

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

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17 **Abstract:**

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

40 manner. The IoT-enabled platform can provide various decision support tools and
41 services to different stakeholders, for improving the efficiency and effectiveness of
42 daily operations, decision making, collaboration, and supervision throughout on-site
43 assembly processes of prefabricated construction.

44

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

47 **1. Introduction**

48 Prefabrication has been widely adopted by Hong Kong Housing Authority (HKHA),
49 who is the main provider of public housing in Hong Kong, for its public housing
50 projects, due to its more efficient, cleaner and safer working environment, and better
51 quality (Tam et al. 2007; Hong et al. 2016; Li et al. 2016). For example, the public
52 housing project at Tuen Mun Area 54 Site 2, Phases 1 & 2, makes use of 11 types of
53 precast elements, including precast façade, semi-precast slab, volumetric precast
54 bathroom, tie beam, staircase, parapet, refuse chute, half landing, water meter room, lift
55 machine room and main roof slab. Some of them are proposed by the general contractor.

56 As a ‘sweet point’ of balancing construction cost and labour requirement (Tam et al.,
57 2002), contractors adopt a 6-day cycle for the typical floor (usually 20 to 30 units) on-
58 site assembly in high-rise public housing projects since 1990s in Hong Kong. Among
59 the processes of on-site assembly, BIM serves as a useful platform for facilitating the
60 on-site assembly services (OAS) of prefabricated construction for its benefits of
61 providing collaborative working teams and decision makers with the physical and
62 functional representations of prefabricated components (Sacks et al. 2010; Frédéric et
63 al. 2014; Chen et al. 2015; Niu et al. 2016). For example, the status of prefabrication
64 components could be traced and visualized in BIM platform for supporting the progress
65 control (Ergen et al. 2007, Zhong et al. 2015).

66 However, the well-formatted information of prefabricated component at the right time
67 in the right location is still insufficient to further raise the efficiency of collaborative
68 working and decision making in on-site assembly services when adopting BIM in
69 prefabricated construction projects (Yin et al. 2009). For example, the location
70 information of both outdoor and indoor resources through positioning technologies
71 such as RFID (radio frequency identification), UWB (ultra-wideband), and GPS (global
72 positioning systems) have been synchronized in BIM for safety management (Fang et
73 al., 2016), while few studies integrate the accurate location information of on-delivering
74 prefabricated components into BIM platform for monitoring the right components to be
75 assembled in the correct position in a safer manner (Zhong et al. 2017). Additionally,
76 the information of changes, cost and schedule are delivered from previous processes
77 (i.e., design, manufacturing, logistics) could be updated to a centralized BIM platform
78 for sharing the information among different stakeholders (Li et al. 2017; Niu et al. 2017;
79 Issa et al. 2017). However, this information is usually re-entered incompletely,
80 inaccurately and untimely into various isolated systems (i.e., enterprise resource
81 planning (ERP)) of the different stakeholders in most of the current project practices,
82 which could not efficiently support the decision making in the OAS (Pang et al. 2015).
83 These problems can be further deteriorated in Hong Kong particularly due to the
84 numerous constraints such as limited resources and space (Wong et al. 2003; Chun et
85 al. 2009; Alavi et al. 2016). The solution for such situation is still a void to be filled.
86 To handle these challenges, an Internet of Things (IoT) enabled platform is to be
87 developed in this research by deploying BIM as the basic infrastructure underlying in
88 its system structure. This research employed a typical design science research
89 methodology (Peffers et al. 2007), which consists of six steps of problem identification
90 and motivation, definition of the objectives for a solution, design and development,

91 demonstration, evaluation, and communication, in the research and development.

92 Section 2 is the literature review which also identified the need of BIM and IoT-based

93 OAS management system. Section 3 describes the objectives of the BIM and IoT-based

94 OAS regarding field interviews, the design of SCOs, and the development of the OAS

95 decision support system. The demonstration of the system on a real project and the

96 evaluation are given in Section 4. Conclusions appear in Section 5. The specific

97 objectives of this research are: (1) To investigate and analyse business process and

98 requirement of on-site assembly of prefabricated construction; (2) To propose the

99 architecture design and develop the Internet of Things enabled platform; (3) to apply

100 the developed platform to practical project to test its performance and effectiveness.

101 This centralized BIM platform not only integrates the information delivered from the

102 previous stages but also synchronizes the location information of prefabricated

103 components for facilitating the real-time communication and coordination among the

104 different stakeholders for better decision making in the OAS. The innovativeness of

105 this platform, by looking at whole processes of the on-site assembly of prefabricated

106 construction, is to increase their connectedness by using BIM as an information hub to

107 connect information and communication technology (ICT) enhanced SCOs. The

108 architecture of the IoT-enabled platform has considered the business processes, the

109 stakeholders, the information flow, the visibility and traceability of the real-time data.

110 It uses the service-oriented open architecture as a key innovation to enable the platform

111 as a service. Given its potential to manage building information throughout processes

112 of OAS, the IoT-enabled platform is considered as a significant component of the

113 HKHA's overall ICT architecture and systems, which aims to re-engineer the OAS of

114 prefabricated construction in Hong Kong for a better support of decision making.

