIM parameters. On the other hand, KM in construction projects benefits from 3D visualization of BIM. BIM-supported KM can not only express knowledge in the geometric form but also visualize the outcomes of KM. In contrast with knowledge representation in the text form, 3D visualization of BIM has the potential to facilitate the mutual understanding of knowledge between project parties. As a centralized and integrated platform, BIM enables different project parties to collaboratively work on a single model. The model offers an important opportunity for project parties to contribute their knowledge and expertise. In addition to the main advantages of BIM-supported KM mentioned above, more advantages of BIM-supported KM can be found in the integrated framework (see Figure 6). All these advantages demonstrate the possibility to transform from IT-based KM into BIM-supported KM. Current research on BIM for KM is still developing. Some key issues have not fully been considered in current research on BIM-supported KM. The weaknesses within BIM-related research on KM call for future research efforts.

4.4.2. Future research directions

Compared to design and construction, the FM phase is much longer and has more relevance to the realization of value for money. Unlike design and construction, emerging studies on BIM-supported KM do not make enough efforts for the FM phase. Future research should consider integrating KM and BIM to improve the effectiveness of FM. Although the importance of lifecycle management has been increasingly highlighted in the construction industry in recent years, little research evidence can be found for BIM-supported KM from the perspective of project lifecycle. In theory, BIM is generally recognized as a key to lifecycle thinking and a novel approach to pursue lifecycle management. More research attention should be given to BIM-supported lifecycle KM in the future. On one hand, BIM-supported lifecycle KM will fully utilize the potential of BIM. On the other hand, BIM-supported lifecycle KM will maximize the possibility of achieving project success.

