Bridging BIM and building (BBB) for information management in construction: The underlying mechanism and implementation

Ke CHEN[1], Weisheng LU[2]

Abstract

Purpose—How to make effective use of building information modeling (BIM) for information management (IM) is a challenging question in the field of construction project and asset management (CPAM). Chen et al. (2015) answered this question by developing a conceptual framework of 'bridging BIM and building (BBB)'. However, the underlying mechanism through which BBB can truly impact IM remains unclear. The purpose of this paper is thus to demystify the mechanism linking BBB and IM.

Design/methodology/approach—Drawing upon the IM literature, this study proposes three IM requirements, namely, requirements on information quantity, quality, and accessibility, as significant mediators between BBB and IM. To verify this proposition, a two-year, participatory case study was conducted based on a real-life construction project in which a BBB system was implemented.

Findings—The results of the case study supported the proposition that by enhancing the information quantity, quality, and accessibility BBB could favorably contribute to IM in construction.

Practical implications—This paper provides knowledge about system architecture,

[1] Corresponding author, Department of Construction Management, Huazhong University of Science and Technology, Wuhan, China; Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, Email: chenkecm@hust.edu.cn;
[2] Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, Email: wilsonlu@hku.hk;

components, and their linkage in an operable BBB system. It also provides empirical experience about BBB implementation.

Originality/value—This study is among the first attempts to streamline the theoretical discourses relating to BBB for IM in a construction context. It contributes to the construction IM by directing attention to key IM requirements and processes rooted in the IM literature.

Keywords: building information modeling; information management; information quantity; information quality; information accessibility

1. Introduction

Construction project and asset management (CPAM) generally involves multi-disciplinary professionals working together to construct and manage a given asset. Against this backdrop, the critical role of information management (IM) to overall CPAM performance cannot be overemphasized. CPAM in essence is an array of decisions made by different participants across the lifecycle of an asset based on the available information (Flanagan and Lu, 2008). Given the complex nature of CPAM nowadays, these decisions are more closely interrelated. This implies the reality of even greater uncertainty caused by increasingly dynamic information on which decision-making is dependent. The management of information, in layman's terms, is the making of accurate information available at the right time in the right format to the right person (Chen et al., 2015). The fundamental goal of IM is to support efficient and effective decisions by harnessing the value of information (Choo, 2002). In this way, IM is key to managing changes, informing decisions, and maintaining the integrity of an asset's functional and physical attributes to meet the demands of the owners, users, etc., i.e., to establish the configuration of a CPAM approach that is tuned to the project at hand (Love et al., 2014; Tezel and Aziz, 2017).

The importance of IM coupled with the rapid advancement of information technologies has directed the attention of CPAM towards building information modeling (BIM) (Eastman et al., 2011). As the digital representation of physical and functional characteristics of a facility, BIM is widely accepted to be an effective tool to store, integrate, and share dynamic information from different stages of an asset's planning, construction, and occupation to facilitate communication and the use of information (Eastman et al., 2011; Love et al., 2014; Xu et al., 2014).

The potential benefits of BIM in supporting IM have been broadly discussed in the ample set of literature (e.g., Demian and Walters, 2014; Hoeber and Alsem, 2016; Beach et al., 2017). In understanding the potentials of BIM, many researchers acknowledge the existing obstacle of bringing BIM into play in practices, which raises immediate questions about how to make effective use of BIM for IM in real-life construction projects (e.g., Xu et al., 2014; Chen et al., 2015; Edirisinghe et al., 2017). Notably, Chen et al. (2015) have partly answered this question by developing a conceptual framework of 'Bridging BIM and Building (BBB)'. The BBB conceptual framework highlights the importance of information synchronization between BIM and actual CPAM processes, which echoes the concepts of a Cyber-Physical System (CPS) (Anumba et al., 2010) and a digital twin (Tao et al., 2017) in a broader sense. Chen et al. (2015) further argued that the potentials of BIM are more likely to be achieved if utilizing BIM in a way towards BBB, i.e., continually updating a BIM model with accurate, reliable project information and supporting the timely sharing of information.

Several researchers have recognized Chen et al.'s (2015) conceptual framework of BBB (e.g., Ghaffarianhoseini et al., 2017; Sun et al., 2017). Nevertheless, at least three questions remain unaddressed in the existing literature. First, the underlying mechanism, or figuratively, the 'epistemological link', through which BBB could support IM remains unclear. Second, issues about how to develop possible system architectures of the BBB conceptual framework have yet to be fully addressed. Finally, with some notable exceptions, very few studies have empirically examined the contribution of BBB to IM in construction.

This paper draws upon the BBB conceptual framework and the IM literature to make three contributions. First, it demystifies the underlying mechanism of how BBB could contribute to IM. Three IM requirements, namely, requirements on information quantity, quality, and accessibility are identified as significant mediators between BBB and IM. Second, it introduces the system architecture and the deployment procedures of BBB. Third, it illuminates the implementation of a BBB system in a real-life prefabricated construction project. Based on this project, a case study has been done to empirically test the demystified 'epistemological link' between BBB and IM.

The following section reviews the relevant literature, covering explanations of IM in CPAM and the role of BIM for IM. In Section 3, the authors proceed to discuss the mechanism linking BBB and IM by identifying significant IM requirements. In Section 4, a system architecture of BBB and its operational procedures are provided. A case study is presented in Section 5, and the evaluation results about how BBB can improve IM are provided in Section 6. Conclusions are drawn in the final segment of the paper.

2. Literature review

2.1 IM in CPAM

For all types of organizations, IM is critically relied upon to harness the value of information for environmental adaptation and internal coordination (Choo, 2002). IM is an umbrella term for activities associated with organizational participants' information-related behaviors and how they help achieve their strategic purposes (Choo, 2002). The primary elements of IM procedures include the development of information systems for and policies around the work of information acquisition, storage, retrieval, processing, interpretation, communication, and use (Maes, 2007).

