https://doi.org/10.1016/j.autcon.2018.01.001

An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction

Clyde Zhengdao Li a; Fan Xue b; Xiao Li c; Jingke Hong d; Geoffrey Qiping Shen e

[a] Assistant Professor, College of Civil Engineering, Shenzhen University, Shenzhen, China. Email: clydelee718@gmail.com

[b] Research Assistant Professor, Department of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Hong Kong. Email: xuef@hku.hk

[c] Ph.D. Candidate, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: shell.x.li@connect.polyu.hk

[d] Research professor, School of Construction Management and Real Estate, Chongqing University, Chongqing, China. Email: hongjingke@cqu.edu.cn

[e] * Corresponding author, Chair Professor of Construction Management, Department of Building and Real Estate, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hung Hom, Hong Kong. Telephone: +852 2766 5817. Email: bsqpshen@polyu.edu.hk

Abstract:

Building Information Modelling (BIM) serves as a useful tool in facilitating the on-site assembly services (OAS) of prefabricated construction for its benefits of powerful management of physical and functional digital presentations. However, the benefits of using BIM in the OAS of prefabricated construction cannot be cultivated with an incomplete, inaccurate, and untimely data exchange and lack of real-time visibility and traceability. To deal with these challenges, an Internet of Things (IoT)-enabled platform is designed by integrating IoT and BIM for prefabricated public housing projects in Hong Kong. The demands of the stakeholders were analysed; then smart construction objects (SCOs) and smart gateway are defined and designed to collect real-time data throughout the working processes of on-site assembly of prefabricated construction using the radio frequency identification (RFID) technology. The captured data is uploaded to cloud in real-time to process and analyse for decision support purposes for the involved site managers and workers. Visibility and traceability functions are developed with BIM and virtual reality (VR) technologies, through which managers can supervise the construction progress and approximate cost information in a real-time manner. The IoT-enabled platform can provide various decision support tools and services to different stakeholders, for improving the efficiency and effectiveness of daily operations, decision making, collaboration, and supervision throughout on-site assembly processes of prefabricated construction.

Keywords: Internet of things; BIM; on-site assembly services; prefabricated construction; decision support system

1. Introduction

Prefabrication has been widely adopted by Hong Kong Housing Authority (HKHA), who is the main provider of public housing in Hong Kong, for its public housing projects, due to its more efficient, cleaner and safer working environment, and better quality (Tam et al. 2007; Hong et al. 2016; Li et al. 2016). For example, the public housing project at Tuen Mun Area 54 Site 2, Phases 1 & 2, makes use of 11 types of precast elements, including precast façade, semi-precast slab, volumetric precast bathroom, tie beam, staircase, parapet, refuse chute, half landing, water meter room, lift machine room and main roof slab. Some of them are proposed by the general contractor. As a 'sweet point' of balancing construction cost and labour requirement (Tam et al., 2002), contractors adopt a 6-day cycle for the typical floor (usually 20 to 30 units) on-site assembly in high-rise public housing projects since 1990s in Hong Kong. Among the processes of on-site assembly, BIM serves as a useful platform for facilitating the on-site assembly services (OAS) of prefabricated construction for its benefits of providing collaborative working teams and decision makers with the physical and functional representations of prefabricated components (Sacks et al. 2010; Frédéric et al. 2014; Chen et al. 2015; Niu et al. 2016). For example, the status of prefabrication components could be traced and visualized in BIM platform for supporting the progress control (Ergen et al. 2007, Zhong et al. 2015).

However, the well-formatted information of prefabricated component at the right time in the right location is still insufficient to further raise the efficiency of collaborative working and decision making in on-site assembly services when adopting BIM in prefabricated construction projects (Yin et al. 2009). For example, the location information of both outdoor and indoor resources through positioning technologies such as RFID (radio frequency identification), UWB (ultra-wideband), and GPS (global positioning systems) have been synchronized in BIM for safety management (Fang et al., 2016), while few studies integrate the accurate location information of on-delivering prefabricated components into BIM platform for monitoring the right components to be assembled in the correct position in a safer manner (Zhong et al. 2017). Additionally, the information of changes, cost and schedule are delivered from previous processes (i.e., design, manufacturing, logistics) could be updated to a centralized BIM platform for sharing the information among different stakeholders (Li et al. 2017; Niu et al. 2017; Issa et al. 2017). However, this information is usually re-entered incompletely, inaccurately and untimely into various isolated systems (i.e., enterprise resource planning (ERP)) of the different stakeholders in most of the current project practices, which could not efficiently support the decision making in the OAS (Pang et al. 2015). These problems can be further deteriorated in Hong Kong particularly due to the numerous constraints such as limited resources and space (Wong et al. 2003; Chun et al. 2009; Alavi et al. 2016).The solution for such situation is still a void to be filled.

To handle these challenges, an Internet of Things (IoT) enabled platform is to be developed in this research by deploying BIM as the basic infrastructure underlying in its system structure. This research employed a typical design science research methodology (Peffers et al. 2007), which consists of six steps of problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication, in the research and development. Section 2 is the literature review which also identified the need of BIM and IoT-based OAS management system. Section 3 describes the objectives of the BIM and IoT-based OAS regarding field interviews, the design of SCOs, and the development of the OAS decision support system. The demonstration of the system on a real project and the evaluation are given in Section 4. Conclusions appear in Section 5. The specific objectives of this research are: (1) To investigate and analyse business process and requirement of on-site assembly of prefabricated construction; (2) To propose the architecture design and develop the Internet of Things enabled platform; (3) to apply the developed platform to practical project to test its performance and effectiveness.

This centralized BIM platform not only integrates the information delivered from the previous stages but also synchronizes the location information of prefabricated components for facilitating the real-time communication and coordination among the different stakeholders for better decision making in the OAS. The innovativeness of this platform, by looking at whole processes of the on-site assembly of prefabricated construction, is to increase their connectedness by using BIM as an information hub to connect information and communication technology (ICT) enhanced SCOs. The architecture of the IoT-enabled platform has considered the business processes, the stakeholders, the information flow, the visibility and traceability of the real-time data. It uses the service-oriented open architecture as a key innovation to enable the platform as a service. Given its potential to manage building information throughout processes of OAS, the IoT-enabled platform is considered as a significant component of the HKHA's overall ICT architecture and systems, which aims to re-engineer the OAS of prefabricated construction in Hong Kong for a better support of decision making.

2. Literature review

The advanced OAS planning and control systems initiated from the Last Planner® System (LPS®) which is a production management system that applies pull and look-ahead planning to remove constraints and make downstream activities ready (Ballard, 2000). Weekly work planning is adopted to reduce uncertainty and find relevant causes for variances. LPS also uses the percentage of the plan completed (PPC) to measure and monitor the process (Ballard, 2000; Kim et al., 2014). However, LPS is difficult to visualize the flow of work process (Sacks et al., 2009). Building Information Modelling (BIM) can be utilized to simulate and visualize the construction process with 3D geometric models and ample information to facilitate communication among stakeholders (Sacks et al., 2009). In addition, LPS is the weekly work planning that may lead to a long response time to address daily constraints. Sacks et al. (2010) developed the KanBIM concept which can manage day-to-day status feedback and support human decision making or negotiation among stakeholders. As prefabricated construction contains multiple phases from manufacturing, logistics to site assembly, the direct use of LPS and BIM in prefabricated construction has an apparent gap related to the interoperability and real-time traceability of information. Dave et al. (2016) therefore developed a communication framework by adopting IoT (Internet of Things) to strengthen the use of Lean Construction management and tracking technologies such as RFID and GPS, which are critical components of IoT, to track the status of workers, materials, and equipment in the whole process. A conventional RFID system contains an antenna, a transceiver (RFID reader) and a transponder (Radio Frequency tag). The antenna sets up an electromagnetic area where the tag detects the activation signal and responds by transmitting the stored data from its memory through radio frequency waves (Wang et al., 2016). RFID can be applied to monitor unit status during manufacturing and site assembly stages while GPS can be adopted to locate the units during logistics phase and calculate the remaining time to site. One RFID-enabled BIM platform has been developed for prefabricated construction by researchers in Hong Kong (Zhong et al., 2015; Li et al., 2016). The platform's architecture has three dimensions: infrastructure as a service (IaaS), platform as a service (PaaS) and software as a service (SaaS). The IaaS level contains hardware and software layers. The hardware layer consists of the SCOs (Niu et al., 2015) and the Gateway, while the software layer involves a Gateway Operating System (GOS) to manage the SCOs. SCOs with functional data and data collection devices are enabled by the RFID system and other innovative technologies. RFID was firstly introduced as a sister technology to replace barcode system for identifying items. By comparing it with barcode system and magnetic strip system, RFID can store a relatively large number of data. This data can be encrypted to increase data security. It is possible to read data from multiple tags in one time thus increase the efficiency of data processing. In comparison with barcode or magnetic system, no direct contact between a RFID reader and the tagged items is needed as it uses radio wave for data transmission. In addition to reading data, it is possible to write data back to the RFID tag, which greatly increases the interaction between items, systems, and people. The GOS is developed to aggregate and pre-process the massive real-time data such as Industry Foundation Classes (IFC) data converted from BIM software (e.g. Revit), GPS data, RFID data (e.g. schedule, cost, production attributions) and point cloud data. In addition, the PaaS level is related to the data source management services (DSMS) which facilitate the heterogeneous information and application systems by applying XML/JSON-based BIM model and connecting the backend RFID system with BIM model. This enhances the initial BIM platform to a multi-dimensional one. The SaaS level consists of three management services (manufacturing, logistics, and on-site assembly) to enhance the information sharing and communication for stakeholders' decision-making at different stages. This study details the deployment and application of the on-site assembly services to try to improve the dilemmas of current project practices in Hong Kong including: (1) Construction sites in Hong Kong are often compacted, with only limited space for storing large and cumbersome components (Jaillon and Poon 2009). Thus, site management is often on the critical path for the success or failure of a construction project. Under this circumstance, a Just-In-Time (JIT) delivery and assembly are desired but currently in Hong Kong, normally a site manager should reserve components/materials of 1.5 stores on site as a buffer. The JIT delivery of prefabrication components is yet to be harvested; (2) Verification of the components is inefficient (Demiralp, Guven et al. 2012), mainly due to the wide use of paper or paint labels. Workers should pay attention to the verification process sequentially, which will lead to extra labor and time cost. Yet, the accuracy of the verification process is not guaranteed since the paper-based documents, or even handwriting and modified labels are usually ambiguous; (3) Current practice may cause safety issues. Construction workers on the sites are usually busying with their operations, some of which need enough space e.g. for crane towers to hoist various components to proper positions (Mao, Shen et al. 2015). If the required spaces are occupied, serious safety issues may be occurred; (4) If too many components are placed on a construction site, workers may have difficulties to find out proper components (from a large pile of similar components) for a specific trade (Shin, Chin et al. 2011). This has been reported in casino projects in Macau. To identify the proper components through effective real-time information collection approach is highly desired. Currently, no such platform, like IKEA's "assembly instructions", has been developed to guide on-site assembly to make it more efficient. This research is highly motivated to develop such platform that can inherit information from prefabrication production and cross-border logistics and used it to facilitate the on-site assembly process.

