Bridging BIM and building: From a literature review to an integrated conceptual framework

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Abstract

A Building Information Model (BIM) is at risk of being 'blind and deaf' if its contained information cannot be synchronized with ongoing building processes in a real-time manner. Previous studies have attempted to explore solutions to the problem, with a view to making BIM a more useful decision-support system. However, an integrated conceptual framework summarizing these studies and structuring future development in the area is missing. Based on an *ex post facto* critical review of 75 papers of this kind published over the past decade, this paper proposes a conceptual framework for **b**ridging **B**IM and **b**uilding (BBB), which highlights the importance of synchronizing information between BIM and real-life building processes. The framework is further illustrated through a case study of prefabricated housing construction in Hong Kong. With this integrated conceptual framework, future research on BBB can proceed on a more solid footing.

Keywords: Construction project management; Building Information Modeling (BIM); information and communication technologies; literature review; conceptual framework.

1. Introduction

The importance of information in contemporary construction project management cannot be overemphasized. Managing a construction project involves using available information and knowledge to make a web of decisions across processes including architecture, engineering, construction, and operation (AECO) (Flanagan and Lu, 2008). A comprehensive taxonomy of information in regards to construction project management is yet to be defined; however, it normally comprises building geometry, spatial relationships, and quantities and properties of building components (Pratt, 2004). Lu *et al.* (2013) identify information as a new element in construction project management, a view which has encouraged the authors' own theoretical stance that a building can, in fact, be perceived of as a cluster of information, the management of which can achieve better AECO performance. It has become a truism that the main objective of information management is to support decision-making by ensuring that accurate information is always available at the right time in the right format to the right person, and it is against this backdrop that the development of Building Information Modeling (BIM) has gained momentum.

According to the U.S. National BIM Standard (2007), BIM is "a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle" (p.149). Eastman *et al.* (2008), on the other hand, intentionally and consistently use the term 'BIM' to describe the activity of modeling building information. In this study, we use 'BIM' to refer to both the activity of modeling and the digital and virtual representation/model of a physical building.

BIM has been adopted by an increasing number of AECO firms to manage project information and support information sharing between stakeholders (Goedert and Meadati, 2008); gradually, it is becoming an indispensable information platform for decision-making in construction. Nevertheless, in current practice, a BIM is largely disconnected from the real-life physical building processes throughout its life-cycle. For example, an architectural or structural model, however it is detailed by architects or engineers, will remain static if the information contained within it cannot be synchronized with the ongoing building process. A BIM is thus at risk of being 'blind and deaf' to ongoing AECO processes, while an 'as-built' model can more reliably and usefully support information exchange and decision-making throughout the project life-cycle. Manually updating information in a BIM in line with the physical building process has been found to be interruptive, tedious (Li *et al.*, 2009), time-consuming and error-prone (Anil *et al.*, 2013). To this end, researchers around the world have attempted to develop methods and technologies such as Auto-ID to facilitate the integration of virtual models and physical construction (e.g. Flanagan *et al.*, 2014).

What seems to be lacking, however, is a conceptual framework highlighting the theoretical perspective of **b**ridging **B**IM and **b**uilding (BBB), which means connecting the information contained in BIM with physical building processes to make BIM reflecting real-life situations. Such a framework could help summarize research work in BBB, which has developed in a piecemeal fashion to date. It could also make it possible to theorize a building as a cluster of information; BBB, currently performed via different information and communication technologies (ICTs), has actually become a general research question at the fore of information management (IM) for decision-making in contemporary project management. Further, an integrated conceptual framework would help structure strategic development directions in this area, allowing future research on bridging BIM and building to proceed on a more solid footing.

The aim of this research, therefore, is to develop a conceptual framework that: (1) summarizes the research work related to BBB; (2) highlights the concept of bridging BIM and building; and (3) structures the future directions of research work in this area. It does so by critically reviewing a body of literature comprising 75 papers published in six academic journals over the past decade. Based on the literature review, a conceptual framework is developed and illustrated using a case study. The rest of this paper is structured as follows. The research method of this study is elaborated in Section 2. The results of the literature review are presented in Section 3. Based on the results, the conceptual framework for BBB is developed and presented in Section 4. Section 5 is a case study of the use of radio frequency identification (RFID)-enabled BIM in prefabricated housing production in Hong Kong to illustrate the critical issues in BBB. Sections 6 and 7 comprise the discussion and conclusions respectively.

2. Research methods

As previous studies have touched upon issues relating to bridging BIM and building (BBB), the development of the conceptual model of BBB starts with a critical literature review. Literature review is defined as "a systematic, explicit, and reproducible method for identifying, evaluating, and interpreting the existing body of recorded work" (Fink, 1998, p.3). It develops the connection between related research works, and helps to identify the current achievement in a specific field and highlight important issues to be solved (Cooper, 1998). Given the difficulty of searching every related research work, delimitation to determine the boundary of the research is often necessary. Here, three criteria were considered during delimitation of the BBB literature:

(1) Only papers in peer-reviewed English journals are reviewed;

(2) The topic of the papers should be strictly limited to the use of virtual models with real-life project information; and

(3) Papers on construction informatics, which describe data acquisition from the physical

environment but have no relationship to the virtual models, are excluded.