Given the complexity of CPAM, the literature commonly agrees that IM strategically benefits decision-making and problem-solving across a project's lifecycle (e.g., Chassiakos, 2007; Xu et al., 2014). A construction project can be viewed as a process of aligning numerous separate resources upon a particular location over a reasonable amount of time and sequence, at bearable prices, and with desired quality (Sawhney et al., 1998). In order to be well managed, it requires superiorly performed coordination and sets a high standard for the elimination and handling of uncertainty and interdependence between activities (Dubois and Gadde, 2002). Uncertainty in construction could be caused by those unpredictable and uncontrollable factors existing in both the internal and external environments of an asset. While all businesses confront unpredictability and uncontrollability, the construction industry is especially vulnerable to such factors due to its heterogeneous production process (Dubois and Gadde, 2002).

Another determinant of CPAM complexity—interdependence—arises from the close interrelationships between decisions made at all stages of an asset (Lu and Olofsson, 2014). For example, for construction and facility management activities, various personnel need decisions made by designers, e.g., the design drawings, to support their decision-making and ongoing work (Nourbakhsh et al., 2012). A trivial change in one design decision may produce a domino effect, altering activities throughout the construction and operation stages (Love et al., 2014). As such, uncertainties present in the miscellaneous activities and interdependencies between participants throughout an asset's lifecycle pose real challenges to realizing CPAM configuration. Thus, an adequate amount of high quality, accessible information is needed for making decisions as rationally as possible (Amendola, 2002). Hence, IM is essential to CPAM by solving information problems arising from uncertainty and interdependency that participants and their activities often circumvent (Martínez-Rojas et al., 2015).

2.2 Prior research on BIM for IM

Since its introduction three decades ago, BIM has rapidly developed. This cutting-edge information technology management system has been applied to CPAM in most global construction industries (Eastman et al., 2011). BIM enables novel ways for project stakeholders to illustrate design, construction, and operations details, as well as more effective exchange and use of information, thereby developing a more agile and in-depth understanding of the configuration of CPAM (e.g., Xu et al., 2014; Love et al., 2014). As Love et al. (2014) argued, the benefits of BIM are realized most when it allows different stakeholders to perform their roles more efficiently and effectively.

Prior studies have exposed BIM's various capabilities for supporting IM (e.g., Love et al., 2014; Hoeber and Alsem, 2016; Beach et al., 2017). In understanding the benefits of BIM, many studies focused on conceptualizations and expressed the potentials of BIM in future scenarios as "idealistic goals" (Miettinen and Paavola, 2014). However, many researchers suggest the conceptualization of BIM's potentials cannot validate its effectiveness (e.g., Barlish and Sullivan, 2012; Zheng et al., 2017). According to them, BIM continuously effects the ways participants do their work. Thus, the evaluations on BIM should consider the entire process of associated operations instead of solely focusing on the final results. Furthermore, from the empirical perspective, very few studies have empirically assessed the significance of BIM to IM in construction. The existing empirical BIM studies, nonetheless, fail to offer a systematic, detailed link between BIM and its advantages in supporting IM.

2.3 Recapitalizing the conceptual framework of BBB

A potential reason to the above-specified deficiencies in both the theoretical and empirical BIM literature is the fact that using BIM alone cannot provide a permanent IM platform for alleviating the problems caused by the temporary nature and heterogeneity (e.g., uniqueness, fragmentation, and discontinuity) of construction projects. As Chen et al. (2015) argued, an architectural or structural BIM model would remain static if the information it contains cannot be synchronized with dynamic project processes. Thus it risks being 'blind and deaf', failing to go very far in supporting IM in construction. An 'as-built' BIM model that reflects the ongoing CPAM process, comparatively, is proposed to be more reliable and effective in supporting IM across an asset lifecycle. Against this proposition, Chen et al. (2015) developed the conceptual framework of BBB to take full advantage of BIM.

Chen et al. (2015) defined BBB as "connecting the information contained in BIM with physical building processes to make BIM reflecting real-life situations". The BBB conceptual framework consists of the building layer, intermediate layer, and BIM layer (see Figure 7 in Chen et al. [2015]). The building layer involves activities in a project, of which various types of information are collected and processed. The intermediate layer organizes information storage and interoperability. The BIM layer refers to the BIM model, which presents the real-life project situation for decision support. According to the principle of the BBB conceptual framework, as the project progresses, the BIM model should be updated continuously with information passing through the intermediate layer and integrating with BIM objects accordingly. Considering the linkage between BIM's potentials and the BBB conceptual framework, this paper shows its importance in providing a conceptualized way for empirical evaluations on impacts of BIM through demystifying the mechanism through which BBB contributes to IM.

3. Mechanism linking BBB and IM

BBB underlines the management of information rather than technology. Accordingly, an operable system developed following the BBB conceptual framework (thereafter named a BBB system) should allow the collection, storage, process, and communication of various types of project information, providing seamless connectivity between BIM and the physical project process. A BBB system influences the satisfaction of three IM requirements, namely, information of adequate quantity, high quality, and easy accessibility. These requirements in turn are important antecedents for desired IM performance. Thus, the authors posit that these three IM requirements mediate the links between BBB and IM in construction.

Information quantity

This requirement defines the need for a sufficient amount of information in order to cope with uncertainty. As argued by Galbraith (1973), the more diverse the goals, the more variable the tasks, and the more significant the interdependencies, the more information necessary to reduce uncertainty. Construction projects need more than just a variety of information on interdependent tasks, resources, technologies, etc. Information emerges continuously whenever a task completes or a new task is issued. When only limited information is available, serious problems like project delays and budget overrun can ensue (Eastman et al., 2011). Thus, IM in construction should ensure the collection and processing of a sufficient amount of information in a timely and continuous manner.

A BBB system can significantly enable the provision of a sufficient amount of information. Hajian and Becerik-Gerber (2009) explained that the use of BIM together with data-acquisition technologies allows comprehensive project information to become available. This is understood by connecting users' information needs and BIM's definition. In construction projects, managers and workers' information needs essentially relate to building components. Information from each component relates to an entity, e.g., material and labor, centered on a component. In a BIM model, a digital object represents a building component. The implementation of BBB allows a BIM object to timely reflect all information related to its corresponding physical component (Eastman et al., 2011). In so doing BIM can provide the comprehensive information that encompasses design documents, construction progresses, stakeholders, resources, activities, changing relationships, etc. Thus, the authors assert that the implementation of a BBB system meets the IM requirement of information quantity.