In order to delimit the bountry of application and process in this study, the scope of the on-site assembly of prefabrication components phase, is described as follows: (1) this phase beings when the prefabrication components arrive at the construction site and are checked by the on-site foreman after being delivered by the third-party logistics company; (2) the inputs are the delivery of prefabrication components and relevant documentation; (3) this phase concludes when the delivered prefabrication components are assembled and pass their respective inspections; and (4) the outputs are the completion of the superstructure work. General steps for on-site assembly are as shown in Figure 1.

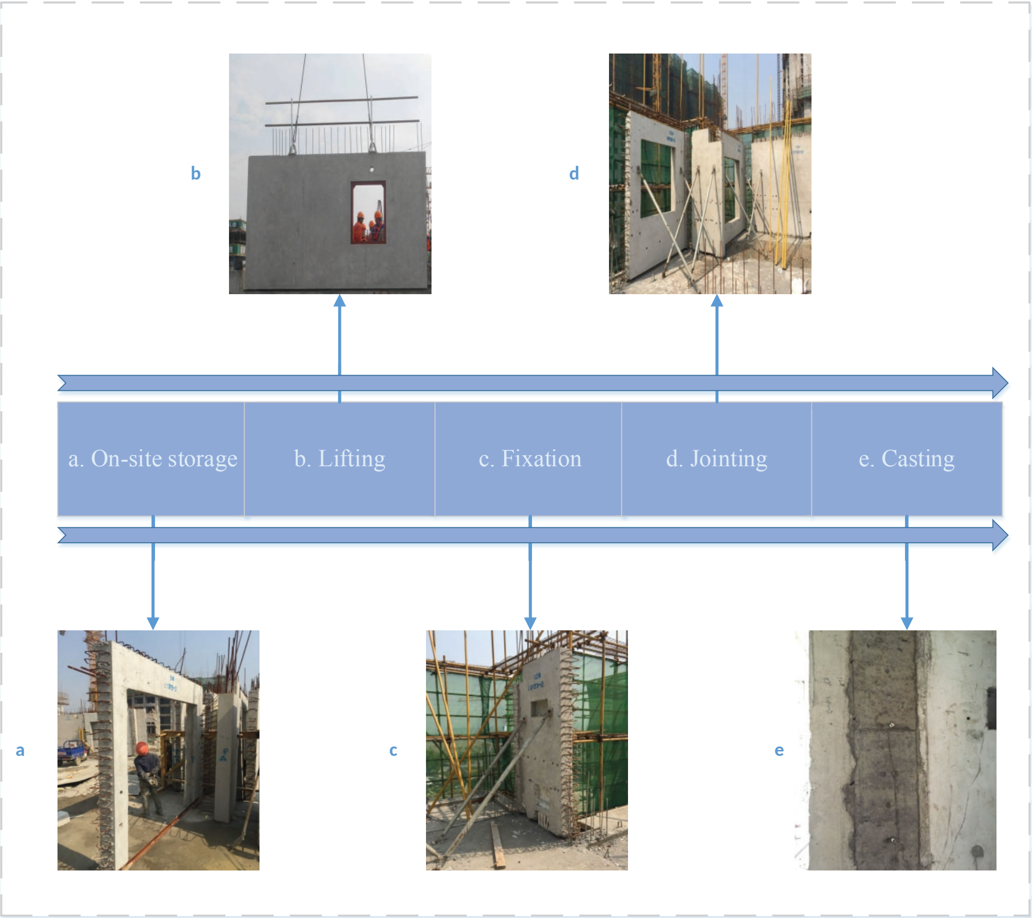


Figure 1 General steps for on-site assembly

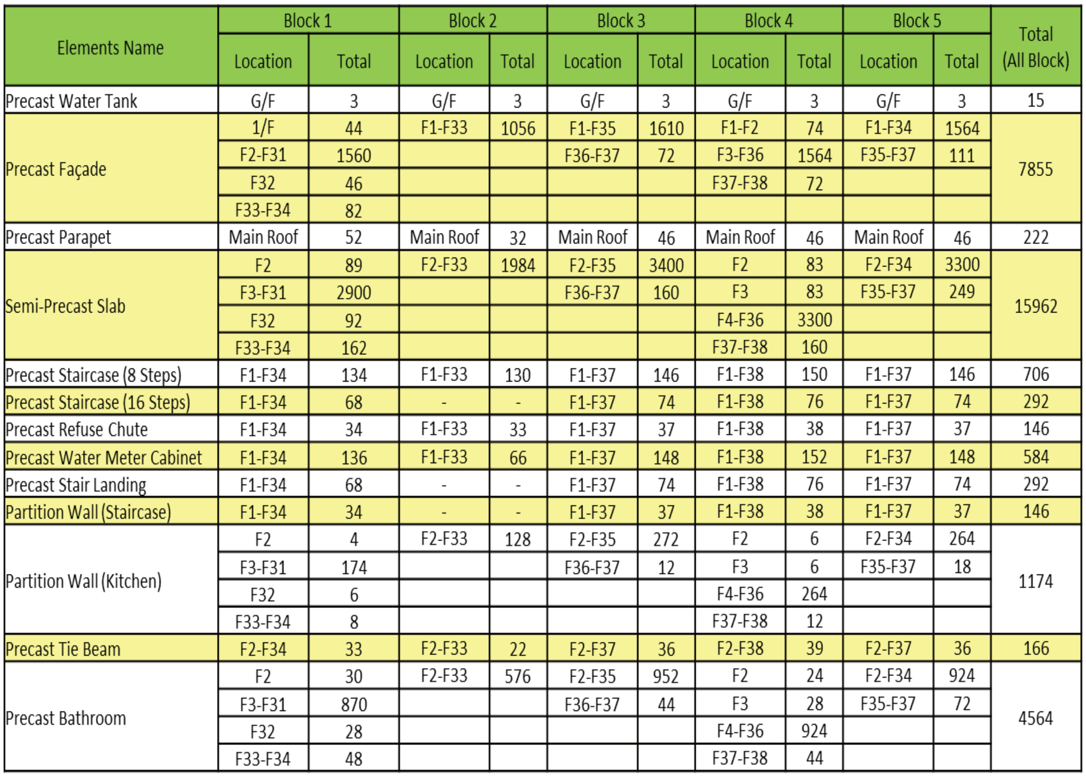
3. Architecture design and development of Internet of Things enabled platform

3.1 Analysis of business process and requirement

The purpose of this section is to analyse the business processes, identify business needs and requirements regarding to on-site assembly. Through an interview with the Qualified Engineer on 9th July 2014, this section summarizes the key information and analysis results from the on-site assembly for solution design of the proposed platform. The purpose of the business process analysis (BPA) is to map the processes of on-site assembly of prefabricated construction and identify the requirements of major stakeholders involved in these processes. These stakeholders include the client, the main contractor and their sub-contractors. Relevant findings can provide useful information for the system design of the IoT-enabled platform.

The surveyed Tuen Mun project (Area 54) proposes to build five 34-38 story buildings, providing about 5,000 units and with the expectation of holding more than 14,000 people. Detailed information regarding prefabrication components to be used can be seen in the Table1. Figure 2 below provides a typical layout of the use of prefabrication components.

Table 1 Summary of the use of prefabrication components in the surveyed project



Elements Name	Block 1		Block 2		Block 3		Block 4		Block 5		Total (All Block)
	Location	Total	Location	Total	Location	Total	Location	Total	Location	Total	
Precast Water Tank	G/F	3	G/F	3	G/F	3	G/F	3	G/F	3	15
Precast Façade	1/F	44	F1-F33	1056	F1-F35	1610	F1-F2	74	F1-F34	1564	7855
	F2-F31	1560			F36-F37	72	F3-F36	1564	F35-F37	111	
	F32	46					F37-F38	72			
	F33-F34	82									
Precast Parapet	Main Roof	52	Main Roof	32	Main Roof	46	Main Roof	46	Main Roof	46	222
Semi-Precast Slab	F2	89	F2-F33	1984	F2-F35	3400	F2	83	F2-F34	3300	15962
	F3-F31	2900			F36-F37	160	F3	83	F35-F37	249	
	F32	92					F4-F36	3300			
	F33-F34	162					F37-F38	160			
Precast Staircase (8 Steps)	F1-F34	134	F1-F33	130	F1-F37	146	F1-F38	150	F1-F37	146	706
Precast Staircase (16 Steps)	F1-F34	68	-	-	F1-F37	74	F1-F38	76	F1-F37	74	292
Precast Refuse Chute	F1-F34	34	F1-F33	33	F1-F37	37	F1-F38	38	F1-F37	37	146
Precast Water Meter Cabinet	F1-F34	136	F1-F33	66	F1-F37	148	F1-F38	152	F1-F37	148	584
Precast Stair Landing	F1-F34	68	-	-	F1-F37	74	F1-F38	76	F1-F37	74	292
Partition Wall (Staircase)	F1-F34	34	-	-	F1-F37	37	F1-F38	38	F1-F37	37	146
Partition Wall (Kitchen)	F2	4	F2-F33	128	F2-F35	272	F2	6	F2-F34	264	1174
	F3-F31	174			F36-F37	12	F3	6	F35-F37	18	
	F32	6					F4-F36	264			
	F33-F34	8					F37-F38	12			
Precast Tie Beam	F2-F34	33	F2-F33	22	F2-F37	36	F2-F38	39	F2-F37	36	166
Precast Bathroom	F2	30	F2-F33	576	F2-F35	952	F2	24	F2-F34	924	4564
	F3-F31	870			F36-F37	44	F3	28	F35-F37	72	
	F32	28					F4-F36	924			
	F33-F34	48					F37-F38	44			

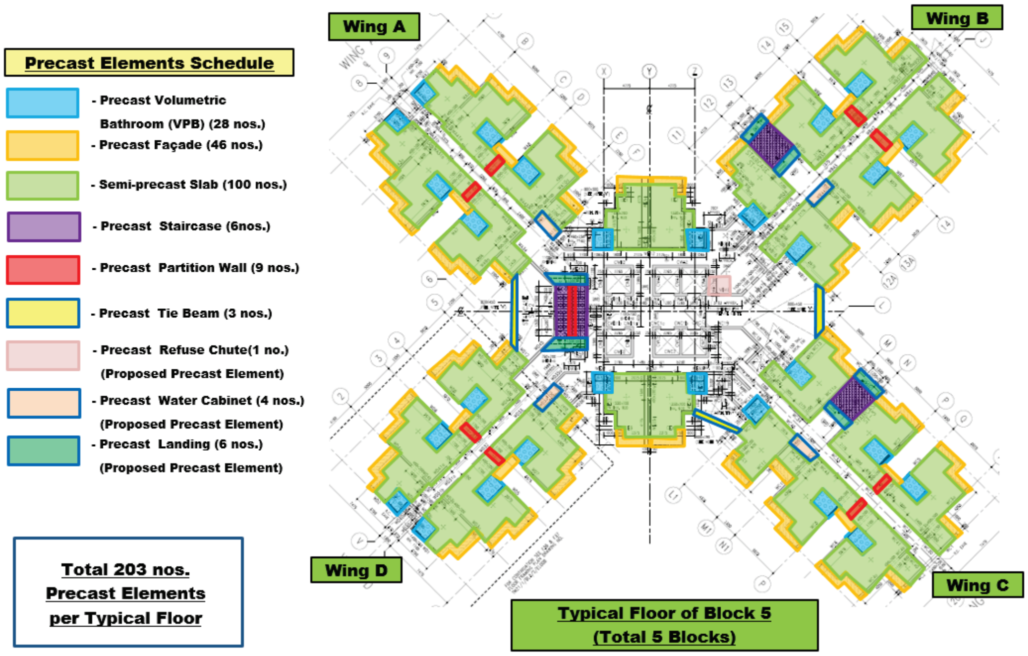


Figure 2 Layout of the typical floor of a typical block in the surveyed project

The related business processes are described in Figures 3. Figure 3 presents the major on-site installation process of prefabrication components. All activities in the process are (expected to be) carried out at Tuen Mun project site. The typical workflow of erection of prefabricated elements onto a residential construction are also investigated. Activities in Figure 3 are carried out within one typical floor (1/F or up).

