INCORPORATING KNOWLEDGE OF CONSTRUCTION AND FACILITY MANAGEMENT INTO THE DESIGN IN THE BIM ENVIRONMENT

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Many studies have highlighted the importance of early project phases, during which the levels of uncertainty and stakeholder influence are considerably high, but the cost of change is substantially low. Construction projects become increasingly complex and require the early involvement of project participants. Consequently, the knowledge of construction contractors and facility management (FM) teams should be considered in the design phase to improve project management. Building information modelling (BIM) is an object-oriented and parametric-based information technology, which is characterised by digital representation, project lifecycle simulation and collaborative working. However, existing studies have considerably focused on BIM-based information management and limited research has considered BIM-based knowledge management (KM). This study aims to explore collaborative KM during design in the BIM environment. Semi-structured interviews and questionnaire surveys are conducted to collect qualitative and quantitative information from people working in the construction industry in the UK and Ireland. A conceptual framework is developed based on the analysis results to illustrate how knowledge of construction and FM can be incorporated into the design phase in the BIM environment. BIM's potential for KM has been identified in this study. Moreover, the expectations and requirements of BIM-based KM are also identified that include technical, process and cultural aspects. Consequently, this study provides new insights into the transformation from BIM to building knowledge modelling (BKM).

Keywords: BIM, knowledge management, collaboration

INTRODUCTION

Construction is a knowledge-intensive industry. Compared with information that answers 'when', 'where', 'who' and 'what' questions, knowledge answers 'how' and 'why' questions. Knowledge management (KM) is the process of capturing, storing/retrieving, transferring and applying knowledge (Alavi and Leidner 2001) and is driven by the integration of people, processes and technologies, whereas information is mainly technology driven. As projects become increasingly complex, various disciplines must be involved in these projects thus the requirements for KM have increased. To improve KM in the construction industry, different types of information technology (IT) have been applied.

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Building information modelling (BIM) is a new-generation IT in the construction industry which has achieved considerable progress in information management because of its parameter-oriented modelling method and its capability to retain graphic and non-graphic information. Only a few studies have explored BIM at the knowledge level, including Wang and Leite (2016) for BIM-based KM during design, Ho *et al*., (2013) for BIM-based KM during construction and Motawa and Almarshad (2013) for BIM-based KM during operation and maintenance (O&M). However, no study has yet considered collaborative KM in the BIM environment. Additionally, Dainty *et al*., (2017) explained that BIM's power of aspiring integrated work, collaboration and innovation is overstated because political reform agendas centred recently on BIM. Therefore, information from practitioners working in the industry should be collected to reflect the potentials and expectations of BIM for KM, particularly in terms of collaborative KM.

Moreover, the potential risks of constructability, operability and maintainability in large and complex projects are difficult to identify in advance. To proactively address these problems, construction contractors and FM teams must be involved in the design stage. Early contractor involvement (ECI) aims to appoint contractors earlier than normal to assist in planning and design (Samuel and Ron 2016). Early facilities management involvement (EFMI) represents a process, in which FM experts are introduced in planning and design to raise the potential O&M issues (Meng 2013). Although a few studies have explored ECI and EFMI, no research has used BIM to aid in the early engagement process. To fill in the knowledge gap, this study selects semi-structured interview and questionnaire survey as the main research methods to explore how the knowledge of construction contractors and FM teams can be incorporated into the design process in the BIM environment. This study answers the following questions. (1) How is the knowledge of construction contractors and FM teams involved in the design stage of existing projects? (2) Can BIM potentially aid KM? (3) What are the expectations and future trends of BIM-based KM for ECI and EFMI? Lastly, a conceptual framework is developed to summarise the expectations on BIM-based KM for ECI and EFMI.