Information quality

This requirement defines the need of quality information to handle equivocality and quickly specify the required information. In construction projects, managers often need to translate events into information, and then transmit, communicate, and transform it into decisions. Great equivocality might emerge during this process, causing difficulties in communication and decision-making (Weick, 1979). It is also worth noting that, when seeking to satisfy the requirement on information quantity, an additional piece of information may also trigger divergence and ambiguousness, thus increasing equivocality (Espejo and Watt, 1988). Furthermore, when information is overwhelmed, users find it hard to identify the information they need promptly, which in turn hinders their decisions (Choo, 2002). Thus, a well performed IM involves more than processing the amount of information; information quality is also a core concern (Daft and Weick, 1984).

A BBB system is a significant enabler of the provision of quality information. First, by minimizing the manual work in the collection and processing of information, BBB eliminates the difference between information in BIM and the physical construction and avoids losses of information (Chen et al., 2015). The *timeliness* and *accuracy* of information can thus be ensured. Furthermore, through the 3D visualization of information, BBB provides the information of *conciseness* as suggested by organizational researchers (e.g., Daft and Lengel, 1986). Finally, a BBB system enables the intelligent retrieval and fast, responsive presentation of information in response to users' information needs, ensuring the *relevance* of information. The highlighted information attributes, i.e., *timeliness*, *accuracy*, *conciseness*, and *relevance*, most often appear in information researchers' constructs of information quality (e.g., Wand and Wang, 1996). Thus, the authors propose the implementation of a BBB system meets the IM requirement of information quality.

Information accessibility

This requirement defines the need for accessible information to allow efficient and effective decision-making. In construction projects, management information boasts a fairly wide variety, often from disparate sources and not easily accessible when traditional IM approaches are being used (Goedert and Meadati, 2008). Ideally, managers and workers should acquire information from sources that offer quality information. However, information users are found to be inclined toward using sources shown to provide "the most conveniently accessible" information regardless of the quality of that information (Fidel and Green, 2004). Such behavior can massively impede appropriate decision-making. Thus, an effective IM approach needs to make the quality information easily accessible to information users.

A BBB system is a significant enabler of the provision of accessible information as it allows different users to reach information in BIM through a range of mobile terminals, e.g., personal computers, tablets. In so doing, a BBB system qualifies as an application of a web-based management information system (MIS). Lam and Chang (2002) find that project stakeholders can overall check project information without time and location limitations if a web-based MIS is being used. Chassiakos and Sakellaropoulos (2008) also emphasize the contribution of web-based MIS to the interoperability and exchange of information in construction projects. Thus, the authors propose that the implementation of a BBB system meets the IM requirement of information accessibility.

4. BBB system development

4.1 System architecture

In this study, a feasible BBB system is developed based on proper technologies and efforts directed to satisfy the three IM requirements discussed above. The system architecture contains four components, i.e., an *information collection component*, *gateway*, *database*, and *cloud-based BIM platform* (see Figure 1). Between each two components, communication networks are developed to provide channels for bidirectional information transfer and communication. Many types of wired or wireless communication networks exist, including Zigbee and Bluetooth, Wide Area Networks (WAN), and Local Area Networks (LAN). The selection of networks should consider factors, such as cost, distance, and requirements on speed contingent to a particular project. A brief introduction of the four components is presented as follows.

I. The *information collection component* consists of different devices, e.g., laser scanner, Auto-ID, sensors, for sensing both geometric and non-geometric information. The selection of proper devices could be based on the type of required information.

II. The *gateway* provides four essential functions for different formats of information transferring from the physical project to BIM and vice versa. These functions include the configuration of information-acquisition devices, information filtering and pre-processing, temporary storage of information, and manual input of information when necessary. This component can be developed by installing tailor-programmed gateway software in either stationary workstations or hand-held devices, e.g., a smartphone.

III. The *database* is used to store the collected information passing through the gateway and the as-design information retrieved from BIM, which includes but is not limited to the geometry, orientation, and specification of BIM components. The information is stored in different types, like numeric or string types, and can be requested by using the Structured Query Language (SQL).

IV. The *cloud-based BIM platform* processes and visualizes the information and enables information exchange and sharing between stakeholders. This component is developed by transferring the information contained in BIM into required formats, storing the transferred information in the database, using Application Protocol Interface (API) to render interactive 3D graphics, e.g., Web Graphics Library (WebGL), to reconstruct the BIM model in a cloud server, and then programming function modules in BIM to permit the processing of information. The BIM platform is thus cloud-based, which supports remote access to BIM models and services online through a variety of devices. Using protocols such as HTTP and FTP, interfaces between the cloud-based BIM platform and the database are developed to enable the platform to actively request or passively receive data from the database.

<Please insert Figure 1 here>

4.2 Deployment procedures

Four-step deployment procedures are provided to further the system architecture of BBB (see Figure 2). First concerns determining the project management tasks, e.g., schedule control and quality management, needing certain types of information to be managed by BBB. Although BBB ideally can manage all geometric and non-geometric project information, the more types of information to be managed indicate higher cost and requirements on technology, personnel, etc. Next is identifying the types and sources of the required information. The third step is to develop the four BBB components, i.e., information-acquisition technologies, gateway(s), database(s), cloud-based BIM platform(s), by using proper hardware and software technologies. The last step is to integrate all BBB components to form a BBB system that is operable and feasible for managing the required information in the construction project.

<Please insert Figure 2 here>

5. Case study

This section illuminates the implementation process of the BBB system in actual situations. The case is a real-life prefabricated construction project in Hong Kong. One building block of the project was selected to apply the BBB system. The building block has thirty-eight floors and needs 7,103 pieces of prefabricated components of thirteen different types, e.g., façade, slab, and bathroom. All prefabricated components are produced in an offshore prefabrication factory (Company A) in Guangdong, China. The transportation services are provided by a third-party logistics company (Company B). The main contractor (Company C) is a leading local Hong Kong contractor. In this case study, the authors performed two roles: (1) consultants for providing a BBB system to the managers and workers of the three companies; and (2) observers on the BBB system implementation without any intervention on managers and workers' daily operations.