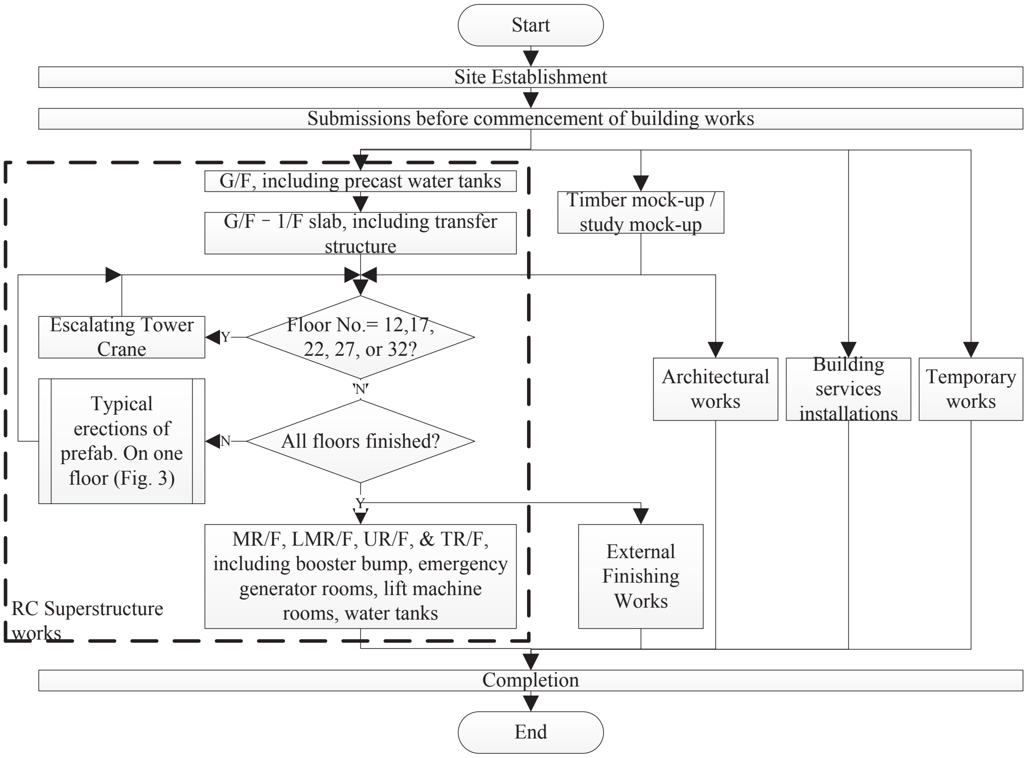


Figure 3 Work flow of a typical residential construction with prefabricated element

As shown in Figure 3, the on-site assembly phase can generally be divided into five main stages, namely site establishment, temporary works, superstructure works, architectural works and building services installations. Stages 2 to 5 can be carried out concurrently, which may not be on the same floor though, in the schedule. Prefabrication assembly is most relevant in the third stage (i.e. superstructure works).

Stage 1 – Site Establishment: The objectives of site establishment are: (1) to provide maximum security to the plant, materials and the installation works; (2) to protect the public and the environment from the installation works; (3) to provide adequate facilities to both the clients and the contractors' staff; (4) to ensure that upon completion of the project, the site is efficiently demobilized and reinstated to project stakeholders' satisfaction. Procedures of site establishment include: protection to existing structures; establish boundaries; remove materials and items; establish accommodation; and establish services.

Stage 2 – Temporary works: Temporary works in the project mainly include (1) tower crane erection; (2) material hoist erection and (3) passenger hoist erection.

Stage 3 – Superstructure works: This stage is the main focus for the BPA on prefabrication on-site assembly. Superstructure works include (1) fabrication and installation of precast water tank; (2) G/F - 1/F including transfer structures; (3) 1/F – 37/F slab, noted that tower crane is planned to be escalated once the slabs of 12nd, 17th, 22nd, 27th and 32nd floor are completed; (4) installation of booster pump, emergency generator rooms, lift machine room and water tanks. The process for one floor (from G/F to 5/F) is significantly longer than that for a floor above 5/F, e.g., 12-70 days for a floor from G/F to 5/F while a 6-day cycle for an upper floor. This is because many issues may be encountered during this period, based on experience.

Stage 4 – Architectural works: Architectural works mainly include finishing works at flats, finishing works at common areas and external finishing work.

Stage 5 – Building Services Installations: After the completion of superstructure works and architectural works, building services-related facilities will be installed, including: (1) Plumbing and drainage installation; (2) Town Gas; (3) Electrical installation; (4) Lift installation and fire services installation.

Typical installation of prefabricated elements involved different participants and locations. Two main locations are (a) the buffer, which is usually near the target building/wing for the convenience of the tower crane, and (b) erection at construction site. Usually the foremen will coordinate the scheduled actions. An operator at the buffer will check the prefabricated elements after they have been unloaded. If there are flaws or defects after delivery, the prefabrication manufacturer will be contacted for further actions; and relevant information shall be recorded. Two groups of prefabricated elements are delivered and erected in turn. One is the vertical components, which include facades, toilets, partition walls, refuse chute, and water cabinets; the other is the horizontal ones which include slabs and staircase. Thereafter, the prefabricated elements are lifted for erection by tower cranes. In a typical erection, a prefabrication element is adjusted horizontally then vertically. Reinforcement is carried out later, followed by inspection. The time required to complete the installation for one typical floor is six days, and this six-day cycle is widely adopted by contractors engaged in public housing construction works. The findings from business process analysis provide necessary information for the system design of the IoT-enabled platform in the upcoming stages of this research. Based on the identified findings and observations on the process flow of on-site assembly, the requirement analysis on this phase is listed in Table 2.

Table 2 Requirements analysis of on-site assembly

NO	Type	Requirement	Priority
Functional Requirements			
1	Production orders	System needs to keep a record of pending prefabricated elements (with or without ID) for current working day, and next days for one floor (e.g., in a 6-day cycle)	Preferred
2	Buffer	Be aware of prefabrication are safely delivered	Must Have

3	Erection inspection	Be aware of prefabrication are erected successfully	Must Have
4	Buffer	Be aware of place where prefabricated components are held	Optional
5	Buffer & Erection inspection	When RFID tag is missing or not working, the delivery and/ or erection can be input by alternative ways (e.g., querying tag ID from RFID service provider followed by a manual input)	Must Have
6	Messaging	Automatic SMS or Android/iOS notifications on prefabrication delivery/ erection/ unexpected issues for stakeholders	Optional
7	Erection inspection	Multiple scanners or floor partitioning for RFID scanning	Optional
8	Erection inspection	Random order RFID scanning within one floor after inspection	Optional
9	Erection inspection & Buffer	Batch upload of photos synchronized or synchronized with hand-held scan data upload	Optional
10	Erection inspection & Buffer	Able to record operators' GPS locations of delivery & erection as EXIF in JPG images and automatically extractable as supplementary location info	Optional
11	Buffer, Erection inspection, & General management	Electronic files (PDF) sharing of inspection reports and progress reports	Preferred
Non-Functional Requirements			
1	Performance	Data and status are available at real-time	Preferred

2	Availability	Accessible through wireless/wired network out of office/ site	Must Have
3	Security	One shared input account for one wing/building	Preferred
4	Availability	Accessible through iOS/Android smart devices (phones/tablets after Jan 2013)	Preferred
5	Security	Binding PC/Phones' IP/MAC addresses of stakeholders	Optional
6	Security	Digital/ vocal signature of inspector and/or buffer operator	Optional

The BPA described the processes of on-site assembly of prefabricated construction in details, by focusing on major installation stages and involved stakeholders. It also identified and prioritizes the requirements of major stakeholders involved in the assembly activities. The findings from BPA provide the basis for the design of system architecture of the IoT-enabled platform in the upcoming stages of this research.

3.2 Functional requirement and UI design

After three rounds of site visits, discussions, and meetings with managers from client and the contractor for construction site, the functional requirement and UI (User Interface) design are raised based on the business processes and requirements analysis which come from real-life pilot companies. The purposes of the functional requirement and UI design of this research include: (1) To introduce the concepts of user and system requirements; (2) To describe functional and non-functional requirements; (3) To explain how software requirements may be organized; (4) To present how the GUIs will be designed; (5) To identify the key components of the IoT-enabled platform; (6) To illustrate the specific functions to the programmers how to carry out detailed design and programming; (7) To descript how the modules could assist end-users for facilitating their operations and decision-making. This section provides the specific requirements of the on-site assembly service including external interface requirements, functional requirements, non-functional requirements, internal requirements, design constraints, logical database requirements and other requirements.

3.2.1 Interface requirements

As shown in Table 3, there will be five groups of target human users and three groups of external software users for OAS, each of which will have its own corresponding user interfaces. All hardware interfaces will be those of the on-site assembly service on top of which it will be running, with due attention should be paid to: (1) CPU usage; (2) Memory usage; (3) Cache file creation; (4) Network communication. Besides, the software interfaces include designated user Applications on Android and modern browsers (e.g., Safari and Chrome) which are compatible with WebGL, HTML 5, and Java Script on Windows/OS X/iOS/UNIX/Linux. Network protocols for systems to communicate include HTTP (and HTTPS), SFTP (Secure File Transfer Protocol), specified XML/JSON (Java Script Object Notation) data management services over SSL (secure sockets layer).