According to our criteria, six journals are selected, namely, *International Journal of Project Management*, *Automation in Construction*, *ASCE Journal of Construction Engineering and Management*, *ASCE Journal of Computing in Civil Engineering*, *Journal of Information Technology in Construction*, and *Engineering, Construction and Architectural Management*. All the six journals have published at least one article fitting the criteria and are highly ranked by construction informatics researchers. The keywords used for searching the relevant papers included 'BIM', 'virtual design and construction (VDC)', ''as-built' model', and 'virtual model'. The contents of each paper were quickly screened by one of the authors to identify whether they should be included or excluded. To decrease potential bias during selection of journal papers, another author double-checked the selected papers. After delimitation, a total of 75 papers published from 2005 to 2014 were identified and considered as recent work.

Preliminary analyses were conducted to determine the basic descriptive information of each selected paper; that is, year of publication, research targets including applications and stages of the project life-cycle, and technologies used to connect the virtual model with physical projects. These descriptive results helped to group the papers before detailed analysis. The advantages and limitations of all possible technologies or methods and their scopes of application were critically analyzed with a view to providing components of the conceptual framework of BBB. The conceptual framework was subsequently evaluated through a case study, feedback from which enhanced the conceptualization of BBB (Fig. 1).

<<Fig. 1 Processes to develop the BBB conceptual framework>>

3. Results of Literature Review

3.1 General descriptions of the literature

The first study hit by the 'selection of papers' is Kim *et al.* (2005), which explores a rapid modeling method to transform data collected by laser range finder to decision-supporting information in the virtual model. Research relating to bridging BIM and building (BBB) has gained momentum, as witnessed increasing publications after 2005. This upward trend shown in Fig. 2 illustrates a growing recognition of the need to enrich information in a BIM by considering its dynamics with the physical construction project. Researchers have now started to explore models and technologies that can facilitate connection between the virtual and the physical (Flanagan *et al.,* 2014), with a view to making BIM a more helpful decision-support system.

<<Fig. 2 Distribution of selected papers in the past decade>>

In these 75 papers, various terms of information model are used other than BIM, such as ‘virtual modeling’ (e.g. Lee *et al.*, 2011), ‘virtual design and construction’ (VDC) (e.g. Mourgues *et al.*, 2012), and ‘3D modeling’ or ‘*n*D modeling’ (e.g. Bansal, 2011; Bhatla *et al.*, 2012; Turkan *et al.*, 2012b; Zhang and Arditi, 2013). This confirms Davies and Harty’s (2011) notion that BIM is a common term for a family of technologies and related practices. However, ‘BIM’ and ‘3D modeling’ are the two most popular terms, adopted by 35 and 34 papers respectively. A convergent use of ‘BIM’ can be observed (Fig. 3), revealing that after years of debate and promotion BIM is now widely accepted, though a single agreed-upon definition is still lacking.

<<Fig. 3 Percentage of adopted terms from 2005–2009 and 2010–2014>>

3.2 Detecting elements for the conceptual framework

The reviewed papers provide supporting elements to this study in its purpose of developing a BBB framework throughout a projects life-cycle. The framework is currently conceptual, however, the reviews of practical technologies and existing preconditions make our framework not only practical but also enlightening.

3.2.1 Target applications of BBB

As shown in Fig. 4, ‘process tracking’ and ‘generating ‘as-built’ models’ are the top two applications. For example, Azimi *et al.* (2011) stored the status information of steel components in radio frequency identification (RFID) tags, this information was then returned to the 3D model so that managers can track the actual process of construction work. Lee *et al.* (2013b) developed algorithms to automatically build a 3D model of entire pipelines based on laser-scan data. Notably, 'safety management' and 'facilities management' are not prevailing applications of BBB in the selected papers, although these have been much advocated recently (Ding *et al.*, 2014). One may notice that the total number of applications is larger than 75 (Fig. 4). This is due to the fact that some studies consider more than one target application. For example, the study carried out by Bosché and Guenet (2014) used laser scanner to generate an 'as-built' model and control the quality of construction works.

<<Fig. 4 Distribution of target applications of BBB>>

3.2.2 Project stages for BBB applications

As shown in Fig. 5, about 70% of the selected papers study applications at the construction stage. This should not come as a surprise; construction is the stage that takes the information from design and materializes a project. It is also the stage that needs information for intensive decision-making. Eight papers study the post-construction stage, at which an 'as-built' model is developed before operation and maintenance has begun. In contrast, only 3 papers considered the integration of virtual models (BIM, 3D model or others) and real-life data for wider applications throughout project life-cycle.

<<Fig. 5 Project stages for BBB applications>>

3.2.3 Technologies for BBB

Fig. 6 depicts the distribution of introduced technologies for data acquisition from real-life processes and integration between virtual models and physical building. There are eight types of technologies in total, amongst which laser scanning, radio frequency identification (RFID), and camera are the most popular technologies proposed for BBB. Other related technologies include augmented reality (AR), geographic information system (GIS), global positioning system (GPS), and sensor.

<<Fig. 6 Technologies adopted>>

3.2.3.1 Laser Scanning

Laser scanning which is adopted in 28 studies digitally captures geometric data and spatial relationships through laser light (Shih and Huang, 2006). As shown in Table 1, it is mainly used for process tracking (e.g. Turkan *et al.*, 2012a) and 'generation of 'as-built' models' (e.g. Arayici, 2007; Tang *et al.*, 2010; Jung *et al.*, 2014). Deviations between the 'as-built' and 'as-designed' models are used to assess the quality of construction work (Akinci *et al.*, 2006). Besides, the spatial data of specific objects support site monitoring (Su *et al.*, 2006), resources tracking (Teizer *et al.*, 2007), and safety management (Cheng and Teizer, 2013).