5.1 Development of the BBB system

As shown in Figure 2, the first two steps of the deployment procedures of BBB is determining the target information necessary for managing and identifying the types and sources of the target information. The authors visited the construction site and the prefabrication factory every other week to observe the existing workflow (see Figure 3) for two months, totalling eight site visits, i.e., four to the prefabrication factory and four to the construction site. By doing so three significant IM problems embedded in the processes of prefabrication production, transportation, and on-site assembly were identified. First, the paper-based IM methods used during the project often caused issues around duplicated information input and loss of information. Second, existing IM methods were not interoperable, preventing managers from the three companies from perceiving a full picture as the project progressed. Third, delayed communication frequently occurred between the three companies, even sometimes within a single company. Consequently, managers and workers seldom had timely information for decisions and guidance for action-taking. Thus, management and operation mistakes were unavoidable and the on-site working processes were often interrupted.

<Please insert Figure 3 here>

The identified problems were confirmed by managers and workers from the three companies through a focus meeting. The meeting participants generally expressed that the information visibility and traceability of prefabricated components should have been more effectively managed to ensure a smooth project delivery. Hence, the required information was identified to be the information about prefabricated components, i.e., quality, status, and location of each prefabricated component, as well as responsible persons and other resources during the offshore production, cross-border transportation, and on-site assembly.

Based on the types and sources of the target information requiring management, the authors compared several technologies (see Figure 1) to select the proper hardware and software for developing a BBB system. The hardware included radio frequency identification (RFID) devices, smartphones, and computers. Two types of RFID tags were used, ultra-high frequency (UHF) tags attached to the reinforcement cage of each prefabricated component and high frequency (HF) tags attached to machinery, e.g., trucks, trailers. Two types of RFID reader were also used, UHF RFID Reader to read UHF tags and Near Field Communication (NFC) module embedded in the smartphone to read HF tags. The smartphone was also used as the mobile gateway. A tailor-made gateway app was installed on the smartphone for two purposes: (1) to configure all tag-attached components for administrating the information collection; and (2) to record additional information by manual input. Computers connected to the Internet were used by the managers to access the web services of the BBB system.

The software of the BBB system was primarily associated with the development of three cloud-based BIM platforms, including the prefabricated production platform (PPP), the prefabricated transportation platform (PTP), and the on-site assembly platform (OAP). Each platform consisted of a smartphone app developed for workers and a web service developed for managers. The OAP database stored the design information of each prefabricated component and the on-site assembly information. PPP and PTP databases stored information on the production and transportation processes, respectively. The three platforms shared one BIM model, which was developed in four steps: (1) develop the BIM model in Autodesk Revit, in which each BIM object, e.g., wall, door, column, has complete design information and a unique name for identification (Chen et al., 2017); (2) organize and import the information of all BIM objects into the database of OAP; (3) generate JavaScript Object Notation (JSON) files by compiling information on BIM objects; and (4) interpret the JSON files by WebGL to show the BIM model on the web services.

5.2 System implementation

The authors first provided four training sessions to the selected managers and workers of the three companies before they began to use the BBB system in their daily work. At the time of system implementation, the construction of the first thirteen floors, i.e., G/F-12/F, of the project had been completed. Therefore, the BBB system was used in the construction of the remaining twenty-five floors, i.e., 13/F-37/F, which had 5,070 prefabricated components. The system was implemented for eleven months from July 2015 to May 2016, after which, the case project was completed. The following reports the actual implementation of the BBB system in the production, transportation, and on-site assembly processes based on the authors' monthly site visits during the eleven-month period of system implementation.

Production**—**To start, the project manager of Company C selected the type of prefabricated components in the web service of OAP and set the date when these components should be delivered to the construction site. OAP automatically generated an order containing all information of required components, e.g., type, component code, and quantity, and sent the order to the PPP. After receiving the order, the manager of Company A established the production plan in the web service of the PPP and set the planned production date of each component. Workers would receive the daily production plan via the smartphone app. During the production, the worker attached a UHF tag to the reinforcement cage of a prefabricated component and scanned the tag to record the production information using the smartphone app. The smartphone app then uploaded the recorded information to the PPP database. In addition, OAP would automatically receive the information on the prefabricated components from PPP and present the information in the BIM model.

Transportation**—**The process started with a delivery order made by the manager of Company C in the web service of OAP. The delivery order was then automatically sent to PPP, in which the manager of Company A established the transportation plan and arranged the loading tasks. Workers of Company A would find the required prefabricated component by scanning its RFID tag. Once confirmed, the component was loaded onto the trailer. The worker linked the loaded component with the trailer by selecting the component code in his smartphone app and scanning the RFID tag of the trailer with the smartphone. In the web service of PTP, the manager of Company B checked the availability of drivers and trucks and assigned transportation tasks. The driver of Company B used the smartphone app to check the transportation task. Before departure, the driver scanned the RFID tag of the truck with the smartphone to confirm it as the correct truck, and also scanned the tag of the trailer for confirmation. On the way from the storage yard towards the construction site, the driver updated the transportation information in the smartphone app when passing the cross-border customs and approaching the construction site. The updated transportation information would be stored in the PTP database and shared with OAP to be shown in the BIM model.

On-site assembly**—**Based on the information on prefabricated components from PPP and PTP, the project manager of Company C formulated the on-site assembly plan, which included allocating labor forces and dispatching machines, in the web service of OAP. Then, workers reviewed their tasks through the smartphone OAP app. After the component was lifted onto the floor, the erection operator scanned the RFID tag to collect its position information by using the GPS sensor of the smartphone. In case the difference between the actual position and the as-designed position exceeded the tolerance, i.e., the component was placed wrongly, corrections would be made immediately before the prefabricated component was connected with the in-situ concreting structure. After that, a quality controller scanned the tag of the installed prefabricated component to record the quality information in the smartphone app. All collected information during the on-site assembly was timely recorded in the database of the

OAP and presented in the BIM model of the web service. The project manager would review the current progress and inventory for placing the next round of order.

6. Evaluating the epistemological link between BBB and IM

6.1 Data collection and analytical methods

In this case study, two types of data were collected for evaluation. The first type of data was about the participants' task operations before and after the implementation of the BBB system. As introduced in Table 1, the operation data before the system implementation were collected through archived project documents and the authors' observation at the prefabrication factory and the construction site. The operation data after the system implementation were recorded by the BBB system and obtained from the authors' observations. The second type of data was the end-users' feedback collected from ten semi-structured interviews. The interviews were conducted at interviewees' offices, each of which took about thirty minutes. The interviewees comprised two workers and one manager from Company A, two drivers and one manager from Company B, and two workers and two managers from Company C (see Table 2). All interviewees were end-users of the BBB system.