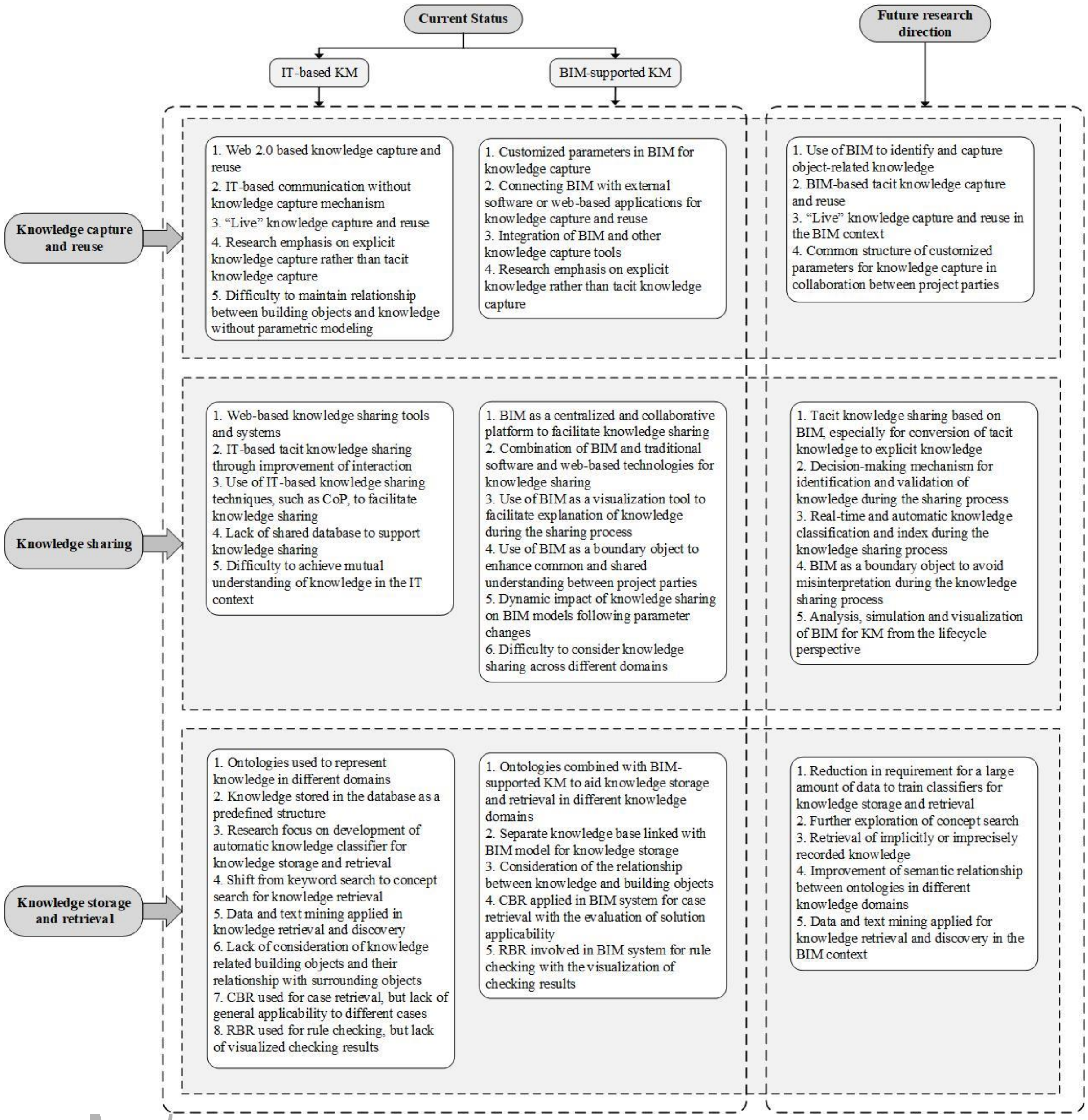

Fig. 6. Integrated framework of IT-based and BIM-supported KM.

Relatively few studies focus on BIM visualization for KM. As a matter of fact, 3D visualization is an important feature of BIM. Different project parties are involved in a construction project. They have different backgrounds, use different terminologies, and undertake different tasks. When knowledge is shared between them, it is easy to cause misunderstanding. The visualization of BIM is helpful to interpret knowledge that is difficult to be understood in the text form. Future research is expected to explore in depth how to better use BIM visualization to enhance the mutual understanding of knowledge between project parties. BIM visualization provides a virtual environment for project management processes and activities. Based on 3D visualization of BIM, possible solutions to project problems can be carefully compared to make informed decisions.

Parametric and object-oriented modeling distinguishes BIM from traditional modeling techniques. Parametric modeling of BIM is used for knowledge capture by creating customized parameters in BIM models. Knowledge capture in this way can establish the relationship between knowledge and building objects. However, there is a lack of BIM parameter structure. Therefore, it is necessary for future research to develop a parameter structure so that different parties in a project can capture knowledge in the same way. Compared to traditional ICT used for collaboration, BIM as a centralized platform allows different project parties to collaborate with each other on a single integrated model. The integrated BIM model provides a shared reference to support knowledge communication between project parties. When knowledge is exchanged and shared through customized parameters, building objects and their relationship may be changed. Such changes describe the dynamic impact of knowledge exchange and sharing in the BIM context.

Future research directions for BIM-supported KM are not limited to those mentioned in the above three paragraphs. More future research directions can be found in the integrated framework (see Figure 6). Since BIM is the next generation of IT application, it is not surprising that the focus of future research is on BIM-supported KM. The highlight of BIM-supported KM does not mean that there is no use of IT-based KM at all. Instead, IT-based KM has been long studied and some of its ideas are still useful for future research. For example, 'live' knowledge capture and reuse, concept search for knowledge retrieval, and semantic technique for knowledge exchange between different knowledge domains can provide some inspiration for future research on KM in the BIM context.

A conceptual model of BIM-supported KM is developed in the form of use case diagram by using UML (see Figure 7). The conceptual model not only includes the KM factors discussed above, but also defines the relationship between them. It further clarifies the possible research directions proposed in the integrated framework. For example, semantic technique, Linked Data and generic ontology should be taken into consideration for the achievement of interoperability between different ontologies if a system applies ontologies in the BIM environment to facilitate effective KM. The conceptual model also provides a reference for project teams or construction companies to customize their own BIM-supported KM systems. In this case, they can select KM factors that are necessary for them from the conceptual model.