<<Table 1 Applications of laser scanning>>

According to the studies, current BBB practice using laser scanning is heavily reliant on manual effort (Anil *et al.*, 2011; Brilakis *et al.*, 2011). Some researchers present approaches and algorithms that can achieve automatic object identification (Bosché *et al.*, 2013; Xiong *et al.*, 2013) and improve object recognition quality (Bosché *et al.*, 2009), and flash LADAR technology enables rapid scanning for highly active situations (Randall, 2011).

3.2.3.2 Auto-ID technology

The use of Auto-ID technology such as 2D barcode and RFID, in the construction industry is not new. Twenty papers adopt RFID for the acquisition of real-life information and integration with the virtual model for the seven applications shown in Table 2.

<<Table 2 Applications of RFID>>

It is found that RFID is suitable for tracking the process of projects where steel (Xie *et al.*, 2011) or prefabricated components (Lu *et al.*, 2011) are used. In addition, RFID facilitates updating material properties and component inventories in the virtual model, which enhances quality control and supply chain management (Sørensen *et al.*, 2009). Real-time locations of workers, equipment and facilities that are tracked and recorded by RFID support safety management (Park and Kim, 2013; Ding *et al.*, 2013), activity monitoring (Azimi *et al.*, 2011; Shahi *et al.*, 2013) and facility management (Shen *et al.*, 2012).

3.2.3.3 Camera

Table 3 shows the main applications of camera for BBB. It has been used to rapidly detect and track static and moving objects including workers and equipment at the construction site (Son and Kim, 2010; Son *et al.*, 2010; Park and Brilakis, 2012). Based on photos taken from different positions and angles, a 'real-life' model can be developed (Dai and Lu, 2010). This model can then be used to calculate the percentage of completion and track the actual construction process (Golparvar-Fard *et al.*, 2009; El-Omari and Moselhi, 2011; Roh *et al.*, 2011). Cameras collect real-life information at a lower cost and with less computational time than laser scanners (Kim *et al.*, 2013), but their accuracy is less in complex environments (Klein *et al.*, 2012). Some researchers have attempted to integrate laser scanning and photogrammetry to overcome the limitations of each (El-Omari and Moselhi, 2008; Zhu and Brilakis, 2009; Dai *et al.* 2012).

<<Table 3 Applications of camera>>

3.2.3.4 Augmented reality

Unlike the other technologies listed in Fig. 7, augmented reality (AR) does not capture physical information and import it into a virtual model; conversely, it displays virtual information in a real-world environment (Yeh *et al.*, 2012; Jiao *et al.*, 2013; Wang *et al.*, 2013). With the help of AR, the as-planned model can be vividly shown at the physical construction site to act as a baseline for process tracking (Kamat *et al.*, 2010) and monitor construction performance (Park *et al.*, 2013; Lee, *et al.*, 2013a; Kwon *et al.*, 2014). In addition, AR provides instruction for workers, helping them to understand the as-planned progress (Wang *et al.*, 2014a). AR is thus a preferred and unique technology for BBB.

3.2.3.5 Global Positioning System and Geographic Information System

Global positioning system (GPS) is the most common tool for outdoor localization and tracking (Taneja *et al.*, 2010). In the selected papers, GPS provides geo-references for retrieval of virtual elements from scanned data (Bosché and Haas, 2007), and can be used in conjunction with RFID to provide location information for construction components (Torrent and Caldas, 2009; Vähä, 2013) or materials (Razavi and Haas, 2010). A geographic information system (GIS) can support the analysis of huge amounts of spatial data (Bansal and Pal, 2008), which in conjunction with BIM can determine the feasible areas for tower cranes to cover all demand and supply points (Irizarry and Karan, 2012) and visually illustrate the flow of material in supply chain management (Irizarry *et al.*, 2013b). Additionally, building 3D models in a GIS environment enhances understanding of project schedules (Poku and Arditi, 2006; Bansal and Pal, 2009).

3.2.3.6 Sensor

Various types of sensor are adopted to collect real-life information including the quality of cast-in-place concrete elements (Akinci *et al.*, 2006), the safety status of underground environments (Ding *et al.*, 2013), and the real-time temperature and oxygen values in a confined working space (Riaz *et al.*, 2014). This real-time information can be transferred to a BIM via wireless network and presented in the visual environment, significantly improving the effectiveness of construction project management.

3.2.3.7 Software, database, and information exchange protocols

Most of the selected papers do not provide information about 3D model or BIM development software. Among those mentioning the software for developing 3D model or BIM, 18 papers adopt Autodesk®Revit® (e.g. Wang *et al.*, 2014b), while 6 and 5 studies use Bentley®MicroStation® and Graphisoft®ArchiCAD® respectively (e.g. Bosché and Haas, 2008; Chin *et al.*, 2008). SketchUp is used by 2 studies (e.g. Teizer *et al.*, 2013) to draw 3D models. Tekla or Autodesk®3ds Max® can model typical building components. For project reviewing, Autodesk®Navisworks® and Bentley®Navigator® are adopted in a few papers (e.g. Zhou *et al.*, 2013; Goedert and Meadati, 2008). As regards databases, 7 papers adopt one among SQL Server, MySQL, and Microsoft Access (e.g. Chin *et al.*, 2008; Motamedi and Hammad, 2009; El-Omari and Moselhi, 2009). The connection between the database and 3D model or BIM software is developed by Application Programming Interface (API) which is programmed by either VB.Net, C# or C++ (e.g. Goedert and Meadati, 2008; Riaz *et al.*, 2014).