<Please insert Table 1 here>

<Please insert Table 2 here>

For analytical purposes, data of the project participants' task operations before and after the system implementation were compared in order to determine whether their working efficiencies were improved or not. The analysis of the second type of data was to interpret how

BBB could impact the performance of IM in this case. The method of phenomenological analysis was adopted since it helps to identify key factors that make given phenomena or experience distinguishable from others and to find out how people are perceiving specific situations they are facing (Pietkiewicz and Smith, 2014).

6.2 Evaluation results

By analyzing the data from the interviews, Table 3 summarizes important interviewee feedback. Explicitly, results associated with impacts of BBB on IM include: (1) providing all information needed for tasks at hand (80% agreed); (2) enabling timely information collection and exchange (100% agreed); (3) providing accurate information for planning and control (90% agreed); (4) allowing end-users to review relevant information through simple operations (90% agreed); (5) presenting the information in a concise way without any redundancy (80% agreed); and (6) assisting remotely track and review the project information (90% agreed). Overall, the feedback showed that the BBB system helped improve information quantity, quality, and accessibility, the requirements of IM, in the case project and participants were satisfied.

<Please insert Table 3 here>

Inquiry into the on-site observation and the recorded operation data revealed the effectiveness of the BBB system implementation in accomplishing the determined project management task, i.e., tracking and monitoring the prefabricated components during off-site production, transportation, and on-site assembly processes. During the prefabrication process, several significant improvements after the use of the BBB system were noted: (1) since both the production orders from Company C and the production tasks made by Company A were in a digital format, the paperwork for information recording was greatly reduced from 250 sheets per day to 125 sheets per day; (2) the efficiency of Company A's reactions to Company C's design and order changes was much higher than before, which successfully reduced the production cycle from ten days to six; (3) the average "working-in-process inventory" was decreased from 110 sets to 98 sets as the manager of Company A made production plans more accurate; and (4) the average time spent locating a prefabricated component for transport decreased from 7-8 minutes to 5-6 minutes, which may be trivial for a single component, but becomes significant considering the sizeable number of total components produced on a single project.

During the transportation process, three key improvements in the process efficiency were made with the aid of the BBB system. First, the average time needed for a driver to receive his/her task and fetch the truck, i.e., "time for order picking", was reduced from 2 to 1.2 hours. The main benefit of this concerned the manager of Company B being able to timely check the most up-to-date transportation plans and plan transportation tasks accurately based on the automatic prioritization of tasks enabled by the web-based BBB system. Second, the average "waiting time for delivery" was reduced from 2 to 1.5 hours, and no delivery error was observed during the entire length of BBB system implementation. Third, the paper documents decreased from five sheets per car to three sheets because delivery dockets became simpler owing to escaping duplicated entry of information.

During the on-site assembly process, two important improvements in process efficiency were brought by the BBB system implementation. Firstly, the synchronization of information contained in the three platforms saved time considerably and reduced the use of resources for daily operation compared to the conventional paper-based method. The BBB system helped the manager of Company C review the real-time locations of prefabricated components, which contributed to site management by determining more accurate on-site buffers to maintain the construction progress. With the help of the BBB system, the time that workers spent on recording the installation of a single wing of twenty-three facades was reduced by fourteen minutes compared to the paper-based method, and the time required for locating a needed component decreased from six minutes to three minutes. Secondly, the manager of Company C reported that three prefabricated components were found to be assembled at the wrong location before the implementation of the BBB system. In contrast, the BBB system confirmed and verified key on-site assembly steps, and no wrong on-site assembly was observed during the system implementation. The accuracy rate of on-site assembly thus increased from 99.85% (i.e., 2030 out of 2033) to 100%, which saved considerable reproduction and reinstallation costs.

7. Conclusion

Over the years, the rapid development of BIM has successfully mainstreamed the system into IM in almost every aspect of the construction project. The conceptual framework of BBB is amongst the first attempts to make BIM more useful for IM by advocating the communication of stakeholders and delineating different technologies and their associated software, database, and information exchange protocols (Chen et al., 2015). This paper furthered the understanding of the BBB conceptual framework and demystified the mechanism through which BBB can truly impact IM. It did so by developing an operable system architecture of BBB and implementing a BBB system in a prefabricated construction project in Hong Kong. A two-year, participatory case study based on this actual project corroborated that BBB can improve IM in construction.

Of particular interest is the research’s attempt to understand the mechanism linking BBB and

IM. This study proposed that the information quantity, quality, and accessibility are significant mediators between BBB and IM in construction, and the case study supported this proposition. Practitioners can pay extra attention to these three aspects in designing their own BBB systems, with a view to making BIM a truly useful decision-supporting tool. It is worth noting that the information quantity, quality, and accessibility identified in this study are by no means the entire aspects for understanding the mechanism through which BBB can impact IM, but they provide directions to crack challenging IM problems in construction projects.

This study contributes to the construction IM literature by directing attention to key IM requirements and processes rooted in the IM literature. It is also of practical significance by providing a system architecture for BBB, its deployment procedures, and good practices that bridge BIM and building for better IM in a construction project context. Although the BBB system and the deployment procedures are illustrated in a prefabricated construction project context, they can be readily transplanted to other projects types, e.g., cast in-situ technologies. The components and their linkage developed in the BBB system architecture are generally applicable to typical scenarios of CPAM throughout a project lifecycle. Future research is suggested to (1) apply the conceptual framework of BBB and develop BBB systems for IM at the operation stage or the configuration management across an asset's lifecycle, and (2) develop more types of BBB systems to manage other types of project information, such as the real-time location of workers and the project cash flow in both cast in-situ and prefabricated construction projects.

Acknowledgement

The authors would like to acknowledge the financial support of the General Research Fund

(GRF) (Grant No.: 17205614) by Hong Kong Research Grant Council (RGC) and the Innovation and Technology Fund (Grant No.: ITP/045/13LP) by the Hong Kong Innovation and Technology Commission (ITC). The authors would also like to thank the Hong Kong Housing Authority and the three companies for conducting the two-year case study.