Table 3 The five sets of target human users and three sets of external software users for OAS

NO	Target human users and external software users	Security level	Characteristic
1	**Management level** (Senior manager, Engineer): Setting up master plan and pattern of assembly cycle, monitor the overall progress and estimated spent.	medium	busy; easy and quick access; concerns more on overall/ abstract/ representation level;
2	**On-site coordinator** (Foreman): Confirm tasks for a flat from master plan with consideration of actual progress and existed exceptions, claim	medium	busy; easy access; building progress and quality centric;

	new and handled exceptions when necessary.		
3	**Prefabrication receiver** (assigned by Foreman): confirm a component is safely delivered to construction site.	low	part-time receiving; low-level certificate;
4	**Erection worker**: confirm a component is correctly erected.	low	hard work; low-level certificate;
5	**Inspector**: confirm the quality of final assembly in the whole structure.	medium	technical/qualified staff;
6	**BIM system**: providing structure and shape data.	high	professional standards; specific software end (Revit);
7	**RFID system**: providing status data of components.	medium	3rd-party solution; data may be slightly delayed (<1 day);
8	**Other services in the platform**: the aforementioned ones and the services to be developed.	medium	high compatibility; small amount/ regular communication;

3.2.2 Functional requirements

Based on the analysis of business process and requirement, a total of four major services are provided in the IoT-enable platform: (1) Assembly management (real-time supervision) services: to provide a toolkit for contractor's managers and engineers to supervise the management of on-site assembly services, which include: visibility service to integrate the project progress in charts and 3D BIM models, and components in 3D BIM models; component tracing service to locate a missing component and return the geolocation or place of storage; component tracking service to filter one or more components in a given criterion, e.g., selecting all installed windows in a storey/floor; (2) Assembly operations services: to provide a toolkit for managers and engineers who are involved in operations of assembly at construction site, which include: planning service to break down a job plan (typically floor plan) into tasks in charts; components order listing helper service: to provide an information list for site coordinators and production services, partially depended on component tracking service; assembly scheduling service to make floor plans and daily plans by associating personnel with planned tasks; component tracing/ tracking service; duplicated component tracing and tracking service; (3) Assembly exception handling services: to implement part of preplans for some of the unexpected cases, which include: progress exception handling service to provide follow-up tools for the cases where the progress is not carried out on-time; component exception handling service to record when an important (e.g., RFID tagged) component encounters defects or replacement; (4) Assembly notification services: for facilitating in reminding and notification for users, with different reminders sent to subscribed users, such as progress summary, component list to be delivered today, and summary of inspection result, which include Email notification service to send Email alerts for managers and engineers who work in office, SMS notification service, and mobile app notification service.

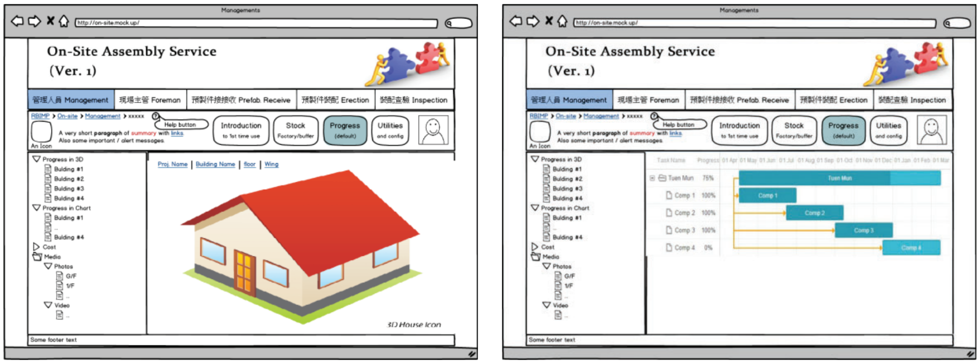
3.3.2.2 Functions of management tools

The functions of management tools for management level listed in Table 4 and Figure 4 below.

Table 4 The functions of management tools for management level

Introduction	Toolkit for management level
Trigger	As specified in the Graphical User Interfaces (GUIs) in Figure 4.
Inputs	Pre-written graphic/text of introduction; or 3D WebGL/chart component-based graphics with selectable criteria
Processing	Read the current progress, data via this software from the database; or editing the master plan of project
Outputs	Return and present the content on web or app
Error	Show information and hints on data input, user privilege, and

Handling	software compatibility errors, or return to log in



a. Mockup UI for 3D graphics of project/building/floor progress

b. Mockup UI for Gantt chart of progress with schedule

c. Mockup UI for chart of estimated cost according to progress

d. Mockup UI for stock and Geolocations of in-process prefabricated components

Figure 4 Mockup GUIs for 3D graphics of project/building/floor progress

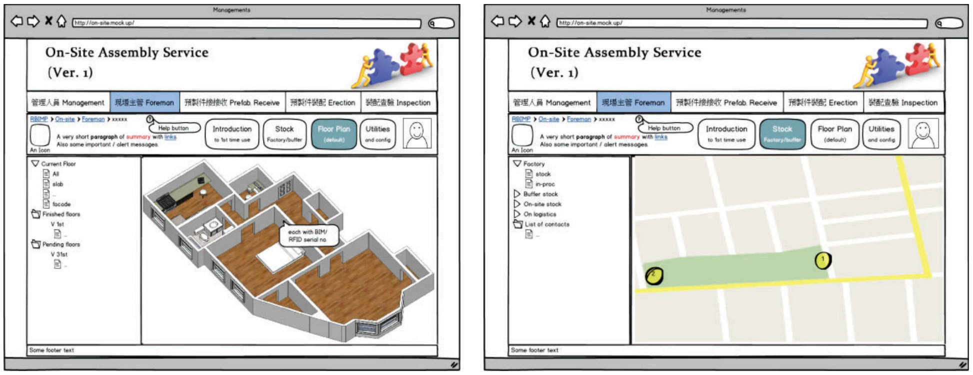
3.3.2.3 Functions of operation tools

The functions of management tools for on-site operation level listed in Table 5 and Figure 5 below.

Table 5 The functions of management tools for on-site operation level

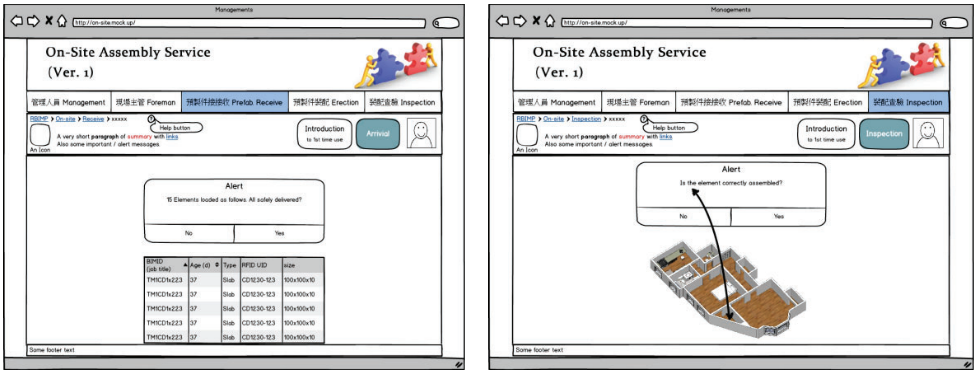
Introduction	**Toolkit mainly for on-site operation level**
Trigger	As specified in the GUIs in Figure 5.
Inputs	Pre-written graphic/text of introduction; or 3D WebGL/map component-based graphics with selectable criteria

Processing	Read/write the necessary information (detailed floor plans, component shape ad status, etc.) and process with this software from/to the database
Outputs	Return and present the content on web or app
Error Handling	Show information and hints on data input, user privilege, and software compatibility errors, or return to log in



a. Mockup UI for floor plan review for foreman

b. Mockup UI for stock and geolocations of in-process prefabricated components for foreman



c. Mockup UI for receiving prefabricated components

d. Mockup UI for confirmation of inspection of installation

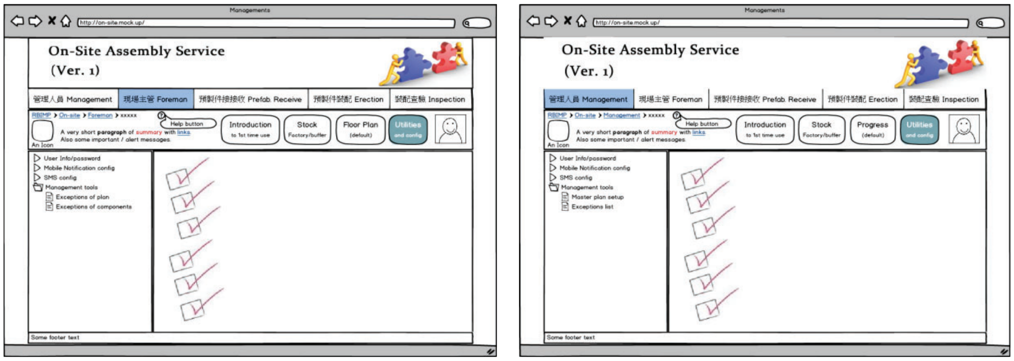
Figure 5 Mockup GUIs for floor plan review for a foreman

3.3.2.4 Functions of exception handling and notification tools

The functions of management tools for managers, engineers and on-site coordinators o track exceptions and receiving progress/exceptions updates are listed in Table 6 and Figure 6 below.

Table 6 The functions of management tools for managers, engineers and on-site coordinators

Introduction	**Toolkit to track exceptions and receiving progress/exceptions updates**
Trigger	As specified in the GUIs in Figuge 6.
Inputs	Selectable list of events (exceptions and progress) to notify; exceptions tracking and updating
Processing	Read/write the pre-defined event information via this software from/to the database
Outputs	Return and present the content on web or app
Error Handling	Show information and hints on data input, user privilege, and software compatibility errors, or return to log in



A very short paragraph of summary with links.
Also some important / alert messages.

a. Mockup UI of notifications and exceptions handling for foreman

b. Mockup UI of notifications and exceptions handling for management

Figure 6 Mockup GUIs for notifications and exceptions handling for foremen and managers

3.2.3 Non-functional requirements

Non-functional requirements may exist for the following attributes. Often these requirements must be achieved at a system-wide level rather than at a unit level. The requirements are stated in Table 7 in measurable terms. The deployment of the system would was planned on cloud servers, thus many conventional system-level requiments (e.g., system downtime and mean time between failure) was easily met.

Table 7 Non-functional requirements

Performance	**Response time**
	The maximum response time for the submission of any request will be 1 minute.
	Capacity
	The maximum number of recognizable items is limited to 100,000 for each building.
Reliability	**Maximum bug rate**
	There will be a maximum of 1 bug in 1,000 lines of codes.
	Maximum time to repair
	In case of cloud outage, the site users (type 2-5 in Table 3) will store the data in the designated smartphone Application to be uploaded when the system is ready; while the service for the mangment user (type 1 in Table 3) will be down. A typical system reboot time takes 10 seconds, and a scheduled cloud maintainance can be a few hours.
Availability	**Back-end internal computers**
	The system shall provide storage of all databases and cache files on a redundant computer and another cloud storage located in a different continent.
	Operational availability
	The service shall provide users with a minimum operational availability of 99.9%.
Security	**Security considerations**

	The on-site assembly service will ensure the privacy of user job status and ensure full control over job execution, so that alteration of scheduling criteria or actual resource allocation is not possible without administrator authority.
	Data transfer
	(1) The system shall use SSL in all transactions that may include confidential information. (2) The system shall automatically log out all users after a period of inactivity. (3) The system shall confirm all transactions with the user's smartphone application or web browser. (4) The system shall not leave any cookies on the user's computer after logging out.
	Data storage
	(1) The user's web browser shall not display a user's password except for user's manual request (e.g., on a smart phone). It shall always be echoed with special characters representing typed characters. (2) The system's back-end services shall store encrypted passwords of users instead of orignal ones. (3) The system's back-end services shall only be accessible to authenticated administrators. (4) The system's back-end databases shall be encrypted and accessible to authenticated administrators.
Maintainability	**Maintenance**
	(1) The administration will not support job migration for the purpose of decreasing resource fragmentation. (2) The on-site assembly service shall permit the upgrade of software without down time.