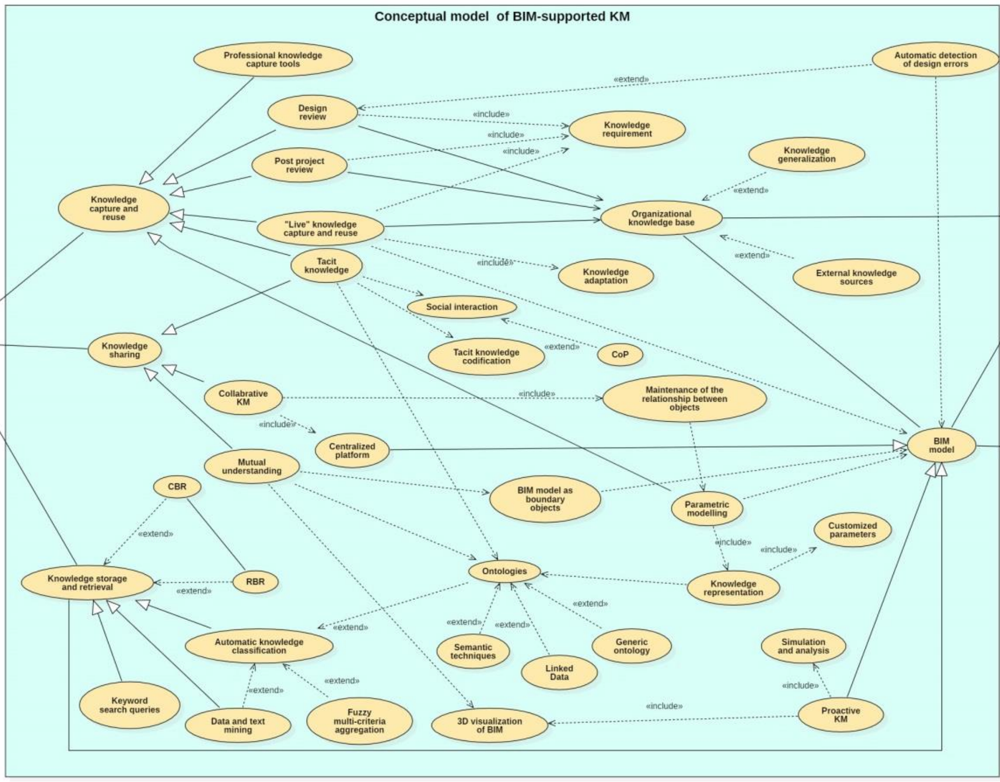

Fig. 7. Conceptual model of BIM-supported KM system.

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5. Conclusions

Construction processes and activities are always knowledge-intensive. Various IT tools or systems have been applied in the construction industry to facilitate KM. Compared to existing IT tools or systems, BIM is a revolutionary IT application. A total of 115 papers on IT-based KM published between 1989 and 2018 and 73 papers on BIM-supported KM published between 2006 and 2018 are reviewed in this research. Based on the literature review, this research identifies the current research status and gaps, which are followed by the possibility of using BIM to overcome the gaps of IT-based KM. Subsequently, future research directions are recommended in this research for BIM-supported KM. An integrated framework is developed to illustrate current and future research trends of IT-based KM and BIM-supported KM in terms of knowledge capture and reuse, knowledge sharing, and knowledge storage and retrieval.

BIM has distinctive features, such as parametric and object-oriented modeling, collaborative working, and digital visualization. These distinctive features provide BIM-supported KM with some obvious advantages over IT-based KM, e.g. (1) parametric and object-oriented modeling links KM activities and building objects through customized parameters; (2) BIM allows project parties to collaboratively work together and share knowledge based on a central platform; and (3) dynamic visualization with digital representation enhances the mutual understanding of knowledge between project parties. All these demonstrate a great potential of BIM to support KM and reveal the necessity of transforming IT-based KM into BIM-supported KM. BIM-supported KM is just emerging and still developing. For example, BIM-related research on KM pays little attention to project lifecycle although managing a project from the lifecycle perspective is a key focus of BIM. For this reason, further improvement will make it possible for BIM-supported KM to realize its full potential.

The transformation from IT-based KM into BIM-supported KM characterizes the major contribution of this study. Every research may have inevitable limitations. This study adopts a literature review as the only methodology. A lack of empirical support is the main limitation of this study. For this reason, follow-up research is needed to collect empirical data and provide empirical evidence. Based on empirical evidence, follow-up research can modify the integrated framework and the conceptual model proposed in this study. Follow-up research should investigate to what extent BIM is used for KM in today's construction practice. It is also important for follow-up research to identify what are required or expected for BIM-supported KM systems. Originally, BIM is developed for the management of building information. Knowledge is generally recognized as a higher-level representation than information. It is hoped that this study becomes one of the frontier research attempts that initiate a new era of BIM application.

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