115 **2. Literature review**

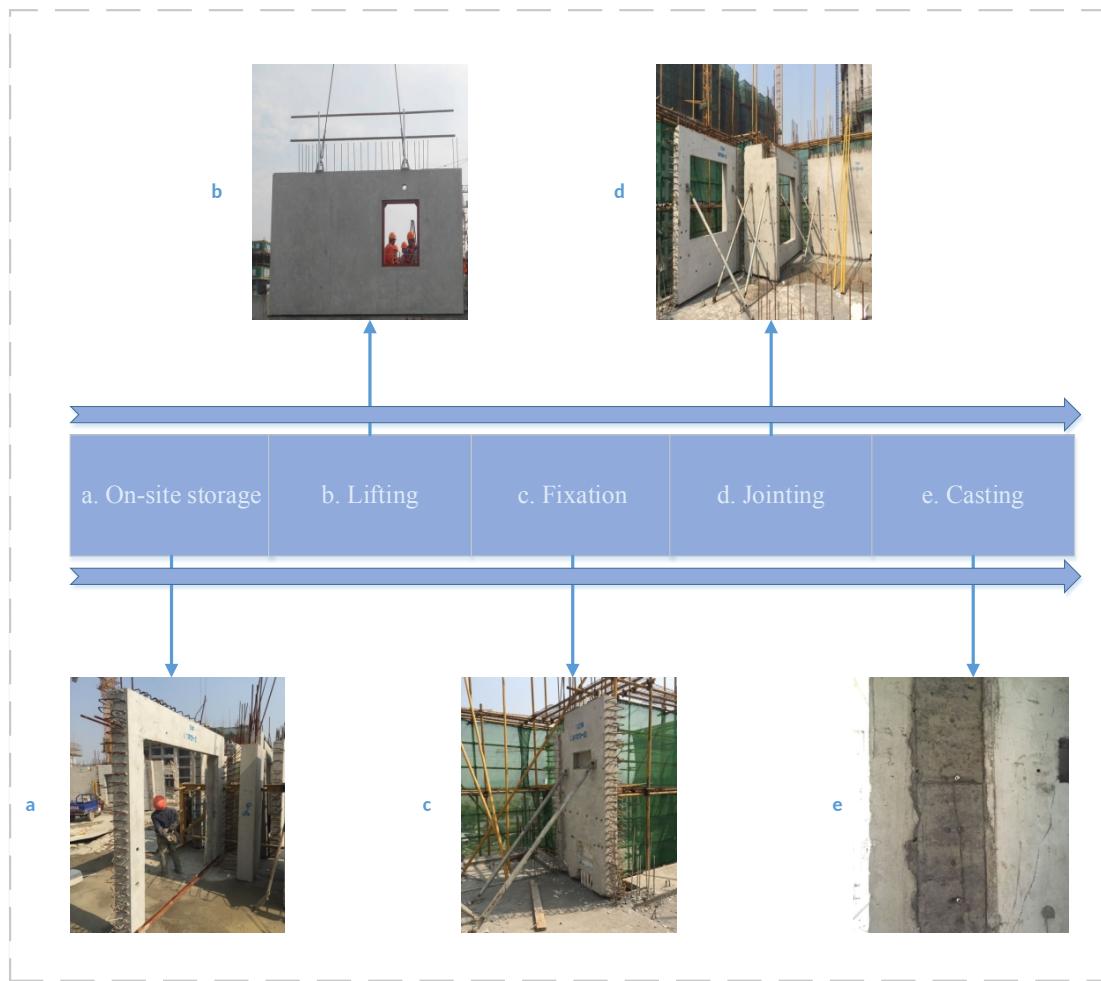
116 The advanced OAS planning and control systems initiated from the Last Planner®
117 System (LPS®) which is a production management system that applies pull and look-
118 ahead planning to remove constraints and make downstream activities ready (Ballard,
119 2000). Weekly work planning is adopted to reduce uncertainty and find relevant causes
120 for variances. LPS also uses the percentage of the plan completed (PPC) to measure
121 and monitor the process (Ballard, 2000; Kim et al., 2014). However, LPS is difficult to
122 visualize the flow of work process (Sacks et al., 2009). Building Information Modelling
123 (BIM) can be utilized to simulate and visualize the construction process with 3D
124 geometric models and ample information to facilitate communication among
125 stakeholders (Sacks et al., 2009). In addition, LPS is the weekly work planning that may
126 lead to a long response time to address daily constraints. Sacks et al. (2010) developed
127 the KanBIM concept which can manage day-to-day status feedback and support human
128 decision making or negotiation among stakeholders. As prefabricated construction
129 contains multiple phases from manufacturing, logistics to site assembly, the direct use
130 of LPS and BIM in prefabricated construction has an apparent gap related to the
131 interoperability and real-time traceability of information. Dave et al. (2016) therefore
132 developed a communication framework by adopting IoT (Internet of Things) to
133 strengthen the use of Lean Construction management and tracking technologies such as
134 RFID and GPS, which are critical components of IoT, to track the status of workers,
135 materials, and equipment in the whole process. A conventional RFID system contains
136 an antenna, a transceiver (RFID reader) and a transponder (Radio Frequency tag). The
137 antenna sets up an electromagnetic area where the tag detects the activation signal and
138 responds by transmitting the stored data from its memory through radio frequency
139 waves (Wang et al., 2016). RFID can be applied to monitor unit status during

140 manufacturing and site assembly stages while GPS can be adopted to locate the units
141 during logistics phase and calculate the remaining time to site. One RFID-enabled BIM
142 platform has been developed for prefabricated construction by researchers in Hong
143 Kong (Zhong et al., 2015; Li et al., 2016). The platform's architecture has three
144 dimensions: infrastructure as a service (IaaS), platform as a service (PaaS) and software
145 as a service (SaaS). The IaaS level contains hardware and software layers. The hardware
146 layer consists of the SCOs (Niu et al., 2015) and the Gateway, while the software layer
147 involves a Gateway Operating System (GOS) to manage the SCOs. SCOs with
148 functional data and data collection devices are enabled by the RFID system and other
149 innovative technologies. RFID was firstly introduced as a sister technology to replace
150 barcode system for identifying items. By comparing it with barcode system and
151 magnetic strip system, RFID can store a relatively large number of data. This data can
152 be encrypted to increase data security. It is possible to read data from multiple tags in
153 one time thus increase the efficiency of data processing. In comparison with barcode or
154 magnetic system, no direct contact between a RFID reader and the tagged items is
155 needed as it uses radio wave for data transmission. In addition to reading data, it is
156 possible to write data back to the RFID tag, which greatly increases the interaction
157 between items, systems, and people. The GOS is developed to aggregate and pre-
158 process the massive real-time data such as Industry Foundation Classes (IFC) data
159 converted from BIM software (e.g. Revit), GPS data, RFID data (e.g. schedule, cost,
160 production attributions) and point cloud data. In addition, the PaaS level is related to
161 the data source management services (DSMS) which facilitate the heterogeneous
162 information and application systems by applying XML/JSON-based BIM model and
163 connecting the backend RFID system with BIM model. This enhances the initial BIM
164 platform to a multi-dimensional one. The SaaS level consists of three management