	(3) The Mean Time To Fix shall not exceed one person day.

Portability	**Naming convention**
	All codes prefer to the Hungarian notion.
	Ease of moving to another system
	Can be used on all desktop computers and smart phones with modern borwsers

3.2.4 Logical database requirements

The logical database of on-site assembly service consists of 4 sets of data tables, including: (1) Project and tasks; (2) Imported Data from BIM and RFID systems; (3) Exceptions and handling; (4) Users and notifications. The 4 sets of data tables are supporting the 4 group of services, respectively. Figure 7 shows a detailed composition of the 4 sets of tables. Set a) consists of tables “project”, “masterPlan”, “floorPlan”, and “dailyTypePlan”; set b) includes “BIM_component”, “RFID_record”, and “compType”; set c) include “exFPlan” and “exComp”; set d) include “users” and “notifications”. The primary keys and foreign keys can also be found in the figure.

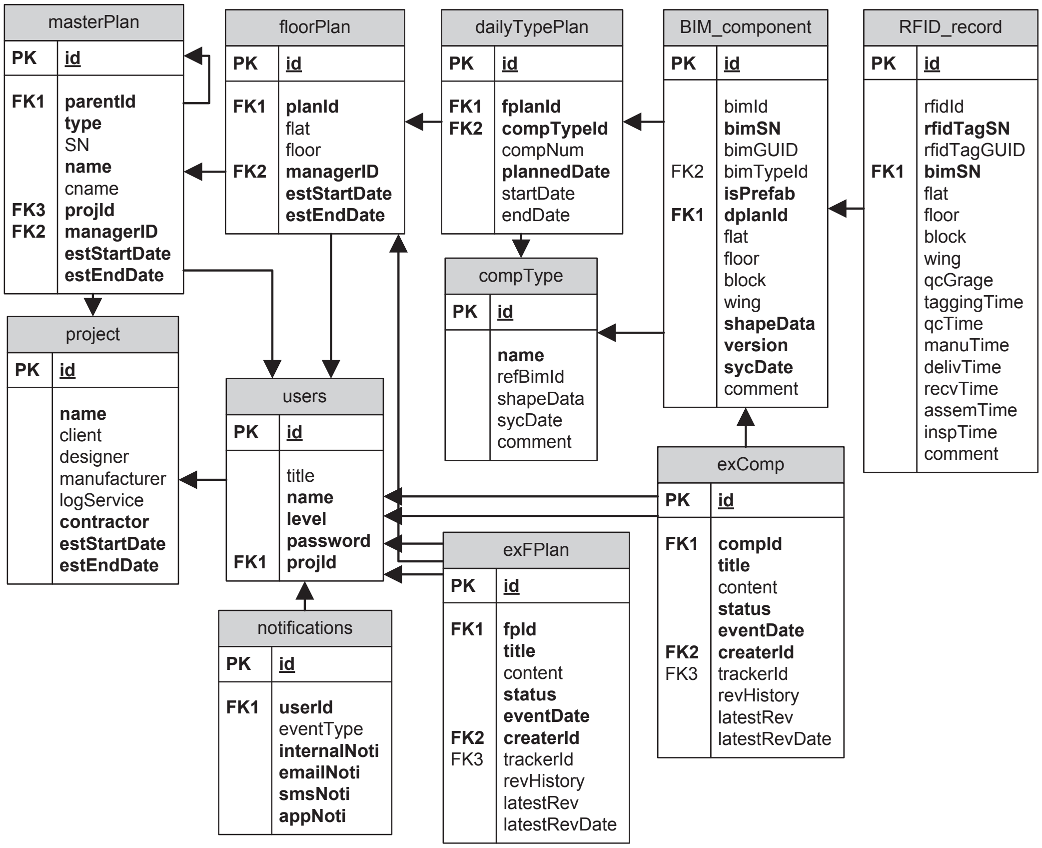


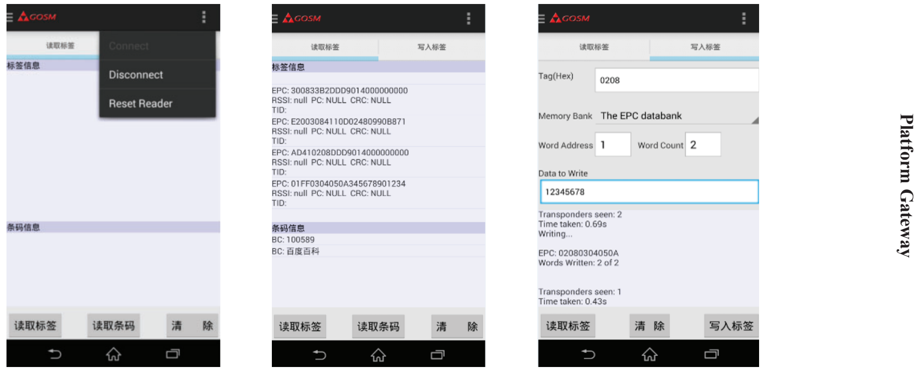
Figure 7 Database model diagram of the logical database of OAS information system.

The highest amount of data, which is not exceeding 10^5 records (usually $<10^4$ for a building) for a project, is expected to be found in table “BIM_component” and “RFID_record”. However, the attribute “shapeData” in table “BIM_component” can be as large as 10^4~10^5 bytes. So the total physical size of the database can be up to 10^{10} bytes (10GB) in assumed projects. The number of simultaneous users is expected to be less than 10.

3.3 Smart construction object and smart gateway

SCOs are typical construction resources such as tools, machinery, materials, which are converted into smart objects through binding them with different RFID devices, as shown in the Figure 8. The purpose of SCOs is to create an intelligent construction environment within the typical prefabrication production sites such as shop-floors, warehouse, logistic and supply chain, and construction sites. SCOs are building blocks for such intelligent environment, within which they can sense and interact with each other. Thus, the processes of on-site assembly could be carried out smoothly.

a. TSL 1128 Bluetooth UHF RFID Reader b. SAMSUNG Note 3 (SM-N900) c. UHF RFID Tag



```
EPC: 300833B2DDD9014000000000
RSSI: null  PC: NULL  CRC: NULL
TID:
EPC: E2003084110D02480990B871
RSSI: null  PC: NULL  CRC: NULL
TID:
EPC: AD410208DDD9014000000000
RSSI: null  PC: NULL  CRC: NULL
TID:
EPC: 01FF0304050A345678901234
RSSI: null  PC: NULL  CRC: NULL
TID:
```

```
BC: 100589
BC: 百度百科
```

Tag(Hex) 0208
Memory Bank The EPC databank
Word Address 1 Word Count 2
Data to Write 12345678

```
Transponders seen: 2
Time taken: 0.69s
Writing...

EPC: 02080304050A
Words Written: 2 of 2


Transponders seen: 1
Time taken: 0.43s
```

a. Connection b. Read function c. Write function

Figure 8 smart construction objects and gateway

Typical construction resources are converted into SCOs through various tagging schemes. Firstly, critical prefabrication components such as volumetric kitchens, toilets, precast facades, will be tagged individually. That means item-level tagging scheme is adopted because they easily influence the progress in prefabrication housing construction. For non-critical materials, such as dry walls, and building blocks, tray-level or batch-based tagging scheme is adopted. That means tags are attached to the trays which carry multiple minor prefabrication components. In the pilot study, the RFID tags, as shown in Figure 8, are Ultra High Frequency (UHF) tags protected in strong Acrylonitrile Butadiene Styrene (ABS) plastic cases and validated individually before planting. Each tag supported up to about 30 cm when embedding on the steel ribbons inside concrete. A data operability of each was validated before planting. For various workers, such as machine operators, vehicle drivers, logistics operators, and on-site assembly workers, they are tagged with smart staff cards. These construction resources attached with tags are passive SCOs. The deployment of RFID readers follows a systematic approach. Once bound by RFID readers, they become active SCOs that can sense and detect the passive SCOs. Both active and passive SCOs can sense and interact with each other to create an intelligent construction environment. They carry critical information that will be updated at different locations.

Gateway performs several key functions in the research. Firstly, it connects and hosts a set of SCOs through wired or wireless communication standards. It not only allows workers/operators to access information such as prefabrication production status, but also defines, configures, and executes the corresponding prefabrication construction agents through various services. Secondly, it communicates and interacts with upper-level decision-making systems through providing useful and real-time information on standardized format. It acts as a bridge between the frontline SCOs and upper-level decision-making systems. For example, the gateway can connect and control RFID readers through Bluetooth, and send data to cloud servers via 4G or WiFi. Bluetooth data transfer can be carried out between the main device and other devices at any time, the main device can select the slave device to access. Especially, it can be in the way to change equipment between fast conversion. This greatly improves the stability of Bluetooth connectivity. Thus, decisions and their executions could be seamlessly synchronized in prefabrication housing production. Thirdly, it processes, caches, and exchanges real-time data and events locally and temporally. To this end, complex event processing technology is used to integrate the construction information into a standardized scheme, which could be understood, shared and used among different EISs in the construction industry. Finally, it provides a rich set of facilities for service definition, configuration and execution. The concept of service-oriented agents is adopted to represent the SCOs through a plug-and-play fashion.

The Gateway uses an operating system named GOS to achieve a flexible, modularized and re-configurable framework, where applications and solutions are designed and developed as web services. GOS aims to provide an easy-to- deploy, simple-to-use and flexible-to-access solution for the construction industry. Within the GOS, multi-agent based models are used to ensure the versatility and scalability of Gateway. Therefore, communication and interactions between SCOs and other services is facilitated by using an XML/JSON-based message exchanging protocol.

SCOs and Gateway can capture the real-time construction data to support the decision-making in client's enterprise information system. SCOs and Gateway can enhance the data sharing within the high level decision-making entities and front-line construction sites. The advanced decision-makings could real-timely be reflected in the construction site, while, the real-time data such as prefabrication manufacturing progresses, prefabrication transportation statuses could be fed back to stakeholders on real-time basis. SCOs and Gateway can form a closed-loop information interaction throughout the prefabrication housing construction.

3.4 Overall architecture design

The IoT-enabled platform of on-site assembly services comprises four key components, as shown in Figure 9. They are smart construction objects, platform Gateway, decision support system, and data source services. As shown in Figure 9, from the right to left, SCOs are passive and active construction objects equipped with RFID devices. Gateway connects, manages, and controls the SCOs through defining, configuring, and executing the construction logics. Decision support system is to suit the on-site assembly services in Hong Kong. To enhance the data sharing and interoperability among BIM, stakeholders' information systems, and the IoT-enabled platform, data source services are designed to use XML/JSON-based data sharing mechanism for this purpose. Under the architecture, the decision-making systems can use the real-time data for advanced decision-makings.