References

Amendola, A. (2002). Recent paradigms for risk informed decision making. Safety Science, 40(1-4), 17-30.

Anumba, C. J., Akanmu, A., and Messner, J. (2010). Towards a cyber-physical systems approach to construction. In Construction Research Congress 2010: Innovation for Reshaping Construction Practice (pp. 528-537).

Barlish, K., and Sullivan, K. (2012). How to measure the benefits of BIM—A case study approach. Automation in Construction, 24, 149-159.

Beach, T., Petri, I., Rezgui, Y., and Rana, O. (2017). Management of collaborative BIM data by federating distributed BIM models. Journal of Computing in Civil Engineering, 31(4), 04017009.

Chassiakos, A. P., and Sakellaropoulos, S. P. (2008). A web-based system for managing construction information. Advances in Engineering Software, 39(11), 865-876.

Chen, K., Lu, W., Peng, Y., Rowlinson, S., and Huang, G. Q. (2015). Bridging BIM and building: From a literature review to an integrated conceptual framework. International Journal of Project Management, 33(6), 1405-1416.

Chen, K., Lu, W., Wang, H., Niu, Y., and Huang, G. G. (2017). Naming objects in BIM: A convention and a semiautomatic approach. Journal of Construction Engineering and

Management, 143(7), 06017001.

Choo, C. W. (2002). Information management for the intelligent organization: The art of scanning the environment. Information Today, Inc.

Daft, R. L., and Lengel, R. H. (1986). Organizational information requirements, media richness and structural design. Management Science, 32(5), 554-571.

Daft, R. L., and Weick, K. E. (1984). Toward a model of organizations as interpretation systems. Academy of Management Review, 9(2), 284-295.

Demian, P., and Walters, D. (2014). The advantages of information management through building information modelling. Construction Management and Economics, 32(12), 1153-1165.

Dubois, A., and Gadde, L. E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation. Construction Management and Economics, 20(7), 621-631.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons.

Edirisinghe, R., London, K. A., Kalutara, P., and Aranda-Mena, G. (2017). Building information modelling for facility management: are we there yet?. Engineering, Construction and Architectural Management, 24(6), 1119-1154.

Espejo, R., and Watt, J. (1988). Information management, organization and managerial effectiveness. Journal of the Operational Research Society, 39(1), 7-14.

Fidel, R., and Green, M. (2004). The many faces of accessibility: Engineers' perception of information sources. Information Processing & Management, 40(3), 563-581.

Flanagan, R., and Lu, W. (2008). Making informed decisions in product-service systems. In

IMechE Conference, Knowledge and Information Management Through-Life. Institute of Mechanical Engineers, London.

Galbraith, J. R. (1973). Designing complex organizations. Addison-Wesley Longman Publishing Co., Inc.

Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., and Raahemifar, K. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges. Renewable and Sustainable Energy Reviews, 75, 1046-1053.

Goedert, J. D., and Meadati, P. (2008). Integrating construction process documentation into building information modeling. Journal of Construction Engineering and Management, 134(7), 509-516.

Hajian, H., and Becerik-Gerber, B. (2009). A research outlook for real-time project information management by integrating advanced field data acquisition systems and building information modeling. In Computing in Civil Engineering (2009) (pp. 83-94).

Hoeber, H., and Alsem, D. (2016). Life-cycle information management using open-standard BIM. Engineering, Construction and Architectural Management, 23(6), 696-708.

Lam, H. F., and Chang, T. Y. P. (2002). Web‐based information management system for construction projects. Computer-Aided Civil and Infrastructure Engineering, 17(4), 280-293.

Love, P. E., Matthews, J., Simpson, I., Hill, A., and Olatunji, O. A. (2014). A benefits realization management building information modeling framework for asset owners. Automation in Construction, 37, 1-10.

Lu, W., and Olofsson, T. (2014). Building information modeling and discrete event simulation:

Towards an integrated framework. Automation in Construction, 44, 73-83.

Maes, R. (2007). An integrative perspective on information management. Information Management: Setting the Scene, 11-26.

Martínez-Rojas, M., Marín, N., and Vila, M. A. (2015). The role of information technologies to address data handling in construction project management. Journal of Computing in Civil Engineering, 30(4), 04015064.

Miettinen, R., and Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. Automation in Construction, 43, 84-91.

Nourbakhsh, M., Mohamad Zin, R., Irizarry, J., Zolfagharian, S., and Gheisari, M. (2012). Mobile application prototype for on-site information management in construction industry. Engineering, Construction and Architectural Management, 19(5), 474-494.

Pietkiewicz, I., and Smith, J. A. (2014). A practical guide to using interpretative phenomenological analysis in qualitative research psychology. Psychological Journal, 20(1), 7-14.

Sawhney, A., AbouRizk, S. M., and Halpin, D. W. (1998). Construction project simulation using CYCLONE. Canadian Journal of Civil Engineering, 25(1), 16-25.

Sun, C., Jiang, S., Skibniewski, M. J., Man, Q., and Shen, L. (2017). A literature review of the factors limiting the application of BIM in the construction industry. Technological and Economic Development of Economy, 23(5), 764-779

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., and Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. The International Journal of Advanced Manufacturing Technology, 94(9-12), 3563-3576.

Tezel, A., and Aziz, Z. (2017). Visual management in highways construction and maintenance in England. Engineering, Construction and Architectural Management, 24(3), 486-513.

Wand, Y., and Wang, R. Y. (1996). Anchoring data quality dimensions in ontological foundations. Communications of the ACM, 39(11), 86-95.

Weick, K. E. (1979). The social psychology of organizing. Reading, Mass. Addison-Wesley.

Xu, X., Ma, L., and Ding, L. (2014). A framework for BIM-enabled life-cycle information management of construction project. International Journal of Advanced Robotic Systems, 11(8), 126.

Zheng, L., Lu, W., Chen, K., Chau, K. W., and Niu, Y. (2017). Benefit sharing for BIM implementation: Tackling the moral hazard dilemma in inter-firm cooperation. International Journal of Project Management, 35(3), 393-405.