THEORETICAL BACKGROUND

Early Involvement of Construction Contractors and FM Teams in Design

ECI was proposed by the UK Highways Agency to appoint contractors earlier than normal to aid in planning and design (Samuel and Ron 2016). The benefits of ECI have been identified in existing studies. Firstly, ECI can reduce the probability of potential risks. ECI improves the constructability of design because the contractor's knowledge of building materials and construction methods is considered in this process (Song *et al*., 2009; Motiar and Aminu 2012; Love *et al*., 2014). Gil *et al*., (2001) emphasised the important role of specialist contractors in constructability. They have a sensitive sense of labour, material and equipment availability. Specialist contractors also have a good understanding of suppliers' lead time and reliability because they have a close relationship with suppliers. If contractors and specialist contractors are involved in the design stage of a project, then informed decisions can be made (Gil *et al*., 2001; Song *et al*., 2009; Samuel and Ron 2016). Secondly, potential risks, such as health and safety risks and time and cost overruns, can be proactively avoided (Gil *et al*., 2001; Song *et al*., 2009; Eadie *et al*., 2012; Lenferink *et al*., 2012; Motiar and Aminu 2012; Love *et al*., 2014; Meng 2014; Samuel and Ron 2016). Thirdly, ECI can also improve the relationship among project parties, thereby resulting in increased interaction, mutual trust and respect (O'Connor and Miller 1994; Motiar and Aminu 2012). Fourthly, ECI can provide opportunities to generate innovative design and construction strategies through collaborative effort (Gil *et al*., 2001; Mosey 2009; Lenferink *et al*., 2012; Motiar and Aminu 2012). Eadie *et al*., (2012) indicated that ECI can assist in waste reduction, quality improvement, environmental impact control and sustainability.

FM teams possess extensive knowledge of and experience on O&M, as well as energy consumption and adaptability to future developments. If FM teams are involved in the design phase of a project (EFMI), then the project can gain many benefits. Firstly, EFMI prompts the proactive consideration of potential problems during the design stage. Meng (2013) reported that EFMI facilitates the identification of potential design flaws and the achievement of accurate design, operability, maintainability and serviceability. Mohammed and Hassanain (2010) and Wang *et al*., (2013) added that FM teams can recommend the appropriate equipment and systems in terms of durability and reliability because of their in-depth knowledge of building service systems. Secondly, FM teams can reflect the needs of clients/end users. Consequently, they can obtain benefits from the FM teams' early involvement, such as guaranteeing system or material performance (Dunston and Williamson 1999), increased suitability to meet the clients'/owners' business objectives (Jensen 2009; Meng 2013), good value for money (Mohammed and Hassanain 2010; Meng 2013) and sustainability (Jensen 2009). Additionally, several studies have established a feedback loop between design and FM, in which FM teams report the problems encountered during the O&M phase to the design group. Consequently, the design team can consider similar potential problems in future projects (John *et al*., 2005; Mohammed and Hassanain 2010). Apart from the benefits gained from ECI and EFMI, barriers and challenges have also been identified by existing studies. The six barriers to ECI are responsibility allocation (Jergeas and Van der Put 2001; Samuel and Ron 2016), reluctance to change (Song *et al*., 2009; Jergeas and Van der Put 2001; Love *et al*., 2014), lack of understanding of benefits (Song *et al*., 2009; Eadie *et al*., 2012), lack of mutual trust and respect (Jergeas and Van der Put 2001), loss of competitiveness (Motiar and Aminu 2012) and lack of technical support (Fischer and Tatum 1997; Gil *et al*., 2001; Jergeas and Van der Put 2001). Previous studies have also identified three barriers to EFMI, namely, lack of understanding of benefits (Dunston and Williamson 1999; Meng 2013), lack of common knowledge (Jensen 2009; Meng 2013) and lack of technical support (Jensen 2009).

BIM-Based KM

BIM-based KM is an emerging research field. This KM system integrates KM techniques and BIM to facilitate KM activities. Knowledge capture and retention in the BIM environment are mainly based on customised parameters related to building objects in the BIM model (Deshpande *et al*., 2014). BIM applications enable users to predefine parameters to record knowledge of building objects in the BIM model (Motawa and Almarshad 2013; Deshpande *et al*., 2014). Deshpande *et al*., (2014) developed a BIM-based KM system in which various pre-defined parameters, such as lessons learned and subject experts involved, have been created. These parameters are used to capture and retain knowledge.