The format of information affects the possibility and quality of information exchange. After generating a 3D model or BIM using the software mentioned above, the model is set or transferred to the desired format (e.g. FBX, DWG, STL, 3DS, DXF, IFC) in order to connect it with other software such as Matlab® (Son and Kim, 2010) and ArcView (Poku and Arditi, 2006). For instance, models developed by Bentley®MicroStation® are exported into STL format before integration with data collected by laser scanner (Bosché and Haas, 2008). IFC format provides an appropriate structure for information sharing (Vanlande *et al.*, 2008) and is applied in most of the selected papers to increase interoperability (e.g. Boukamp and Akinci, 2007; Motamedi and Hammad, 2009). Eight papers adopt XML-based format as it can be shared by proper XML interfaces (Irizarry *et al.*, 2013a; Lagüela *et al.*, 2013).

3.3 Summary

The critical literature review provided several insights:

(1) Given that an information-rich BIM can facilitate decision-making in the building process, the attention has increasingly been paid to bridging BIM and building (BBB);

(2) No integrated conceptual framework that summarizes existing research in this area and structures future strategic directions has been proposed;

(3) Most of the selected papers are concerned with 'tracking' and 'generation of an *as-built* model' at construction stage, while wider applications of BBB at other project stages are yet to be explored;

(4) None of the BBB technologies explored in previous studies can satisfy all needs arising throughout a project life-cycle, and software, database, and data exchange protocol issues should be paid more consideration during the course.

(5) There is a general lack of studies on interoperability of data among different BIM software programs and hard data-acquisition technologies.

(6) A collaboration of various technologies could facilitate integration of building information models and physical building processes.

Based on the insights, a framework supporting research and practice is proposed.

4. The conceptual framework for bridging BIM and building

The conceptual framework, as shown in Fig. 7, has three major layers, namely the physical layer, the central database/gateway layer, and the BIM layer.

(1) The physical layer

The physical layer consists of a series of activities ranging from site investigation to demolition following a project lifecycle. Most of these activities require many inputs including time, money, material, and manpower. Meanwhile, they generate various types of information to be detected, collected and retrieved in a timely manner to support decision-making. A collaboration of technologies as introduced in Section 3.2.3 are arranged to acquire all project-relevant data. Lines drawn between the technology and the physical activity indicate the data acquisition.

(2) The central database/gateway layer

In the central database/gateway layer, the information collected throughout the project processes by different technologies is stored, and its format is transferred to work in BIM environment. This layer is of crucial importance for the reason that it ensures the interoperability of information. Besides, the stored information must be secure, thus only authorized stakeholders can access it.

(3) The BIM layer

The BIM layer involves a shared model developed in the design stage, it finally presented the real-life information for stakeholders to conduct a series of decision-making. The information is grouped by type and linked with the digital components in BIM.

Considering each part of the conceptual framework is not always at the same location, all information in digital format is transferred through network. Amongst available communication networks, a local area network (LAN) can interconnect computers in the construction site and support information transfer within a group, while a personal area network (PAN), including Bluetooth and ZigBee, mainly serves individuals over short distances.

<<Fig. 7 The conceptual framework for bridging BIM and building>>

5. Case study

A case study has been adopted to illustrate the practical uses of the conceptual framework for bridging BIM and building (BBB). The case concerns prefabricated housing production in Hong Kong. The developer aims to achieve better time, quality, cost, safety, and environmental records by improving the process using the latest technological instruments such as BIM and Auto-ID. The process comprises an array of decisions to be made, and the developer desires real-time information so that it can make informed decisions and thus achieve its goals. BIM is expected to be the ideal platform to provide this information if it can be synchronized with the prolonged process of prefabricated housing production. A research team was tasked to develop such platform, which includes a large number of sub decision support systems. From the outset, the research team was aware of the existence of studies of this kind but they are in a piecemeal fashion. It was determined to understand the production process, streamlining it, and examining the availability and suitability of technologies first, instead of designing the system architecture hastily. The BBB conceptual framework provides the footing for analysis of this process and exploration of potential technical solutions.

5.1 Design stage

In this project, the design team depart from conventional practice to design directly using BIM. The design has suitable Level of Development (LOD) (e.g. LOD 350) that strikes balance between information sufficiency and BIM 'thinness'. After the completion of design in the BIM environment, a list of prefabricated components and their quantities are extracted from the model and used to purchase the components.

5.2 Manufacturing stage

Detailed design information for the precast elements contained in the BIM is communicated to the manufacturers for prefabrication production. Auto-ID technologies are adopted at this stage to turn all the components into Smart Construction Objects (SCO) (Huang *et al.*, 2008), with a view to bridging the information between the objects and the BIM. Given its strengths (Lu *et al.*, 2011), radio frequency identification (RFID) is adopted as the 'bridging' technology in this case study. Clients and manufacturers explore proper RFID models (e.g. active or passive, and suitable radio frequency) and standards when embedding RFID tags in the precast components (See Fig. 8).