165 services (manufacturing, logistics, and on-site assembly) to enhance the information
166 sharing and communication for stakeholders' decision-making at different stages. This
167 study details the deployment and application of the on-site assembly services to try to
168 improve the dilemmas of current project practices in Hong Kong including: (1)
169 Construction sites in Hong Kong are often compacted, with only limited space for
170 storing large and cumbersome components (Jaillon and Poon 2009). Thus, site
171 management is often on the critical path for the success or failure of a construction
172 project. Under this circumstance, a Just-In-Time (JIT) delivery and assembly are
173 desired but currently in Hong Kong, normally a site manager should reserve
174 components/materials of 1.5 stores on site as a buffer. The JIT delivery of prefabrication
175 components is yet to be harvested; (2) Verification of the components is inefficient
176 (Demiralp, Guven et al. 2012), mainly due to the wide use of paper or paint labels.
177 Workers should pay attention to the verification process sequentially, which will lead
178 to extra labor and time cost. Yet, the accuracy of the verification process is not
179 guaranteed since the paper-based documents, or even handwriting and modified labels
180 are usually ambiguous; (3) Current practice may cause safety issues. Construction
181 workers on the sites are usually busying with their operations, some of which need
182 enough space e.g. for crane towers to hoist various components to proper positions
183 (Mao, Shen et al. 2015). If the required spaces are occupied, serious safety issues may
184 be occurred; (4) If too many components are placed on a construction site, workers may
185 have difficulties to find out proper components (from a large pile of similar components)
186 for a specific trade (Shin, Chin et al. 2011). This has been reported in casino projects in
187 Macau. To identify the proper components through effective real-time information
188 collection approach is highly desired. Currently, no such platform, like IKEA's
189 "assembly instructions", has been developed to guide on-site assembly to make it more

190 efficient. This research is highly motivated to develop such platform that can inherit
191 information from prefabrication production and cross-border logistics and used it to
192 facilitate the on-site assembly process.

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



202
203 Figure 1 General steps for on-site assembly
204

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

206 3.1 Analysis of business process and requirement

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

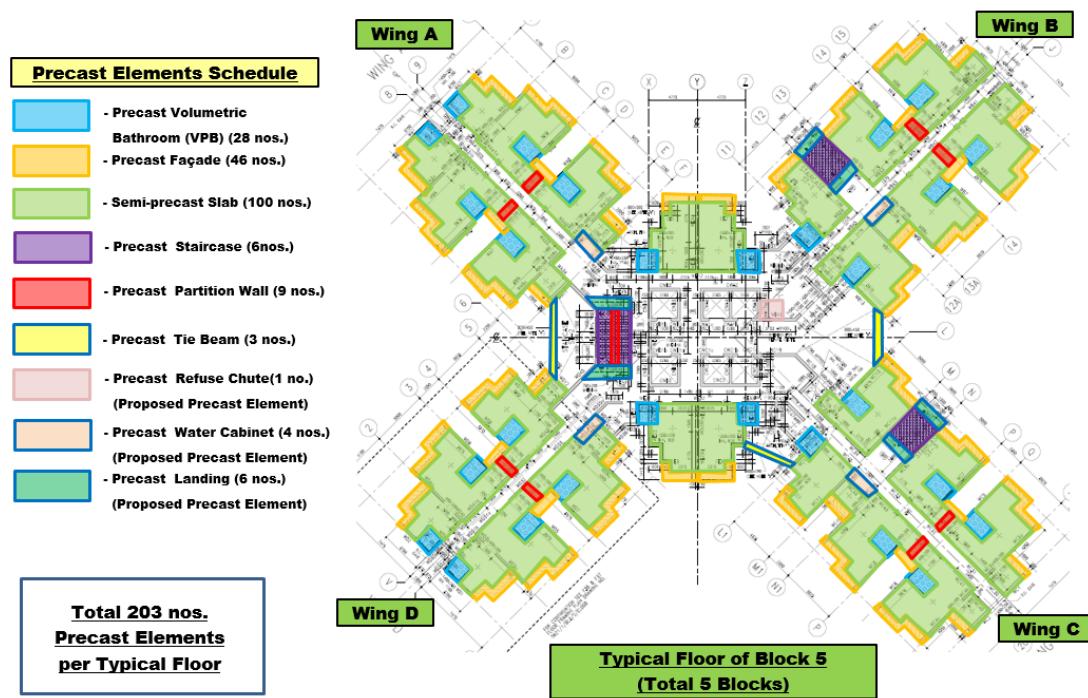
216 The surveyed Tuen Mun project (Area 54) proposes to build five 34-38 story buildings,
 217 providing about 5,000 units and with the expectation of holding more than 14,000
 218 people. Detailed information regarding prefabrication components to be used can be
 219 seen in the Table1. Figure 2 below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

221

222 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									
Precast Water Tank	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			