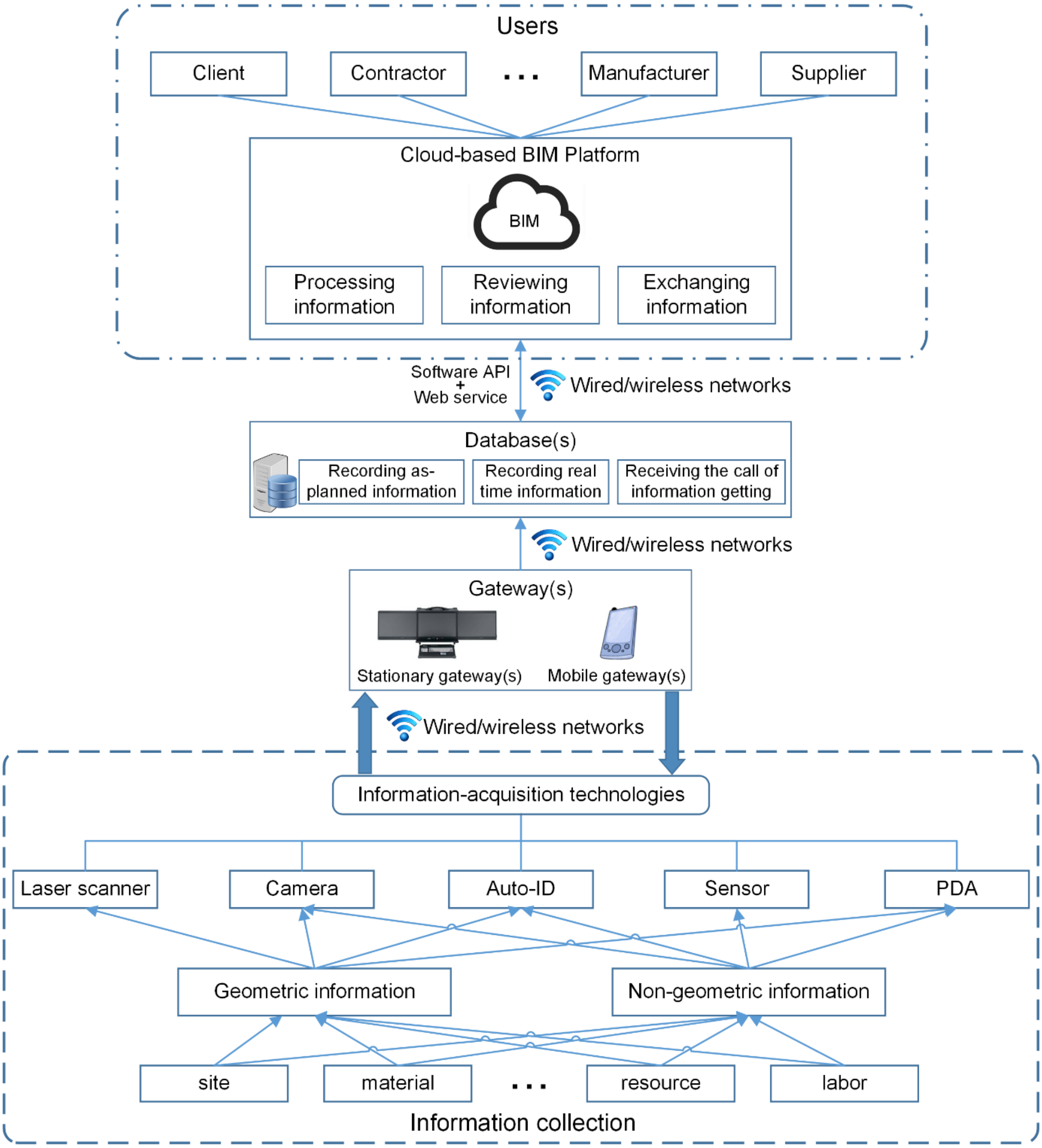

Figure 1. System architecture of BBB

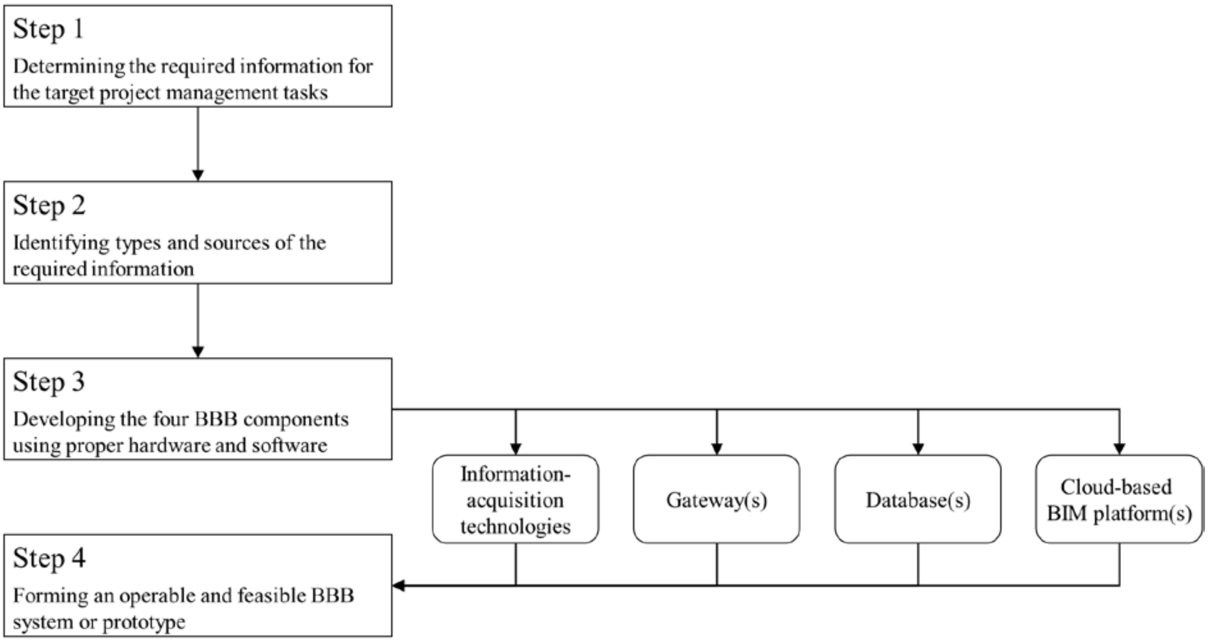

Figure 2. Deployment procedures of BBB

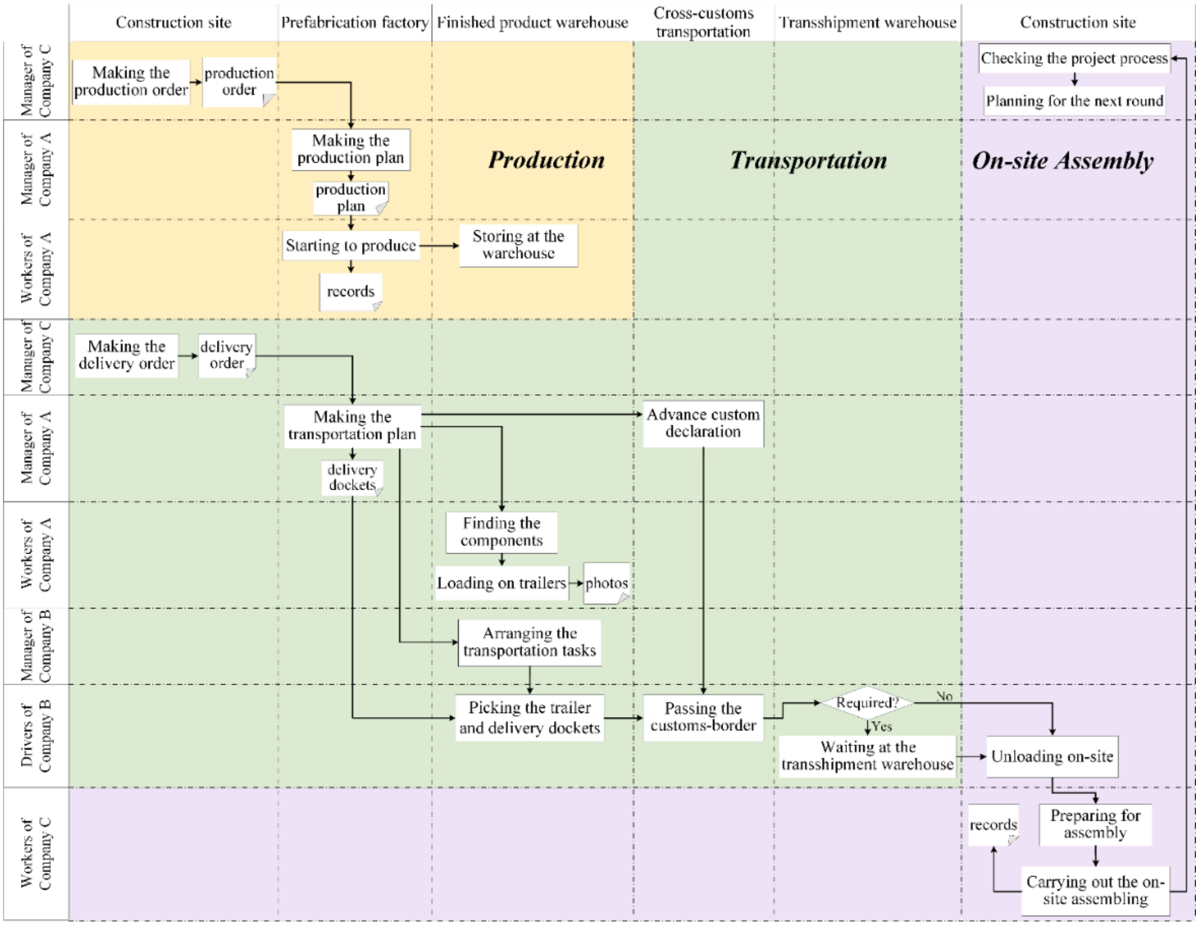

Figure 3. Workflow of the case project

Table 1 Sources of the operation data

Operation data		Source	
		Before the system implementation	After the system implementation
Production	Paper work (sheet/day)	Observation	Observation
	Production cycle (day)	Project documents	BBB system
	Working-in-process inventory (set)	Project documents	Observation
	Locating a component (min)	Observation	BBB system
Transportation	Paper work (sheet/car)	Observation	Observation
	Time for order picking (hour)	Observation	BBB system
	Waiting time for delivery (hour)	Observation	BBB system
On-site assembly	Recording the installation (min/wing)	Observation	BBB system
	Locating a component (min)	Observation	BBB system
	Accuracy rate of on-site assembly (%)	Project documents	BBB system

Table 2 List of interviewees

	Interviewee	Identification code
Company A (Prefabrication factory)	Worker 1	WW1
	Worker 2	WW2
	Manager	WM
Company B (Third-party logistics company)	Driver 1	YD1
	Driver 2	YD2
	Manager	YM
Company C (Main contractor)	Worker 1	GW1
	Worker 2	GW2
	Manager 1	GM1
	Manager 2	GM2

Table 3 Key feedback from interviewees

Type	Interviewee	Feedback
Manager	WM	By adopting the BBB system, information of components could be real-time traced and automatically recorded in the database
	YM	By using the BBB system, the transportation planning and scheduling of our company are facilitated as accurate information about locations and status of delivery tasks could be obtained
	GM1	The BBB system enables real-time information visibility and traceability through a BIM-based approach and seamless collaboration and obstacle-free communications among partners
	GM2	The BBB system allows me to perform real-time monitoring on the components projection, logistics, and the installation. The system allows viewing relevant information of the whole process by simply clicking. It achieves some innovative solutions. For example, I can review the BIM model to check whether a precast façade is installed on the right place
Worker	WW1	It is easy for me to view the up-to-date production tasks assigned to me in the smartphone app
	WW2	I can rely on details of a prefabricated component shown in the smartphone app to conduct production. Before carrying out the production work, I can open the smartphone app to identify the components to be produced. After identifying the correct components, I can use the reader to scan the RFID tag for record
	YD1	The BBB system presented the information of truck and trailer assigned to me in a concise manner.
	YD2	It is not difficult to view the tasks in the smartphone app, and I can get instant response about whether the right transportation task is delivered.
	GW1	I feel that the confirmation of the on-site assembly work is faster than traditional methods
	GW2	I can view the result of task delivery in the single page of the smartphone app