<<Fig. 8 Building components with RFID tags>>

The positions of the tags are indicated in the BIM in order to achieve standardized production. A unique identification number, regulated by a pre-defined naming convention, is set in the tag in order to register the precast components in the central database and link this information with the digital BIM. Tests are arranged to check whether the quality of the precast components can meet the project's requirements. Results are transferred to central database where they are automatically grouped. It is confirmed by the director of the manufacturing company that RFID and the central database offer much convenience for information management than conventional paper-based method.

For precast components meeting the quality requirements, they are properly stored in the yard before delivery. The components are scanned by RFID readers which change the status of components from "Manufacturing" to "In storage" and update such information in the database. Since the components are linked with the digital representation in BIM, the client and the contractor in Hong Kong can remotely monitor the status of the precast components in the BIM, i.e. real-time information visibility and traceability.

5.3 Delivery stage

The schedule of delivery is developed based on the ‘as-planned’ project schedule embedded in the BIM. In this project, a third-party logistics company is responsible for component delivery. Before precast components are loaded onto the truck, the embedded RFID tags are read in order to ensure that the right elements are delivered. Meanwhile, status of those components change from “In storage” to “Delivery” in the database. The client and the contractor in Hong Kong can click on the virtual components in BIM to find out which have been delivered. Once the truck arrives on site, after damage checking, the status changes from “Delivery” to “Received”.

5.4 On-site assembly stage

At installation, workers use handheld RFID readers to scan the tags of the prefabricated components to get the ‘as-design’ locations in the BIM, which guarantees that no prefabricated component will be installed at the wrong location. Given that these are high-rise buildings in Hong Kong, GIS and AR Drone technologies are adopted to provide real-time site information for the installation work. When a component is installed, a worker scans the embedded RFID tag and updates the status from “Received” to “Installed” in both the database and the BIM. The contractor can refer to the status of each component in the virtual model to gain information about the real-time construction process. In this case, the client’s ambition is to achieve ‘Just-in-time (JIT)’ delivery and onsite assembly. The narrow streets and confined site areas in Hong Kong necessitate a JIT operation but, together with the prolonged logistic and supply chain, add to the difficulties of doing so.

5.5 Operation and maintenance stage

Although this case is still at the construction stage, it is expected that the ‘as-built’ BIM, developed by BBB, will be passed on to later stages for building operation and maintenance (O&M). In this project, all components have been installed with RFID tags for identification and tracking and have been connected to the corresponding virtual BIM. One facility can be easily differentiated from others, and facility managers can quickly obtain the exact location of components from the model for periodical inspection, analysis, and maintenance if a problem is discovered. Sensors will also be used to monitor performance and capture operation data. Information such as the amount of water or electricity usage will be accurately recorded in the central database to facilitate O&M.

5.6 Experience learnt for the case study

The conceptual framework does not demanded the integration of the individual construction processes such as design, bid, manufacturing, and build, which might be constrained by practical situations, e.g. bidding is often mandated by authority if this is a project funded by the public sector. Instead, the framework proposes various technologies that can capture real-life information from the physical world, with a view to alleviating the fragmentation and discontinuity existing in existing construction processes. The conceptual framework also lists the possible functions if BIM is adequately enriched with information through BBB. This framework is thus becoming an intuitive tool for mainstreaming the use of BIM and information management; stakeholders well understood their positions in the framework and the potential contributions they can make.

Back to the system development level, the research team has hugely benefited from the conceptual framework. For example, it helped us to analyze the construction project processes, with a flexibility to be modified for either cast in-situ or prefabrication, either for building or other types of projects. A significant and innovative contribution when developing and applying the conceptual framework is to propose a gateway. Nowadays information is collected through different technologies with different formats (e.g. photos, numbers) and different operational systems (e.g. Windows, OS, and Android); with the gateways, the system can deal with the heterogeneous BBB technologies before the information is stored in the database and transferred to BIM. The conceptual framework, with proper modifications, has been used to develop architectures of real RFID-enabled BIM systems for prefabricated housing production.

6. Discussion

The conceptual framework can serve as the foundation for enriched BIM and facilitate construction project management. BIM has the potential to be the catalyst for project managers to reengineer their processes to better integrate the different stakeholders involved in modern construction projects (Bryde *et al.,* 2013). This conceptual framework, informed by the many studies in this field, further highlights the importance of bridging BIM and building (BBB) in this catalyst taking effect. The framework echoes the concept of a cyber-physical system for coordination of virtual models and physical construction introduced by Akanmu *et al.* (2013) and Flanagan *et al.* (2014), although such a system has not yet been tested in a real-world situation.

The BBB framework in the above case can be further understood by linking it with the information systems prevailing in the manufacturing industry, given the similarities between prefabrication construction and manufacturing. For example, Huang *et al.* (2011) developed a conceptual Gateway Product Service System (iGPSS) framework for cost-effective deployment of RFID-enabled manufacturing solutions. Its system structure and the three key components, which can be a very useful reference point if the BBB framework is to be operationalized in prefabrication construction. Where the heterogeneity of a construction project (e.g. fixed job site, and one-off and complex nature) is concerned, the BBB framework can be further comprehended in conjunction with the Open Systems Interconnection model (OSI), which is a conceptual model widely used in structuring the Internet or other communication systems. The OSI characterizes and standardizes the internal functions of a communication system by partitioning it into abstraction layers (Day and Zimmermann, 1983). The multi-layer structure of the BBB conceptual framework is similar to that of the OSI.