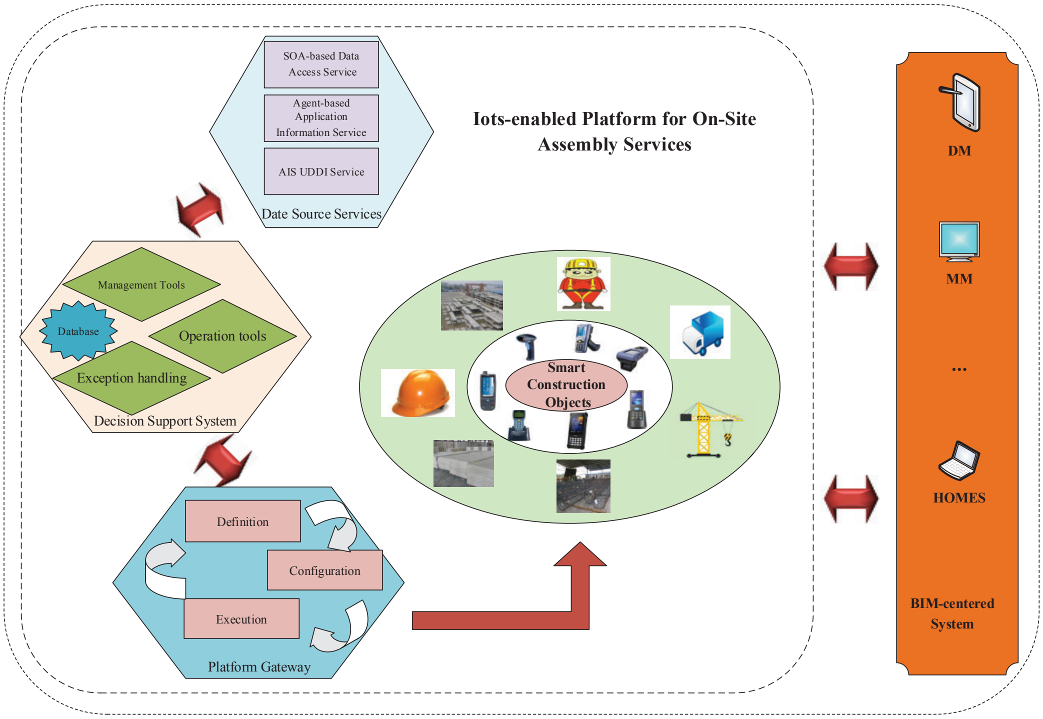


Figure 9 Overall architecture design of the platform

4. Practical application of the on-site assembly platform

4.1 Description of case study

The Tuen Mun project (Area 54, TM54), initially designed by HKHA, proposes to build five 34-38 storey buildings, providing about 5,000 units and with the expectation of holding more than 14,000 people. The construction practice of the 8th-35th storeys of Block 5 of the Tuen Mun project were provided as case study by our partners, due to project period well meet our study. The period of the pilot study was initially set as 5 storeys of Block 5, roughly from early October 2015 to November 2015. The period had later been extended to much more storeys (whole building) of Block 5 till the end of this research. To collect required data, a series of on-site visits and interviews are arranged and conducted toward concerned major stakeholders, including HKHA (Hong Kong Housing Authority) staff members responsible for housing production in the region, managers from precast manufacturers and logistics companies, engineers, and on-site managers of contractors. Besides, engineers who are familiar with the processes of on-site assembly activities are trained to operate the developed devices to run the platform for improving the productivity of OAS, and the management data are automatically collected and uploaded to the platform in real time manner.

4.2 Operational flow of the platform

The developed on-site assembly service facilitates various assembly operations, supervisions and quality checking in the construction site. BIM is integrated into the development of the service to visualize and monitor assembly progress. Several major sub-services, such as on-site assets management service, real-time supervision service, data capturing service and real-time feedback service are exploited to facilitate assembly of precast components. The operational flow of the developed service is shown in Figure 10.

Figure 10 Working Logic of OAS

(1) Staff registration

The staff registration function offers on-site workers an efficient way of logging into the system – by tap their staff cards instead of wasting time in typing passwords. This service uses NFC (near field communication) technology (and their existing staff cards) to identify corresponding workers, foremen, and on-site managers. Moreover, possible violations of site safety regulations, and risks and dangerous activities, can be mitigated for the operators on site.

(2) Order management

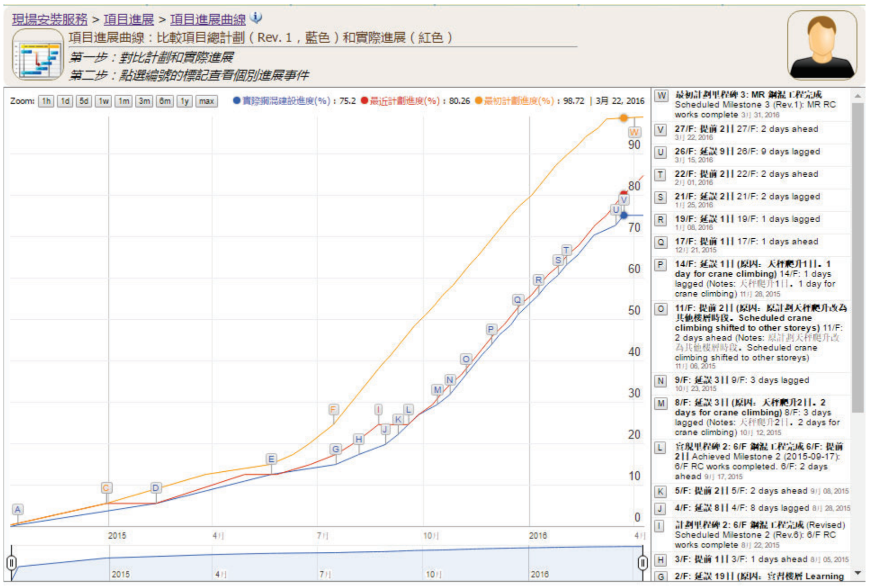
This module can be used by on-site workers and foremen responsible for the assembly of precast elements and by managers who want to check detailed information on an scheduled order and make necessary distributions, confirmations, and modifications. This function communicates with the order databases at manufacturer and logistics companies. The “Orders” module also includes two sub-modules similar to the manufacturer: “Current Orders” and “Import Orders.” The “Current Orders” module provides the orders overview. Users could check the general information of all imported orders and monitor their real-time status using this module. They could also check order details as well as remove and edit orders using this module.

(3) Assembly confirmation and quality checking

This function captures the real-time data of the precast element assembly upon site installation in such a manner that allows meaningful and useful information to be extracted. Once the required precast elements arrive at the site, these are assembled onto the floor and are quality checked. Real-time data regarding current status is captured through RFID reader by on-site foremen. This real-time information is then transferred to the server for processing to facilitate and coordinate various stakeholders and support their decision-making on the project, specifically when the project still has some issues, such as delivery delay of precast components, assembly interruption and other quality problems.

(4) Real-time progress monitoring

The cumulative quantity of precast elements erected based on real-time data collected and the contractor’s master program can be compared using a line chart to identify any delay in site construction progress, as shown in the Figure 11. This service provides a Gantt chart or a 3D virtual reality presentation that uses RFID assembly data to reflect the construction progresses in real-time in terms of prefabrication assembly status, material consumptions and workers' assignments. The main users are HKHA and on-site supervisors responsible for controlling the construction objects and reporting to various stakeholders on the progress, current challenges or barriers.


現場安裝服務 > 項目進展 > 項目進展曲線

項目進展曲線：比較項目總計劃（Rev. 1，藍色）和實際進展（紅色）

第一步：對比計劃和實際進展

第二步：點選編號的標記查看個別進展事件

● 實際鋼混建設進度(%)：75.2 ● 最近計劃進度(%)：80.26 ● 最初計劃進度(%)：98.72 | 3月 22, 2016

W 最初計劃里程碑 3: MR 鋼混工程完成 Scheduled Milestone 3 (Rev.1): MR RC works complete 3月 31, 2016

V 27/F: 提前 2日 27/F: 2 days ahead 3月 22, 2016

U 26/F: 延誤 9日 26/F: 9 days lagged 3月 15, 2016

T 22/F: 提前 2日 22/F: 2 days ahead 2月 01, 2016

S 21/F: 延誤 2日 21/F: 2 days lagged 1月 25, 2016

R 19/F: 延誤 1日 19/F: 1 days lagged 1月 08, 2016

Q 17/F: 提前 1日 17/F: 1 days ahead 12月 21, 2015

P 14/F: 延誤 1日 (原因：天秤爬升1日。1 day for crane climbing) 14/F: 1 days lagged (Notes: 天秤爬升1日。1 day for crane climbing) 11月 28, 2015

O 11/F: 提前 2日 (原因：原計劃天秤爬升改為其他樓層時段。Scheduled crane climbing shifted to other storeys) 11/F: 2 days ahead (Notes: 原計劃天秤爬升改為其他樓層時段。Scheduled crane climbing shifted to other storeys) 11月 06, 2015

N 9/F: 延誤 3日 9/F: 3 days lagged 10月 23, 2015

M 8/F: 延誤 3日 (原因：天秤爬升2日。2 days for crane climbing) 8/F: 3 days lagged (Notes: 天秤爬升2日。2 days for crane climbing) 10月 12, 2015

L 實現里程碑 2: 6/F 鋼混工程完成 6/F: 提前 2日 Achieved Milestone 2 (2015-09-17): 6/F RC works completed. 6/F: 2 days ahead 9月 17, 2015

K 5/F: 提前 2日 5/F: 2 days ahead 9月 08, 2015

J 4/F: 延誤 8日 4/F: 8 days lagged 8月 28, 2015

I 計劃里程碑 2: 6/F 鋼混工程完成 (Revised) Scheduled Milestone 2 (Rev.6): 6/F RC works complete 8月 22, 2015

H 3/F: 提前 1日 3/F: 1 days ahead 8月 05, 2015

G 2/F: 延誤 19日 (原因：實習樓層 Learning

Figure 11 Function for real-time progress monitoring

(5) Progress visualization

Real-time precast construction progress is visualized using an imported BIM Model in a web-based operating platform for monitoring produced elements, under transportation, on-site arrival and erection, which are shown in different colors to indicate the status of precast elements, as shown in the Figure 12. Easy real-time visualization is applied to check against domestic floor actual site construction progress and identify any delay in precast fabrication and delivery. Therefore, all involved project stakeholders could be aware of the current situations and make associated decisions collaboratively.