223

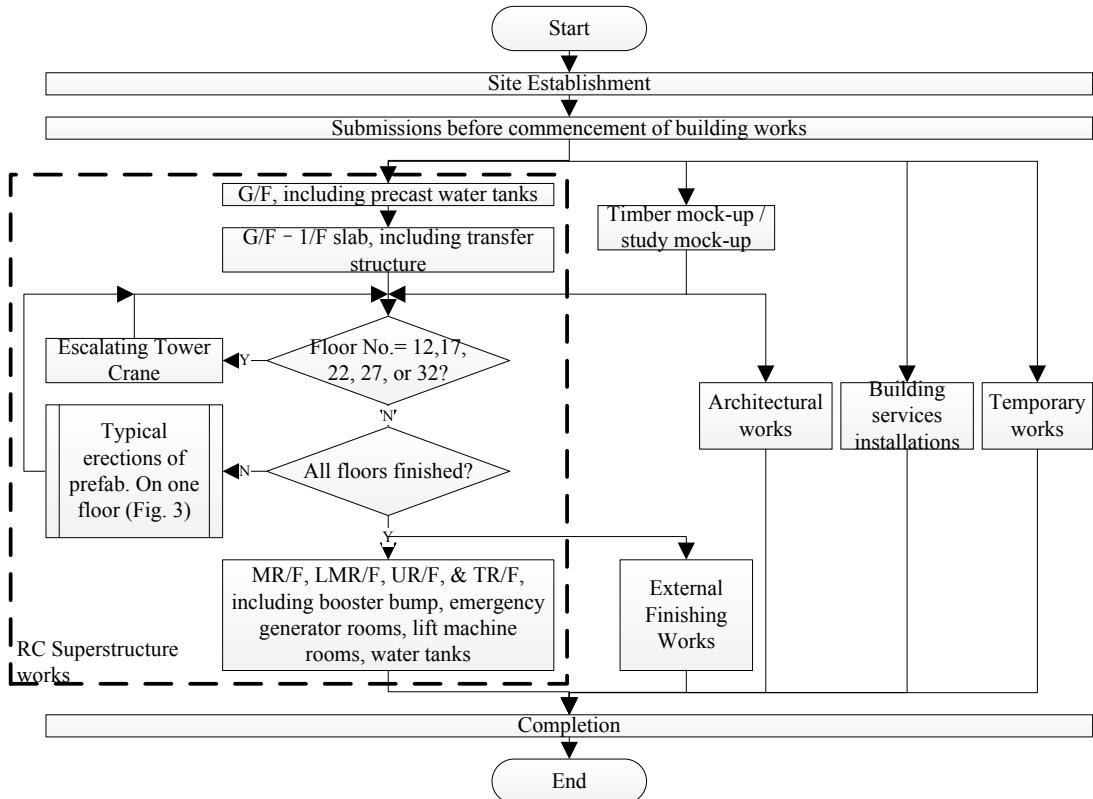


224

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

226

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



232

233

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

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

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

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

250 **Stage 3 – Superstructure works:** This stage is the main focus for the BPA on
251 prefabrication on-site assembly. Superstructure works include (1) fabrication and
252 installation of precast water tank; (2) G/F - 1/F including transfer structures; (3) 1/F –
253 37/F slab, noted that tower crane is planned to be escalated once the slabs of 12nd, 17th,
254 22nd, 27th and 32nd floor are completed; (4) installation of booster pump, emergency
255 generator rooms, lift machine room and water tanks. The process for one floor (from
256 G/F to 5/F) is significantly longer than that for a floor above 5/F, e.g., 12-70 days for a
257 floor from G/F to 5/F while a 6-day cycle for an upper floor. This is because many
258 issues may be encountered during this period, based on experience.

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

261 **Stage 5 – Building Services Installations:** After the completion of superstructure
262 works and architectural works, building services-related facilities will be installed,
263 including: (1) Plumbing and drainage installation; (2) Town Gas; (3) Electrical
264 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

Non-Functional Requirements		
1	Performance	Data and status are available at real-time
3	Erection inspection	Be aware of prefabrication are erected successfully
4	Buffer	Be aware of place where prefabricated components are held
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)
6	Messaging	Automatic SMS or Android/iOS notifications on prefabrication delivery/ erection/ unexpected issues for stakeholders
7	Erection inspection	Multiple scanners or floor partitioning for RFID scanning
8	Erection inspection	Random order RFID scanning within one floor after inspection
9	Erection inspection & Buffer	Batch upload of photos synchronized or synchronized with hand-held scan data upload
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
11	Buffer, Erection inspection, & General management	Electronic files (PDF) sharing of inspection reports and progress reports

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

286

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

292 **3.2 Functional requirement and UI design**

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

305 functional requirements, non-functional requirements, internal requirements, design
306 constraints, logical database requirements and other requirements.

307 **3.2.1 Interface requirements**

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

319

320 Table 3 The five sets of target human users and three sets of external software users
321 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.		
Prefabrication receiver (assigned by Foreman): confirm a component is safely delivered to construction site.	low	part-time receiving; low-level certificate;	
Erection worker : confirm a component is correctly erected.	low	hard work; low-level certificate;	
Inspector : confirm the quality of final assembly in the whole structure.	medium	technical/qualified staff;	
BIM system : providing structure and shape data.	high	professional standards; specific software end (Revit);	
RFID system : providing status data of components.	medium	3rd-party solution; data may be slightly delayed (<1 day);	
Other services in the platform : the aforementioned ones and the services to be developed.	medium	high compatibility; small amount/ regular communication;	

322 3.2.2 Functional requirements

323 Based on the analysis of business process and requirement, a total of four major services
 324 are provided in the IoT-enable platform: (1) Assembly management (real-time
 325 supervision) services: to provide a toolkit for contractor's managers and engineers to
 326 supervise the management of on-site assembly services, which include: visibility
 327 service to integrate the project progress in charts and 3D BIM models, and components
 328 in 3D BIM models; component tracing service to locate a missing component and return
 329 the geolocation or place of storage; component tracking service to filter one or more
 330 components in a given criterion, e.g., selecting all installed windows in a storey/floor;
 331 (2) Assembly operations services: to provide a toolkit for managers and engineers who

332 are involved in operations of assembly at construction site, which include: planning
333 service to break down a job plan (typically floor plan) into tasks in charts; components
334 order listing helper service: to provide an information list for site coordinators and
335 production services, partially depended on component tracking service; assembly
336 scheduling service to make floor plans and daily plans by associating personnel with
337 planned tasks; component tracing/ tracking service; duplicated component tracing and
338 tracking service; (3) Assembly exception handling services: to implement part of
339 preplans for some of the unexpected cases, which include: progress exception handling
340 service to provide follow-up tools for the cases where the progress is not carried out
341 on-time; component exception handling service to record when an important (e.g.,
342 RFID tagged) component encounters defects or replacement; (4) Assembly notification
343 services: for facilitating in reminding and notification for users, with different
344 reminders sent to subscribed users, such as progress summary, component list to be
345 delivered today, and summary of inspection result, which include Email notification
346 service to send Email alerts for managers and engineers who work in office, SMS
347 notification service, and mobile app notification service.