Although studies have acknowledged knowledge sharing in the BIM environment, no research has shown that BIM can be used as a tool to share knowledge. All existing studies have combined the BIM model with knowledge sharing tools, such as web-based system and desktop knowledge sharing platform, to achieve knowledge sharing (Grover and Froese 2016; Ho *et al*., 2013). Ewenstein and Whyte (2009) indicated that visual representations can serve as epistemic objects to facilitate a collective understanding among different epistemic communities. Accordingly, the 3D visualisation of the BIM model can be regarded as the epistemic object for eliminating the boundary among different disciplines to facilitate knowledge sharing.

Existing studies on BIM-based KM have failed to extensively explore knowledge reuse. They do not use BIM to support knowledge retrieval directly but combine technologies that promote knowledge retrieval with BIM to realise the knowledge retrieval function. For example, ontology-based knowledge representation is adopted in a few studies to aid knowledge retrieval in the BIM environment (Park *et al*., 2013; Ding *et al*., 2016). Additionally, Motawa and Almarshad (2013) applied case-based reasoning to a BIM-based KM system to support knowledge retrieval and storage. Although a few studies have explored the KM in the BIM environment, several aspects of KM in construction have yet to be considered. Existing studies of BIM-based KM fail to consider knowledge capture, retention and retrieval in collaboration circumstances. Additionally, a few features of BIM, such as clash detection, simulations and early analysis, have not been considered to support KM.

METHODOLOGY

This study applied two research methods; a semi-structured interview and a questionnaire survey. For the interviews, a qualitative semi-structured interview format was selected because it enables researchers to collect data with relative flexibility. A total of 30 interviewees from different companies belonging to the construction industry in the UK and Ireland participated in semi-structured interviews. The selection of appropriate interviewees was made using a purposeful sampling strategy that is extensively used to identify and select individuals who have experience on a phenomenon of interest. The interviewees work in different disciplines of building projects, namely, design, construction, FM and consultancy. They have at least one year of BIM experience. A total of 19 interviewees had over 5 years of BIM experience. The number of interviewees was confirmed using the information saturation criterion, in which no new information is obtained from additional interviews over an interviewee sample size. Eventually, nine contractors, eight architects, seven FM experts, four consultants, one structural engineer and one client were interviewed. The industrial experts were interviewed face-to-face or through Skype video call. The same open-ended questions were asked in all interviews, following the pre-defined guide for ease of subsequent data analysis. To maintain confidentiality, the interviewees were coded as Interviewee 1, 2, 3 …30 based on the order in which the interviews were conducted. The interview scheme was divided into three sections. In the first section, the interviewees were asked to provide their occupational and company information to determine if they would meet the criteria for this study. In the second section, the interviewees were asked to describe the KM methods used in their project and the potential of BIM for KM. In the last section, the interviewees described their ECI and EFMI experiences and shared their perspectives on BIM for early engagement.

The second method, the questionnaire survey, was developed based on the literature review and was revised according to the suggestions provided by six other BIM experts from the construction industry. The purpose of the questionnaire survey is to obtain people's accurate ideas and opinions on the BIM-based KM system in construction projects. The survey also examined whether the features of BIM can assist construction organisations overcome the challenges to KM. The survey targeted people who had experience in using BIM across the UK. A total of 70 participants from the construction industry were asked to rank the significance of 35 variables that facilitate KM by using BIM. These variables were identified through the literature review. The results collected from the questionnaire were process through exploratory factor analysis using SPSS. This study applied the Kaiser-Meyer-Olkin measure, Bartlett's test and anti-image correlation matrix analysis to confirm the adequacy of the samples and deduct the insignificant variables (denoted as V [number] in the remainder of this paper). Total variance explained, scree plot, rotated component matrix and reliability analysis were used to classify the related variables into different components and to determine the number of components that should be retained.