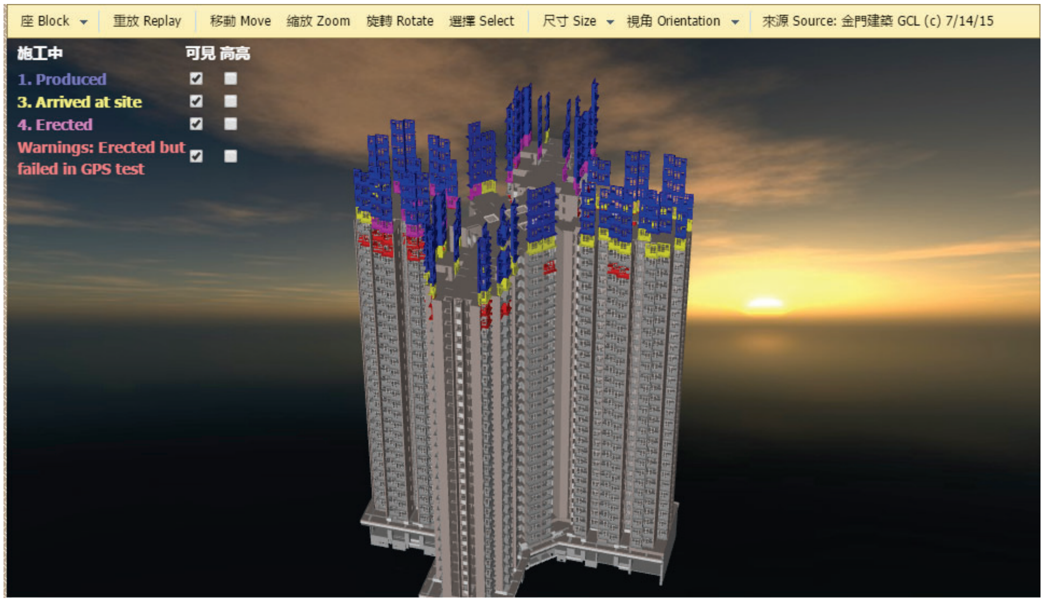


Figure 12 Function for Progress visualization

(6) Error alert

This function is developed to detect the rightness of the assembly of precast elements. Every precast component has a unique serial number that binds with a specific RFID tag and is assembled at a specific location. Coordinates of the location where the RFID tag of precast element installed read with a mobile phone based on GPS can be compared to the design coordinates based on the BIM model, as shown in the Figure 13. The deviation in position can be shown in meters. Any deviation larger than the reasonable tolerance in GPS can be identified manually as an error in precast element installation. Please be noted that because the layout of one typical floor of the studied building is quite large, with about 5,000 m^2 per floor, the minor deviation of GPS position data will not affect the error alert analysis of precast facades and the real-time data collection.

現場安裝服務 > 項目進展 > 項目進展曲線

項目進展曲線：比較項目總計劃（Rev. 1，藍色）和實際進展（紅色）

第一步：對比計劃和實際進展

第二步：點選編號的標記查看個別進展事件

Figure 13 Function for precast component tracing and error alert

After testing, the main advantages of on-site assembly service can be summarized as (1) Time-saving or man-hour saving, where a typical RFID reading of 23 facades for two wings of typical floor takes about 16 mins. However, the current solution spends more than 30 minutes, that is, about ten man-hours per month. The time can be improved further if the factory performs tag checks before every delivery. Time can be improved even further with an offline item cache. (2) Easy access and timely communication, with real-time feedback from assembly sites, real-time tracing of the construction objects, such as precast components, on-site workers and site equipment, are achieved. Real-time data are also used for forming statistical reports and analysis for the decision making of various involved stakeholders.

4.3 Facts on mobile apps and OAS web application

4.3.1 OAS RFID data gathering APP

The OAS RFID Data Gathering APP reads RFID EPC code via the SCO gateway and uploads the time and location to the server accordingly. Example screenshots of the

SCO gateway can be found in Figure 8. During the pilot tests, many challenges were engaged and resolved as follows:

- Using multi-level menu to reduce ambiguity on the system UI.
- A “waterproof” function was developed to make the smart gateway possible to operate in rains.
- English/Chinese versions are switchable from the configuration panel.
- Visual clues for scanning targets, including a list of items to read and their designed locations on a mini map.
- Visual clues for tag position for inexperienced user, including typical locations and brief introduction of each category of SCO.
- An alternative confirmation function by taking photo is designed for handling about 3% incorrect tags (missing or wrong) and less than 1% failed tags (unknown reason).

Also, some challenges not addressed yet:

- The system relies on manual collection (reading) of the data.
- The location data (GPS) of SCOs is only available in 5 days (before setting up semi-precast slabs overhead).
- The location data (GPS) becomes stable after 1 to 2 minutes when an operator climbs to the working roof.

4.3.2 WeChat OAS add-in

In order to extend the functions of OAS to mobile phones and tablets, a WeChat add-in, or Official Account, was developed as a supplementary APP. The main features of the add-in are: The four most valuable functions, including overall progress and a real-time *n*D BIM model, production status, just-in-time logistic information, location test of installation, were deployed on WeChat.

4.3.3 OAS web application

The OAS web application is the main media of use the functions of OAS. It is designed on HTML5 for modern browsers, so the technical issues listed below are about using on PC browsers.

- The *n*D-BIM model related: (1) At the beginning stage, only façades were displayed on the *n*D model: Later, the full precast model of Block 5 was provided, and all reinforced concrete items were imported; (2) Model size too large (about 8MB for real-time frame). The size caused the slow loading: The WebGL data file was redefined. Concrete belongs to the same family was referred to a data class. The heavy class data file was cached as local storage of browser. In this way, the model size was reduced to about 80KB; (3) 4D play-mode still too large (about 9MB) redefined “storey” classes (about 1MB).
- Menu: (1) The first version of menu appearance is plain style, CSS animation was added in the later versions; (2) Menu items were regrouped by objects or functions.
- Progress curve: (1) The (Adobe Flash-based) chart is not working on iOS. It was later changed to a Java script version; (2) Clues for days of delays were added. The tip texts were converted from manual comments of master plan.
- 2D floor map / *n*D BIM only display latest frame: Filters were added on to the toolbar for history data and full-screen / windowed form.
- RC volumes, important dates and plan revisions of each storey were included in master programs (administration) management.
- A calendar based setup GUI was developed for delivery orders (administration) management.
- A GPS data based location test was implemented for a coarse but automatic ways of location checking.
- Hong Kong holidays and special non-working days such as black rain signal were implemented for an automatic delay summary (administration) comments.
- Factory supply status is now available in both chart and text summary.
- Google Maps® was used for display of positioning and GPS.

4.4 Summary of the application

By the end of January 2016, the OAS recorded 667 prefabricated items (all facades), from the 8th floor to the 22nd floor (14.5 storeys, 58 wings). Each item has four important time and corresponding geolocations of manufacturing, delivery start, arrival at site, and erection. According the data, a day of "factory supply shortage" was discovered and was verified by Gammon's independent system. Another unusual installation was detected by GPS location test. The main advantages can be summarized in three categories:

- Time-saving or man-hour saving: (1) A typical RFID reading of 23 facades (2 wings) cost about 16 mins. In contrast, in the current practice a worker spends more than 30 minutes. That is about ten man-hours per month;
- Easy access and presentation: (1) *n*D model on many devices, including PC, tablet, mobile, etc; (2) Main functions are accessible on WeChat for drivers and workers
- Coarse assembly location checking: GPS data can help detect some unusual data

4.5 Scalability testing of the platfrom

The purpose of section is to provide information about scalability testing results coming from several tests on the IoT-enabled platform for on-site assembly services of prefabricated construction. Tests have been performed to evaluate software performance scalability and the compatibility to extend to different projects. The results in this document are then the merge of several tests which are carried out in different parts of the platform representing critical phases in the prefabricated housing supply chain. The purpose of this testing was to simulate predetermined scenarios that represent real-world hosting: (1) Determine the impact of server configuration on software performance; (2) Validate the test case scenarios and overall proposed scale environment; (3) Validate extensibility of hosting different construction projects.

4.5.1 Overview

In a real construction project, the active accounts and their activities are quite limited.

But in the setting of test, we have assumed ten to twenty times of both users and activities per user more than what we have measured during a 7-month pilot study. To replicate a typical large scale service implementation of our platform system, a series of auto tests were built as shown in Table 8.

Table 8 Scalability test deployment

Indicators	Typical Enterprise Customer	Scalability Test Deployment
Active organizational units account	1-3	25
Activities per active account per minute	1-3	60
Client address lists	1	10

The Test scenarios include: (1) Deploying on a shared web server hosted by university, at maximal level of preset load; (2) Deploying on a dedicated web server hosted by university, at maximal level of preset load; (3) Deploying on a renowned cloud server hosted, at maximal level of preset load; (4) Deploying with 7 active projects. The test environment is as shown in the Table 9.

Table 9 Test environment

Server	**Nature**	**Location**	**Operating System**
www.ad.arch.hku.hk	Shared server	HK	Linux
147.8.92.79	Dedicated server	HK	Linux
openshift.com	Cloud server	USA	Linux
Client	**Nature**	**Location**	**Profile**

Client 1	Auto test software (By loadimpact.com)	Brazil	25 users, 60 activities per user per minute
Client 2	Auto test software	Singapore	ditto
Client 3	Auto test software	USA	ditto

4.5.2 Scale testing for different scenarios

The 25 virtual users (VUs) were added incrementally in 5 minutes, i.e., 1 new active user in 12 seconds. The activities increased from 1. During the 5-minute test, thousands of URLs will be requested by the client and 200M to 1G data will be transferred as well. The response time (fully load of a requested page by an activity) was measured.

（1）Scenario 1 - Client 1 + shared server

As shown in Figure 14, the load time was not stable and the data transmission was not acceptable for intentional users. Though we found it was acceptable when using in HK locally.

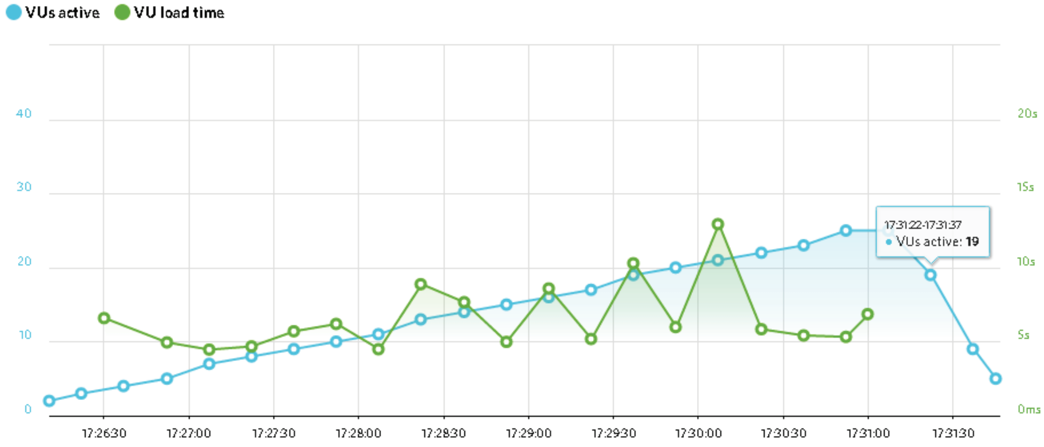


Figure 14 Scale testing result from scenario 1

（2）Scenario 2 - Client 1 + shared server

In this scenario, the load time was much fluent and stable as shown in the Figure 15.