348 **3.3.2.2 Functions of management tools**

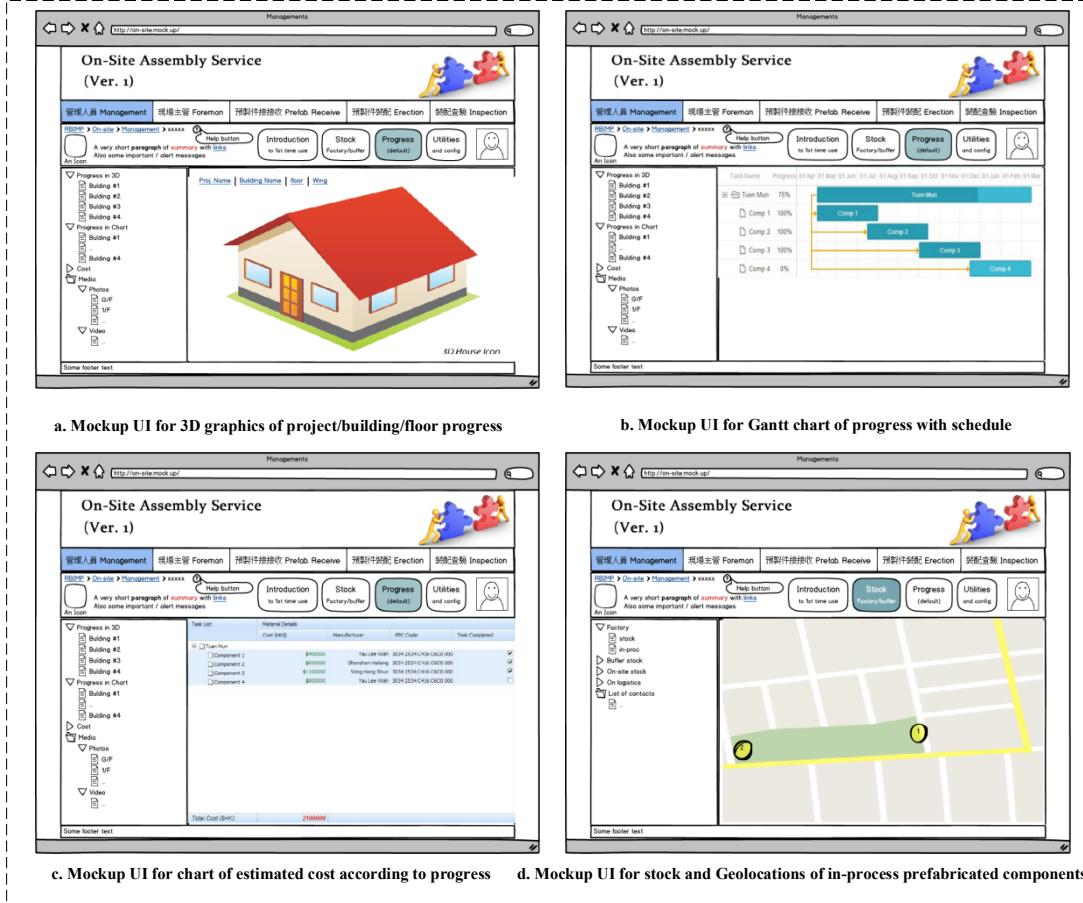
349 The functions of management tools for management level listed in Table 4 and Figure
350 4 below.

351 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

352



353

354

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

3.3.2.3 Functions of operation tools

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

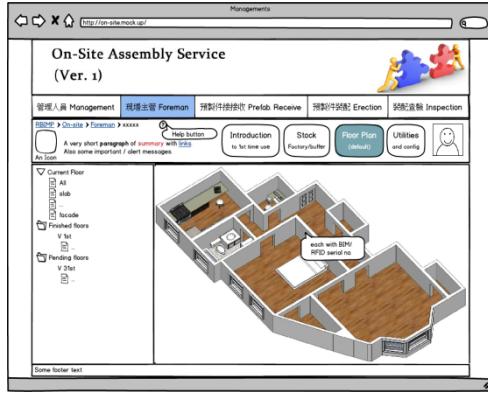
358 Table 5 The functions of management tools for on-site operation level

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

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	Show information and hints on data input, user privilege, and
Handling	software compatibility errors, or return to log in

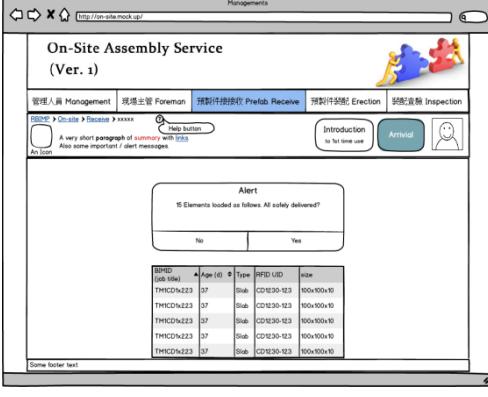
359



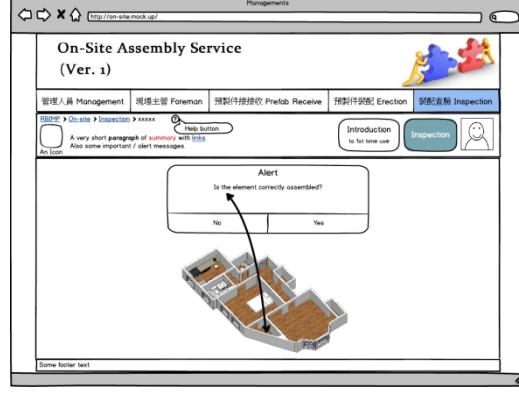
a. Mockup UI for floor plan review for foreman