RESULTS AND DISCUSSION

Early Involvement of Contractors and FM Teams in the Design Stage

The results of the interviews indicate that ECI and EFMI are common in projects. A few interviewees from the design team stressed that contractors should be involved in providing creative suggestions before the detailed design stage. Thereafter, the design team will create the details by considering the contractors' advice. Such scenario is preferred because although the design team understands the benefits of ECI, the team is unwilling to redesign its work based on the suggestions of the contractors. The interviewees also explained that current ECI fails to involve specialist contractors. Accordingly, the interviewees proposed that the advice of specialist contractors should be considered during the design stage because the former has considerable knowledge of technical details (Gil *et al*., 2001). Moreover, a few interviewees mentioned that some specialist contractors even have their own design team. The projects' design team will discuss and confirm the design intention with the specialist contractors. Thereafter, the specialist contractors will directly design the details. The design results are further discussed and confirmed with the projects' design team.

Some interviewees believed that the FM teams should be involved during the entire design process, whereas others believed that considering the knowledge of the FM before proceeding to the detailed design stage is ideal. Interviewees considered that the different opinions were derived from the lack of geometric thinking of the FM members and their inability to visualise design intentions in their minds. Therefore, some interviewees believed that design drawings can improve the efficiency of knowledge exchange during EFMI. This view is supported by Ewenstein and Whyte (2009), who stressed the importance of visual representation for communication between different disciplines. Some studies have also shown that this lack of commonality can result in a conflict of opinions between design and FM teams (Jensen 2009; Meng 2013). By contrast, several interviewees believed that relying excessively on visualisation tools will reduce the efficiency of knowledge exchange between the design and FM teams because the latter will require additional time to understand the drawing before they can provide their suggestions. Additionally, the interviewees emphasised that if the involved FM team lacks knowledge on the business objectives of building end users, then EFMI will be ineffective.

BIM's Potential for KM

In the questionnaire survey, the respondents were asked to rank the significance of 35 variables related to the BIM-based KM. In accordance with the results of the anti-image correlation matrix analysis, the correlation values of V17 and V34 are below 0.5. Thus, 33 variables were subsequently analysed. A rotated component matrix analysis was performed to classify variables into different components. The variables in each component exhibit common characteristics. In the rotated component matrix, the loading value should be above 0.4. Lastly, the 33 variables were classified into nine components. However, a component that contained only 1 variable was excluded. The reliability of the remaining eight components was tested. In the reliability analysis, the confidence interval value was set to 0.95. The Cronbach's alpha values of Components 1, 2 and 6 are 0.834, 0.815 and 0.698, respectively. The value of the other components is nearly or below 0.6, which means poor reliability. Components 1, 2 and 6 are discussed with the results of the interviews (see Table 1). Appropriate tags are assigned to each component to summarise the KM aspects that they explain. Components 1, 2 and 6 explain the proactive KM, lifecycle KM and KM processes, respectively.

Table 1: Matrix of the Rotated Components

Components	Variables	Factor Loadings		
Component 1	V28 Achievement of client requirement	.805		
(Proactive	V27 Avoidance of repeated defects	.708		
KM)	V32 Reduction of conflicts in decision-making	.641		
	V26 Avoidance of potential defects	.631		
	V30 Early informed decision-making	.565		
Component 2	V23 Knowledge used in each project phase		.683	
(Lifecycle	V35 Simulation for early knowledge application		.653	
KM)	V24 Visual-aided knowledge identification		.600	
	V11 KM supported by disciplines from each project phase		.578	
	V20 KM from one stage to another		.527	
	V19 Information in BIM for knowledge improvement		.516	
	V 9 Knowledge capture from other projects		.504	
Component 6	V 6 Knowledge storage (digitalised documents)			.731
(KM	V10 Knowledge sharing among different project phases			.655
processes)	V29 Identification of the relationship between current and past activities for knowledge reuse			.541

The analysis results of the interview also identified three potentials of BIM for KM, namely, knowledge capture and retention, proactive KM and visual-aided KM. For proactive KM, the interviewees explained that BIM exhibits the capabilities of clash detection, simulation and analysis. Thus, designers can proactively solve potential problems based on their experiences. Furthermore, the design team can further optimise their design based on the simulation results. The early analysis of lifecycle cost and energy consumption via BIM application also facilitates early decision-making. The preceding discussions are consistent with the analysis of the questionnaire survey results and those of existing studies, such as Wang *et al.*, (2013). However, the quantitative survey determined that BIM can mitigate conflicts among disciplines during decision-making (V32). This result is consistent with the view of Ho *et al.*, (2013), which stressed that the drawings with supported data stored in BIM can facilitate decision-making. The survey also determined that BIM can promote the use of knowledge to reduce repeated defects (V27). This result was not obtained in the interviews but was indicated by Park *et al.*, (2013). Moreover, the requirements of clients are proactively considered and solved through the involvement of BIM (V28). This result is consistent with Cavka *et al.*, (2017) but was not identified in interviews.