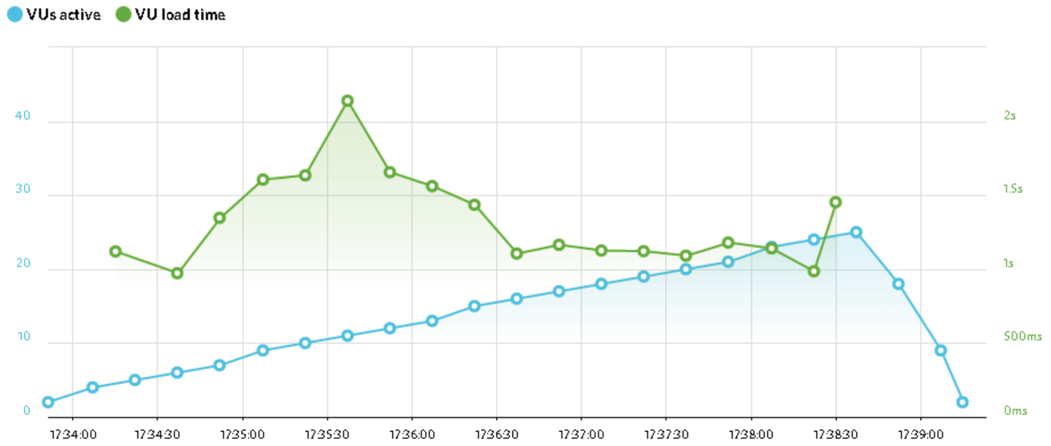


Figure 15 Scale testing result from scenario 2

（3）Scenario 3 - client3 + cloud server (openshift.com)

In this scenario, the load time was quite high at the beginning, but soon reduced to very low level about 100ms, as shown in Figure 16. This was because of the cloud server unloads the system when it is idle and loads and initializes the system when there are requests. In general, the cloud server is the best way of deployment of the system. And once being deployed on cloud, the performance will not be a problem any more.

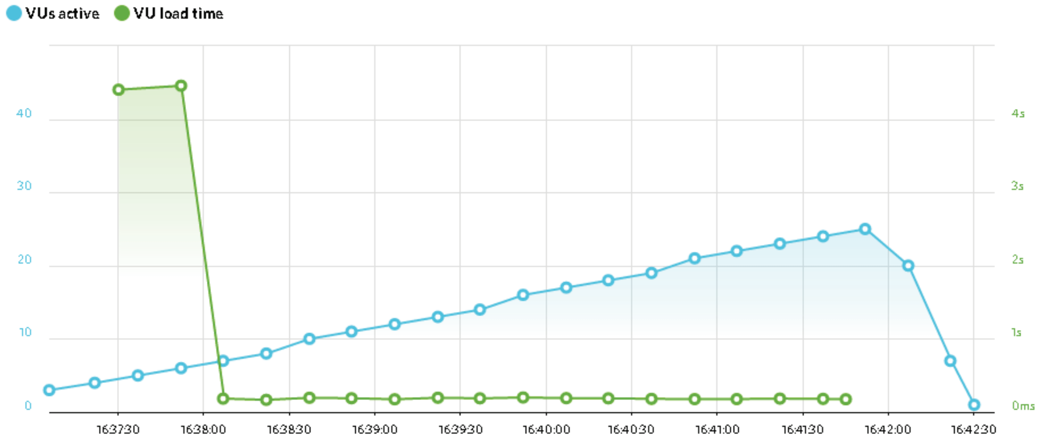


Figure 16 Scale testing result from scenario 3

（4）Scenario 4 - 7 active projects

7 active projects that have used the platform to manage prefabrication construction are hosted to check the stability of platform. The system can work smoothly in all the 7 active projects, and the cloud server deployment showed the best performance in terms of average response time.

4.6 Technology integrity and scalability

The proposed platform is designed and developed under service-oriented open architecture to ensure seamless integration with existing systems (HKHA's BIM and Housing Construction Management Enterprise System (HOMES)), so that the information among them could be shared and synchronized. The integrity and scalability has been carried out through the following aspect: (1) IoT-enabled platform can be easily deployed through existing commercial cloud space, such as Ali Cloud and Amazon Cloud. High performance servers, smart computing resources sharing and virtualization for integrity and scalability can be easily maintained through the provided infrastructure. Specific options, such as public cloud or private cloud, can also be chosen for special security considerations; (2) IoT-enabled platform considers standard data requirement and supports formats of popular BIM systems (such as Revit). Apart from the pilot research, IoT-enabled platform can therefore be conveniently applied to other construction projects; (3) With the developed SCO, Gateway and GOS, IoT-enabled platform supports heterogeneous smart Auto-ID devices and able to handle different RFID tags (such as NFC and UHF tags); (4) Due to the policy of HKHA for change request of HOMES, the interface to integrate IoT-enabled platform with HOMES is not possible to be made until year 2018. However, the data source interoperability services provided in the platform is initially implemented and tested to create adaptive data exchanging interfaces for HOMES and other related systems. Instead of direct integration with HOMES, the platform also provides set of visibility and traceability tools for monitoring the project progress and cost for HKHA and other stakeholders at this stage.

5. Conclusions

Over the years, HKHA has taken a leading role in developing and promoting the application of ICT in general and BIM/ERP/RFID among construction stakeholders. The architecture of the IoT-enabled platform has considered the business processes, the stakeholders, the information flow, and the real-time information visibility and traceability. It uses the service-oriented open architecture as a key innovation to enable the platform as a service. Given its potential to manage building information throughout processes of OAS, IoT-enabled platform is considered as significant part of the HKHA's overall ICT architecture, which aims to reengineering the OAS of prefabricated construction in Hong Kong.

All the collected real-time information from RFID and GPS can be connected with BIM in the developed IoT-enabled platform. Traceability and visibility of the physical building information, progress, and cost are available for the stakeholder to monitor the whole process and make decisions where necessary. The paper-based records can be subsequently freed for many processes and only reserved for verification in key processes. The usage of BIM technique can also be henceforth extended to construction phase. With the developed platform, the main contractor can be benefitted from knowing the real-time information of prefabrication components. The data collection on site becomes effective, reliable and more value-added. Therefore, the whole on-site team of the main contractor can be more resilient when facing changes, such as design changes, order changes, changes due to repairing defective components, etc. The client, HKHA, can be benefited from obtaining real-time information from the prefabrication production to the on-site assembly. The visibility and traceability tools provide useful tools for monitoring and checking the status and quality problems. The multi-dimensional information of cost and progress provided by IoT-enabled platform, can help the client to manage the progress and arrange payment accordingly. Historical information of the stakeholder's performance stored in the IoT-enabled platform can even be used for facilitating contractor and sub-contractor selection.

Despite the various benefits, the limitations of the developed platform in the research should be also outlined for its further development and broader application. Due to the limitations of resource, this research only applies the developed platform to only one practical project for testing its effectiveness. Besides, this research focus more on the development of the functions related to schedule and cost management, while management of safety, quality and construction environment are also important for prefabricated construction project. Despite of the above limitations, the research not only pioneers on developing a platform for on-site assembly services of prefabricated construction with integration of Internet of Things and BIM from a new perspective, but also serving as a solid basis for further research, which may include: improving and extending the applicability of the platform to more practical project to enhance its effectiveness; improving the platform by incorporating more functions related to the management of safety, quality and construction environment.

Acknowledgments

The authors would like to thank the HKSAR ITC/LSCM R&D Centre for funding this research through the Innovation and Technology Support Programme (Project Reference: ITP/045/13LP). The Research Team is also grateful to the Hong Kong Housing Authority and its contractors for supporting and participating in this research via real project applications.

Reference:

Alavi, A. H., H. Hasni, N. Lajnef and K. Chatti (2016). "Continuous health monitoring of pavement systems using smart sensing technology." Construction and Building Materials 114: 719-736.

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

Chung, J. K., M. M. Kumaraswamy and E. Palaneeswaran (2009). "Improving megaproject briefing through enhanced collaboration with ICT." Automation in construction 18(7): 966-974.

Demiralp, G., G. Guven and E. Ergen (2012). "Analyzing the benefits of RFID technology for cost sharing in construction supply chains: A case study on prefabricated precast components." Automation in Construction 24: 120-129.

Ergen, E., B. Akinci and R. Sacks (2007). "Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS." Automation in construction 16(3): 354-367.

Hong, J., G. Q. Shen, C. Mao, Z. Li and K. Li (2016). "Life-cycle energy analysis of prefabricated building components: an input–output-based hybrid model." Journal of Cleaner Production 112: 2198-2207.

Hossein Alavi, A. and A. Hossein Gandomi (2011). "A robust data mining approach for formulation of geotechnical engineering systems." Engineering Computations 28(3):

242-274.

Jaillon, L. and C. S. Poon (2009). "The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector." Automation in Construction 18(3): 239-248.

Leu, S.-S. and S.-T. Hwang (2002). "GA-based resource-constrained flow-shop scheduling model for mixed precast production." Automation in Construction 11(4): 439-452.

Li, C. Z., J. Hong, F. Xue, G. Q. Shen, X. Xu and M. K. Mok (2016). "Schedule risks in prefabrication housing production in Hong Kong: a social network analysis." Journal of Cleaner Production 134, Part B: 482-494.

Mao, C., L. Shen, L. Luo and Z. Li (2015). Identification of Risk Factors Influencing the Implementation of Industrialized Building System in China. Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estate, Springer.

Pang, L. Y., R. Y. Zhong, J. Fang and G. Q. Huang (2015). "Data-source interoperability service for heterogeneous information integration in ubiquitous enterprises." Advanced Engineering Informatics 29(3): 549-561.

Peffers, Ken, Tuure Tuunanen, Marcus A. Rothenberger, and Samir Chatterjee. "A design science research methodology for information systems research." Journal of management information systems 24, no. 3 (2007): 45-77.

Sacks, R., C. M. Eastman and G. Lee (2004). "Parametric 3D modeling in building construction with examples from precast concrete." Automation in Construction 13(3): 291-312.

Shin, T.-H., S. Chin, S.-W. Yoon and S.-W. Kwon (2011). "A service-oriented integrated information framework for RFID/WSN-based intelligent construction supply chain management." Automation in Construction 20(6): 706-715.

Tam, C. M., Deng, Z. M., & Zeng, S. X. (2002). Evaluation of construction methods and performance for high rise public housing construction in Hong Kong. Building and Environment, 37(10), 983-991.

Tam, V. W., C. Tam, S. Zeng and W. C. Ng (2007). "Towards adoption of prefabrication in construction." Building and Environment 42(10): 3642-3654.

Wong, R. W., J. Hao and C. M. Ho (2003). Prefabricated building construction systems adopted in Hong Kong. Proc. of the International Association for Housing Science on Word Congress of Housing: Process and Product, Montreal, Canada.

Yin, S. Y., H. P. Tserng, J. Wang and S. Tsai (2009). "Developing a precast production management system using RFID technology." Automation in Construction 18(5): 677-691.

Zhong, R. Y., Y. Peng, J. Fang, G. Xu, F. Xue, W. Zou and G. Q. Huang (2015). "Towards Physical Internet-enabled Prefabricated Housing Construction in Hong Kong." IFAC PapersOnLine 48(3): 1079-1086.

Zhong, R. Y., Y. Peng, F. Xue, J. Fang, W. Zou, H. Luo, S. Thomas Ng, W. Lu, G. Q. P. Shen and G. Q. Huang (2017). "Prefabricated construction enabled by the Internet-of-Things." Automation in Construction 76: 59-70.

Fang, Y., Cho, Y. K., Zhang, S., & Perez, E. (2016). Case Study of BIM and Cloud–

Enabled Real-Time RFID Indoor Localization for Construction Management Applications. Journal of Construction Engineering and Management, 142(7), 05016003.