The conceptual framework integrates stakeholders throughout the project life-cycle, delineating different information and communication technologies (ICTs) and their associated software, database, and information exchange protocols to make BIM more useful. The framework is thus a powerful tool for practitioners to mainstream their BIM implementation strategies. Notably, the BIM-related software vendor RIB Group has developed a similar framework to introduce its platform iTWO, which can be understood as an information exchange platform between the virtual and the physical in a construction project, and amongst the different stakeholders who are involved in the project (König *et al.*, 2012).

Although investigation of the technologies that can link the virtual model and the physical construction process is nothing new, one of the significant contributions of the integrated framework is to highlight the general conception of BBB. Researchers can theorize bridging BIM and building by linking the area to the general theories of information management while considering the characteristics of project-based organization (e.g. Söderlund, 2004;

Morris *et al.*, 2011). Researchers can also further explore the practical uses of BBB technologies that can make BIM a more useful decision support system. In any case, the developed conceptual BBB framework can serve as solid footing for future research.

7. Conclusions

Researchers over the years have published studies exploring methods and technologies for capturing real-time information from real-life physical project processes and synchronizing it with BIM as a central information platform. These efforts are conceptualized as 'bridging BIM and building (BBB)', which has become a general research question at the frontier of information management for decision-making in contemporary project management. A critical review of existing studies showed that they mainly concern 'tracking' and 'generation of an 'as-built' model' at construction stage, while wider applications of BBB at other stages are yet to be considered. The major technologies explored were laser scanning, RFID, camera, GIS, GPS, and AR. To date, software, databases, and data exchange protocols have been paid scant attention in BBB studies. Collaboration of various technologies could integrate building information models and physical building processes for better project management performance.

Building on the literature review, this study has developed an integrated conceptual framework for BBB. The framework comprises several layers, including a physical layer (representing the actual architecture, engineering, construction, and operation [AECO] activities throughout a project life-cycle), BBB technologies, a BIM layer, and the central database set up between the physical layer and the BIM layer. It can be used by practitioners as a powerful tool for mainstreaming or planning their BIM implementation strategies with a view to improving project management performance. Future research is recommended into theorizing BBB by linking it to the general theories of information management and the characteristics of construction projects and project-based organizations. Researchers are also recommended to further explore the practical uses of BBB technologies that can make BIM a more useful decision-support system. With this integrated conceptual framework, future research on BBB can proceed on a more solid footing.

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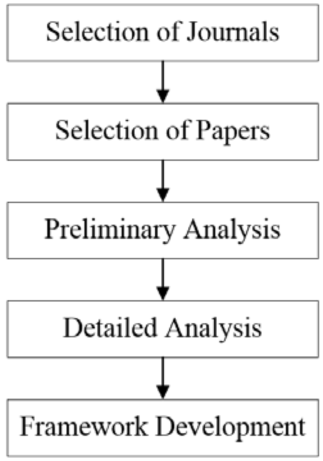