The questionnaire survey and interviews determined that BIM can support KM processes. However, the interviewees only indicated that BIM exhibits the potential for knowledge capture and retention. BIM applications enable users to create the customised parameters that can be used to obtain and retain knowledge (Motawa and Almarshad 2013; Deshpande *et al.*, 2014). The interviewees even suggested that clients/end users should indicate the knowledge that they need. The design team and contractors should also input this required knowledge into the BIM model during the design and construction processes. Thereafter, this knowledge-rich model will be forwarded to the FM team for O&M. However, existing studies only explore the information requirement rather than knowledge requirement by each project parties (Cavka *et al*., 2017). Additionally, the results of the questionnaire survey showed that BIM can support knowledge sharing and reuse, which is indicated in Ho *et al*., (2013).

The questionnaire survey results showed that BIM can facilitate KM throughout the project lifecycle. V24 in the component of the lifecycle KM (Component 2) particularly stressed that the 3D visualisations of BIM can facilitate KM throughout the project lifecycle. Although the interviewees emphasised the importance of the 3D visualisation of BIM, they believed that such visualisation improves the collective understanding among the different disciplines and assists people who lack geometric thinking and cannot visualise things in their mind. Ewenstein and Whyte (2009) emphasised that visual representations can be regarded as epistemic objects to facilitate common understanding among different epistemic communities. The BIM model can be regarded as the so-called epistemic object. Consequently, the efficiency of knowledge sharing is increased. The remaining variables of this component are generated based on the lifecycle evaluation capability and central collaborative platform provided by the BIM applications. Existing studies also confirmed that early simulation and evaluation of BIM can help solve problems from the lifecycle perspective (Wang *et al*., 2013).

Future Development Trend of BIM-Based KM

BIM-based KM is an emerging research field. Consequently, the expectations from the construction industry to identify the future development and research direction of this field must be clarified. The interviewees proposed that BIM-based KM should have the ability to support knowledge capture and retention because BIM exhibits the potential for such purpose. This idea is confirmed in the questionnaire survey (V6 and V9) and existing studies (Motawa and Almarshad 2013; Deshpande *et al*., 2014). The expected BIM-based KM is mainly used to support the involvement of knowledge of contractors and FM teams, thereby requiring a high degree of collaboration in early design. Therefore, interviewees indicated that the processes of capturing and retaining knowledge in the BIM environment should consider the knowledge index that is suitable for different disciplines.

The interviewees suggested integrating knowledge sharing tools into BIM-based KM to realise knowledge sharing. For example, they believed that common data environment (CDE) should be included in BIM-based KM. Although the BIM application at level 2 emphasises the integration of 3D model with related information, this application is created in a separate discipline model. The interviewees further explained that CDE can be viewed as a single source of information collected from those separate models.Consequently, CDE can facilitate collaboration work in construction projects by providing a central repository and data sharing platform. Although CDE is currently used at the information level, the interviewees believed that CDE can also be used at the knowledge level. Additionally, the interviewees infer that CDE relatively alleviates the problem of knowledge redundancy in BIM-based KM because data can be synchronised and updated in a timely manner. Moreover, the interviewees also hope that BIM-based KM can embed a comment function on building objects to establish the relationship between knowledge and building objects. The interviewees also suggested that BIM-based KM requires a discussion module to increase interaction among people. The analysis results of the questionnaire showed that BIM can also be used to share knowledge among the different phases of a project (V10). Wang *et al*., (2013) realised the knowledge exchange between the O&M and design phases.