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

360

361 Figure 5 Mockup GUIs for floor plan review for a foreman

362

363 3.3.2.4 Functions of exception handling and notification tools

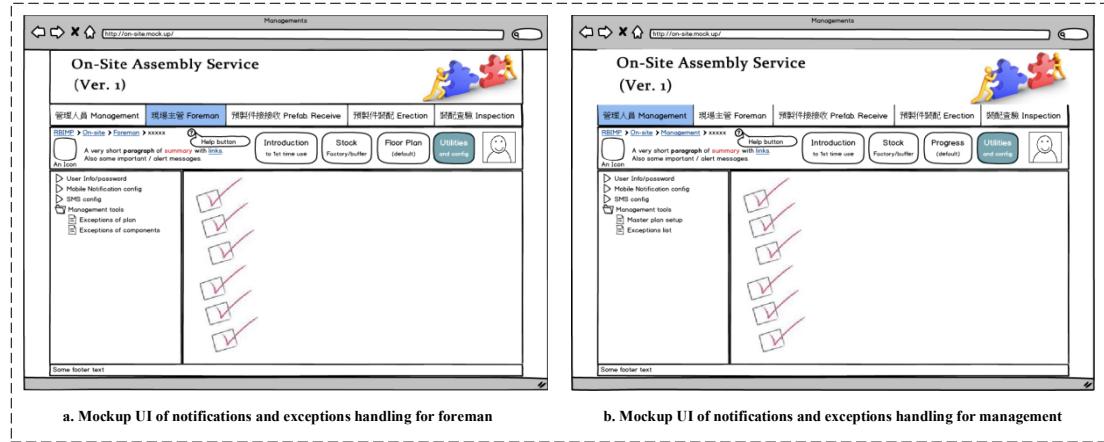
364 The functions of management tools for managers, engineers and on-site coordinators o
 365 track exceptions and receiving progress/exceptions updates are listed in Table 6 and
 366 Figure 6 below.

367

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

Toolkit to track exceptions and receiving progress/exceptions updates	
Trigger	As specified in the GUIs in Figure 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

370



371

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

374 3.2.3 Non-functional requirements

375 Non-functional requirements may exist for the following attributes. Often these
376 requirements must be achieved at a system-wide level rather than at a unit level. The
377 requirements are stated in Table 7 in measurable terms. The deployment of the system
378 would was planned on cloud servers, thus many conventional system-level requirements

379 (e.g., system downtime and mean time between failure) was easily met.

380

381 **Table 7 Non-functional requirements**

Response time	
Performance	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.
Maximum bug rate	
	There will be a maximum of 1 bug in 1,000 lines of codes.
Maximum time to repair	
Reliability	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.
Back-end internal computers	
Availability	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 original 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.
-

Maintenance

- Maintainability**
- (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.

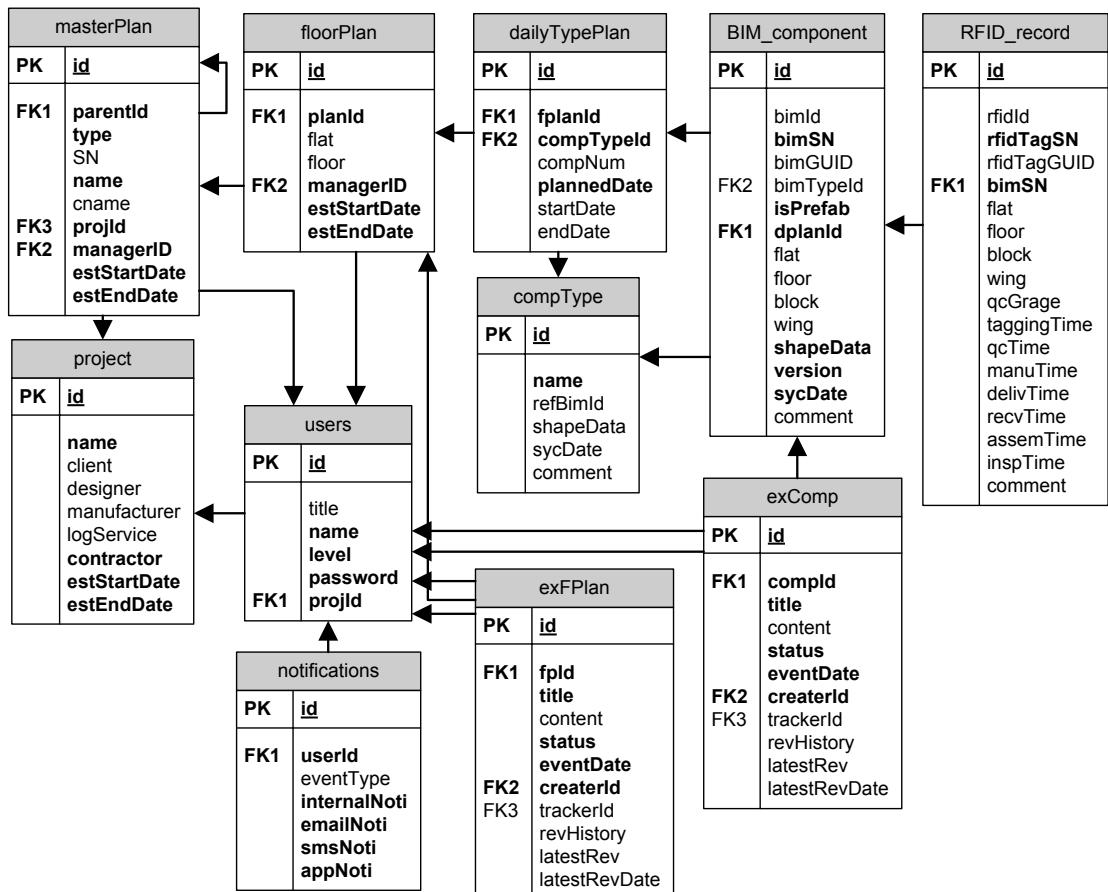
Naming convention	
	All codes prefer to the Hungarian notion.
Portability	Ease of moving to another system
	Can be used on all desktop computers and smart phones with modern browsers