Fig. 1 Processes to develop the BBB conceptual framework

Fig. 2 Distribution of selected papers in the past decade

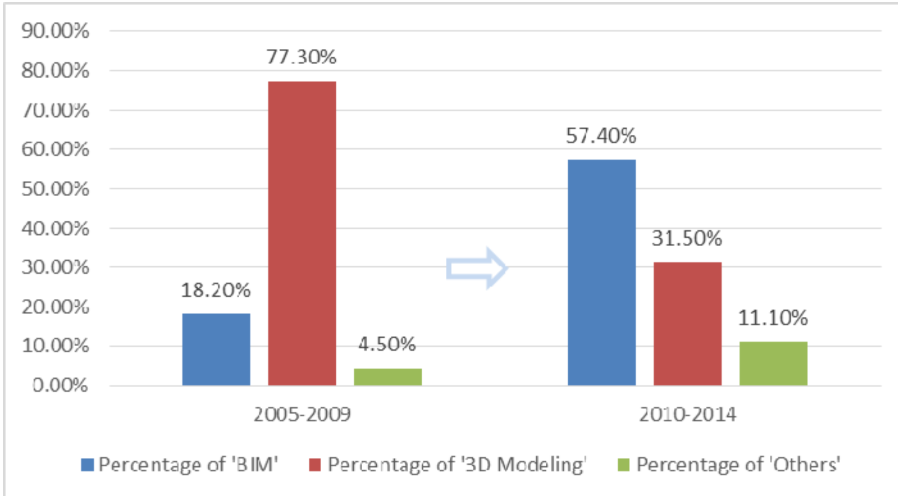

Fig. 3 Percentage of adopted terms from 2005–2009 and 2010–2014

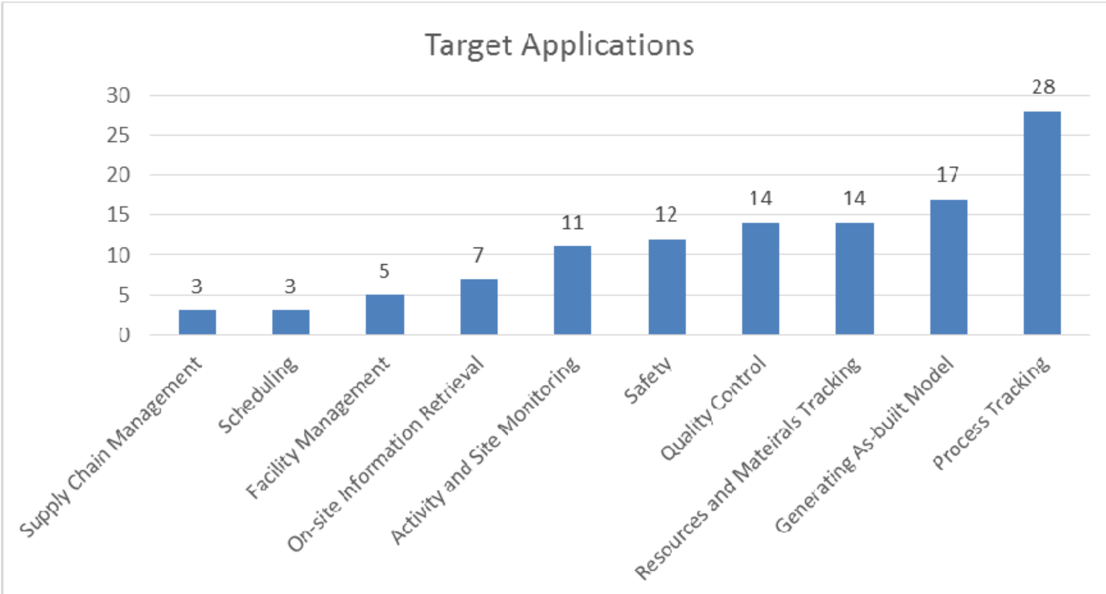

Fig. 4 Distribution of target applications of BBB

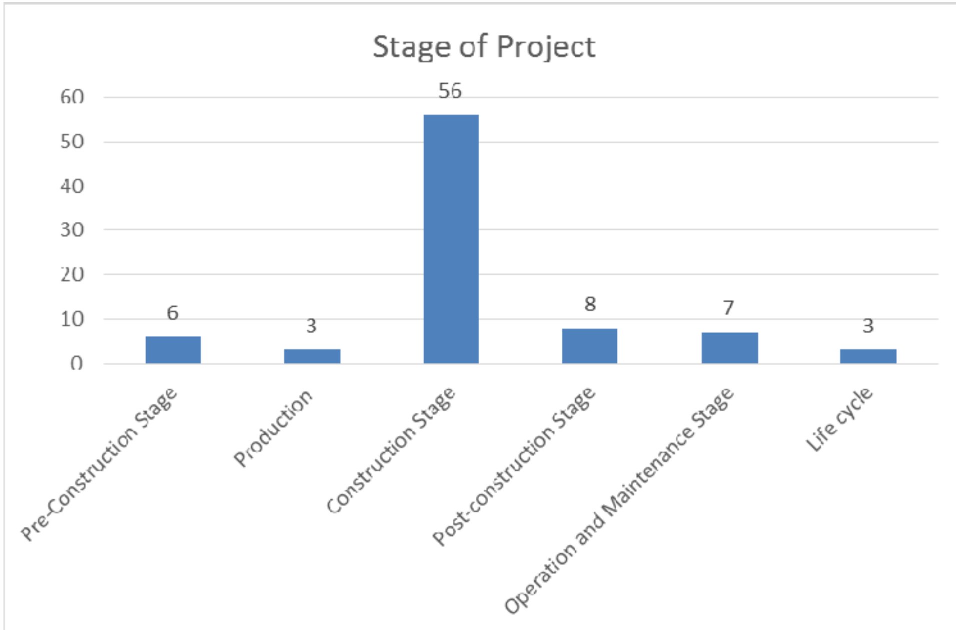

Fig. 5 Project stages for BBB applications

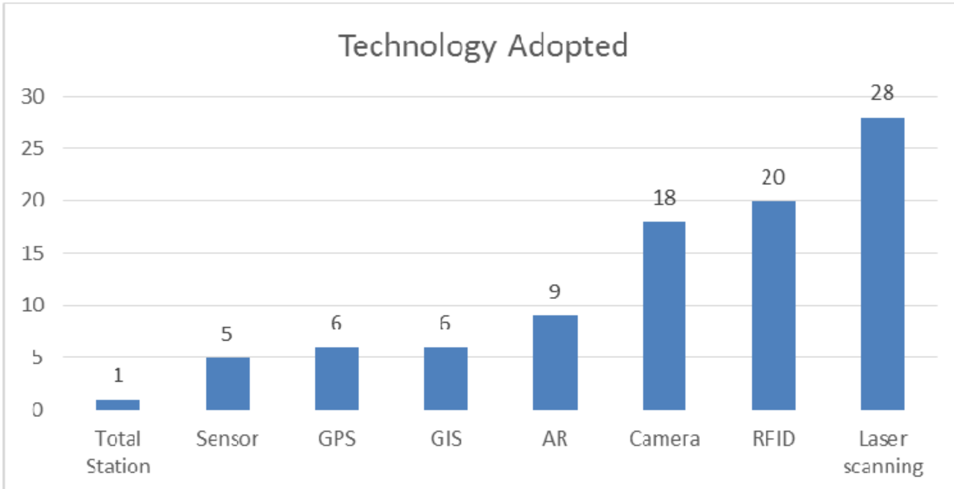

Fig. 6 Technologies adopted

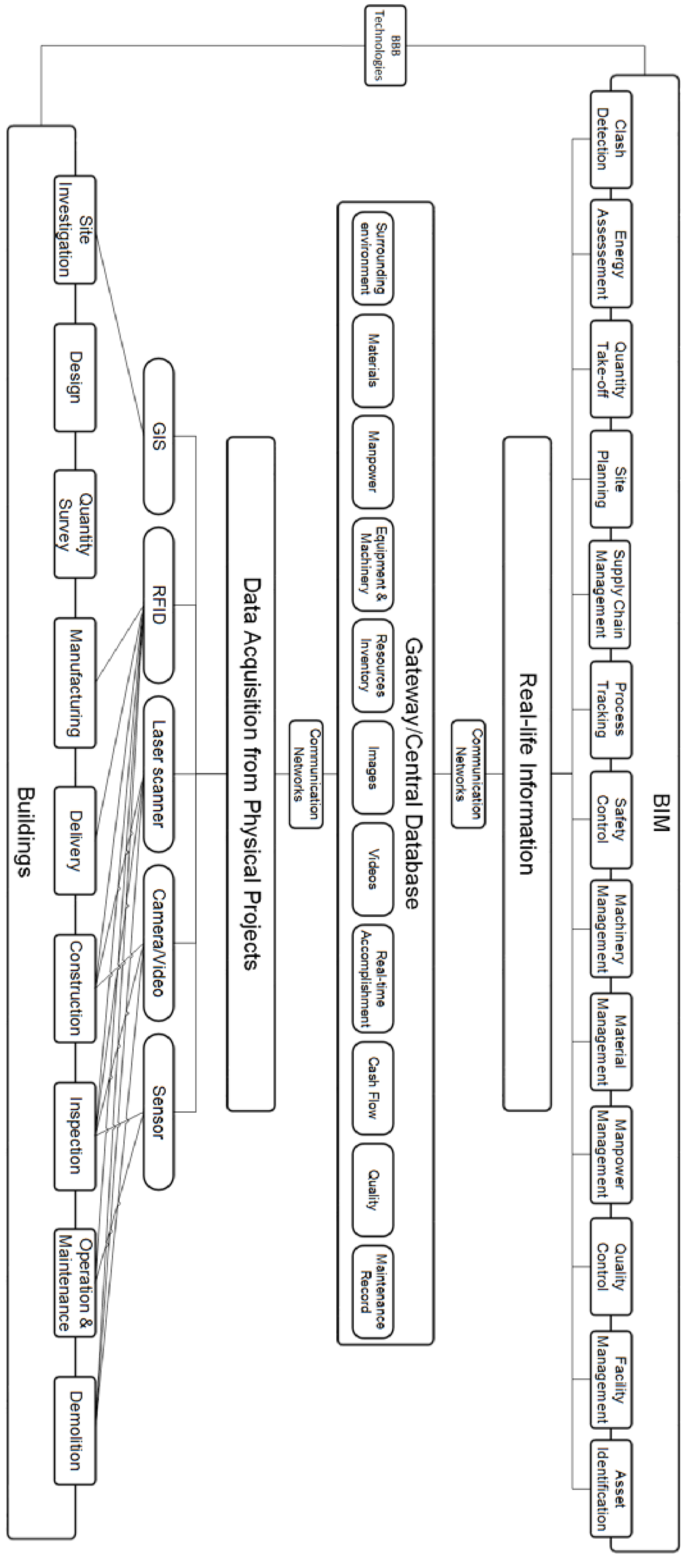

Fig. 7 The conceptual framework for bridging BIM and building