The expectations on knowledge reuse of the interviewees are mainly on the knowledge retrieval process. The interviewees proposed three methods for knowledge retrieval, namely, keywords, screening and knowledge category. Furthermore, the desired knowledge retrieval method should be easy to use in a collaborative environment because the proposed BIM-based KM is utilised to support the early knowledge involvement of contractors and FM team. The interviewees also believed that the BIM features of visualisation, simulation, clash detection and early analysis should be applied to the BIM-based proactive KM. Component 1, which was generated in a rotated component matrix, also stressed the importance of these BIM features for KM. Additionally, V24 and V35 in Component 2 emphasised the visualisation and simulation of BIM for KM throughout a project's lifecycle. These BIM features can serve as a factor triggering proactive application of relevant knowledge in the early project stage to prevent potential problems.

The interviewees also believed that applying a BIM-based KM system is necessary in an appropriate project management process, such as asset information requirement (AIR), employer's information requirement (EIR) and soft landing (SL). AIR is used to specify the information required from an organisation in relation to an asset. EIR is developed based on AIR and is the information required that clients will use during the project development and O&M phases. The information specified in EIR can be used to support decision-making at each employer's decision point. Cavka *et al*., (2017) also stressed the importance of these information requirements in the BIM environment. They developed owner information requirements in the BIM environment for asset management. SL is a strategy that stresses collaboration among the design, construction and O&M phases. This process also includes a post-project evaluation that can provide lessons learned for future projects. Although AIR, EIR and SL are currently applied at the information level, the interviewees proposed that these management strategies can be used as carriers of knowledge to enhance collaborative KM among different disciplines, particularly in the early stage of the project.

Based on the discussion above and the review of previous studies, BIM's potential for KM and the expectations of BIM-based collaborative KM in the early design stage are identified. These expectations are finally classified into three aspects, namely technical, process and cultural aspects. A conceptual framework of BIM-based KM for ECI and EFMI is proposed to summarise BIM's potential for KM and expectations of BIM-based collaboration in early design stage in detail (Figure 1).

CONCLUSION

This study applied semi-structured interviews and a questionnaire survey as the main methods to explore the involvement of contractors and FM teams in the design through BIM-based KM. The existing strategies for the early incorporation of contractors and FM team were firstly explored. Thereafter, BIM's potential of KM was identified. These potentials include knowledge capture and retention, knowledge sharing and visual-aided KM. Moreover, a few features of BIM, such as clash detection, early simulation and analysis, play a role in facilitating a proactive KM. This study also identified expectations for the early involvement of the knowledge of construction contractors and FM teams through the BIM-based KM.

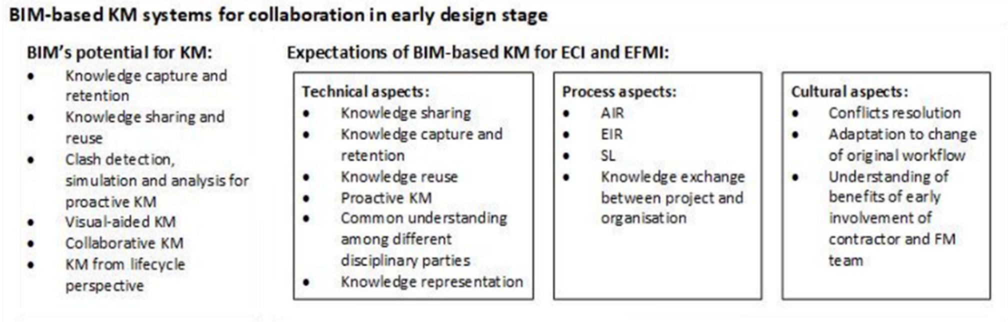

Figure 1: Conceptual framework of the BIM-based KM for ECI and EFMI

These expectations can be classified into three aspects (i.e. technical, process and cultural aspects) based on their characteristics. Lastly, a conceptual framework was proposed in this research. This framework represents a conceptual BIM-based KM system for collaboration in the early design stage, in which BIM's potential for KM and the expectations of BIM-based KM for ECI and EFMI are integrated. This study proposed a research direction for the transformation of BIM to BKM.

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