382

383 **3.2.4 Logical database requirements**

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

392



393

394

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

396

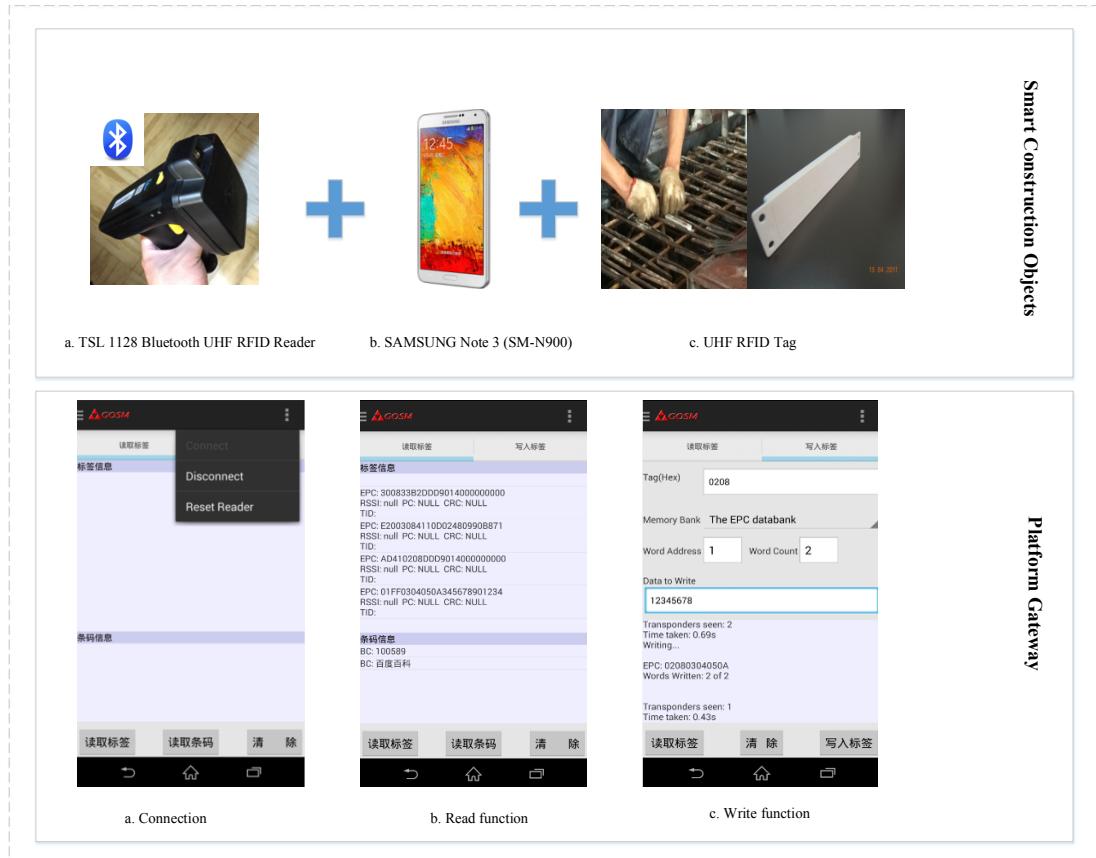
397 The highest amount of data, which is not exceeding 10^5 records (usually $<10^4$ for a
 398 building) for a project, is expected to be found in table “BIM_component” and
 399 “RFID_record”. However, the attribute “shapeData” in table “BIM_component” can be
 400 as large as $10^4\sim10^5$ bytes. So the total physical size of the database can be up to 10^{10}
 401 bytes (10GB) in assumed projects. The number of simultaneous users is expected to be
 402 less than 10.

403 **3.3 Smart construction object and smart gateway**

404 SCOs are typical construction resources such as tools, machinery, materials, which are
 405 converted into smart objects through binding them with different RFID devices, as
 406 shown in the Figure 8. The purpose of SCOs is to create an intelligent construction
 407 environment within the typical prefabrication production sites such as shop-floors,

408 warehouse, logistic and supply chain, and construction sites. SCOs are building blocks
 409 for such intelligent environment, within which they can sense and interact with each
 410 other. Thus, the processes of on-site assembly could be carried out smoothly.

411



412

413

414

415 Typical construction resources are converted into SCOs through various tagging
 416 schemes. Firstly, critical prefabrication components such as volumetric kitchens, toilets,
 417 precast facades, will be tagged individually. That means item-level tagging scheme is
 418 adopted because they easily influence the progress in prefabrication housing
 419 construction. For non-critical materials, such as dry walls, and building blocks, tray-
 420 level or batch-based tagging scheme is adopted. That means tags are attached to the
 421 trays which carry multiple minor prefabrication components. In the pilot study, the
 422 RFID tags, as shown in Figure 8, are Ultra High Frequency (UHF) tags protected in
 423 strong Acrylonitrile Butadiene Styrene (ABS) plastic cases and validated individually
 424 before planting. Each tag supported up to about 30 cm when embedding on the steel

425 ribbons inside concrete. A data operability of each was validated before planting. For
426 various workers, such as machine operators, vehicle drivers, logistics operators, and
427 on-site assembly workers, they are tagged with smart staff cards. These construction
428 resources attached with tags are passive SCOs. The deployment of RFID readers
429 follows a systematic approach. Once bound by RFID readers, they become active SCOs
430 that can sense and detect the passive SCOs. Both active and passive SCOs can sense
431 and interact with each other to create an intelligent construction environment. They
432 carry critical information that will be updated at different locations.

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

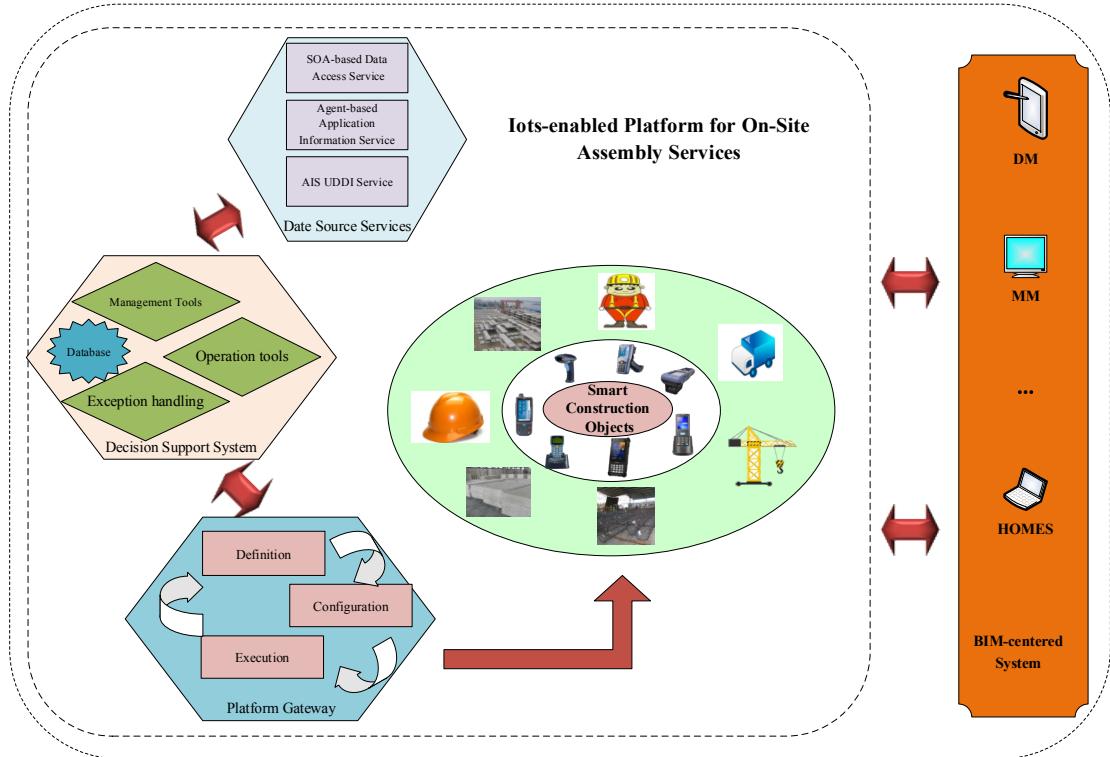
453 The Gateway uses an operating system named GOS to achieve a flexible, modularized
454 and re-configurable framework, where applications and solutions are designed and