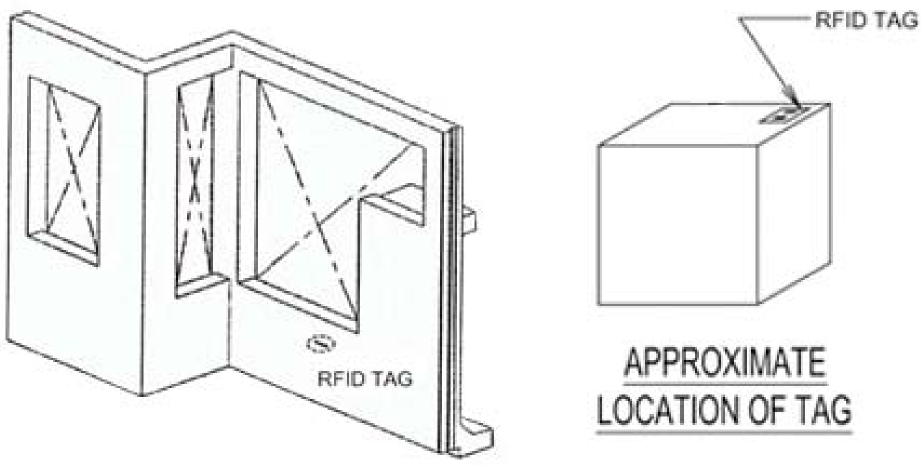

Fig. 8 Building components with RFID tags

Table 1 Applications of laser scanning

	Process Tracking	Generating 'as-built' Model	Quality Control	Activity and Site Monitoring	Safety	Resources and Materials Tracking
Laser Scanning	15	12	7	3	2	2

Table 2 Applications of RFID

	Resources and Materials Tracking	Process Tracking	Safety	Quality Control	Activity and Site monitoring	Facility Management	Supply Chain Management
RFID	11	9	4	4	3	3	2

Table 3 Applications of camera

	Process Tracking	Generating ‘as-built’ Model	Activity and Site Monitoring	Safety
Camera	8	6	3	2