455 developed as web services. GOS aims to provide an easy-to-deploy, simple-to-use and
456 flexible-to-access solution for the construction industry. Within the GOS, multi-agent
457 based models are used to ensure the versatility and scalability of Gateway. Therefore,
458 communication and interactions between SCOs and other services is facilitated by
459 using an XML/JSON-based message exchanging protocol.

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

468 **3.4 Overall architecture design**

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



480

481

Figure 9 Overall architecture design of the platform

482 **4. Practical application of the on-site assembly platform**

483 **4.1 Description of case study**

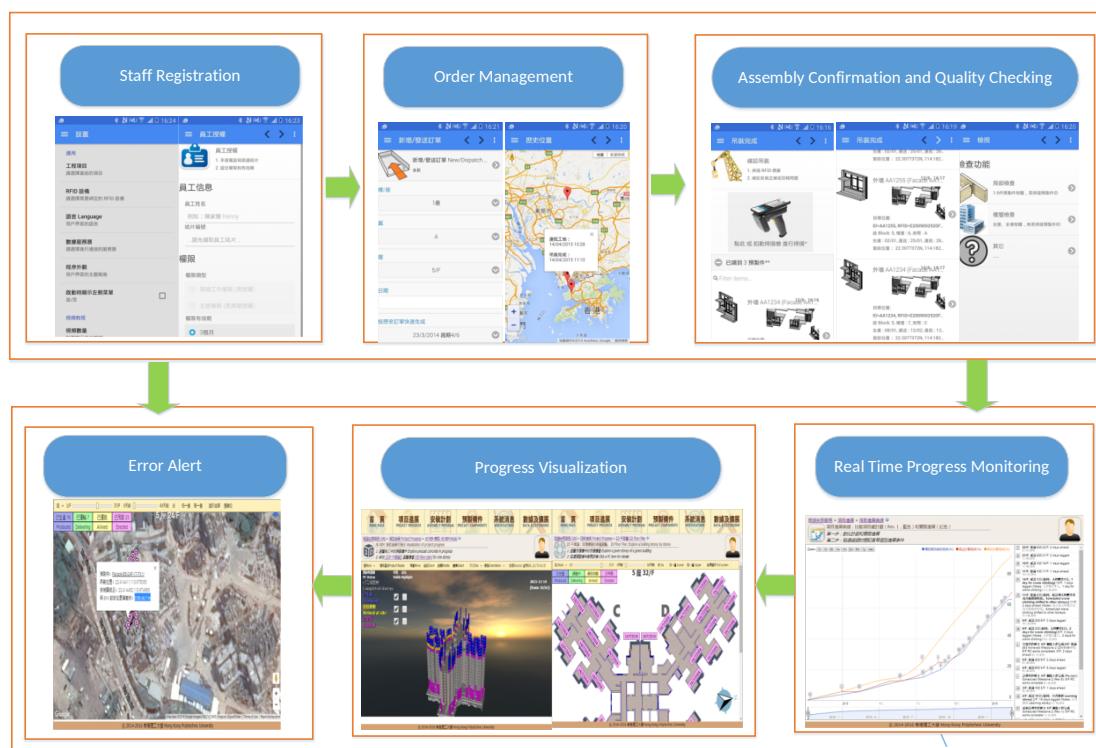
484 The Tuen Mun project (Area 54, TM54), initially designed by HKHA, proposes to build
 485 five 34-38 storey buildings, providing about 5,000 units and with the expectation of
 486 holding more than 14,000 people. The construction practice of the 8th-35th storeys of
 487 Block 5 of the Tuen Mun project were provided as case study by our partners, due to
 488 project period well meet our study. The period of the pilot study was initially set as 5
 489 storeys of Block 5, roughly from early October 2015 to November 2015. The period
 490 had later been extended to much more storeys (whole building) of Block 5 till the end
 491 of this research. To collect required data, a series of on-site visits and interviews are
 492 arranged and conducted toward concerned major stakeholders, including HKHA (Hong
 493 Kong Housing Authority) staff members responsible for housing production in the
 494 region, managers from precast manufacturers and logistics companies, engineers, and
 495 on-site managers of contractors. Besides, engineers who are familiar with the processes

496 of on-site assembly activities are trained to operate the developed devices to run the
497 platform for improving the productivity of OAS, and the management data are
498 automatically collected and uploaded to the platform in real time manner.

499 **4.2 Operational flow of the platform**

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

507



508

509 Figure 10 Working Logic of OAS

510

511 (1) Staff registration

512 The staff registration function offers on-site workers an efficient way of logging into

513 the system – by tap their staff cards instead of wasting time in typing passwords. This
514 service uses NFC (near field communication) technology (and their existing staff cards)
515 to identify corresponding workers, foremen, and on-site managers. Moreover, possible
516 violations of site safety regulations, and risks and dangerous activities, can be mitigated
517 for the operators on site.

518 (2) Order management

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

528 (3) Assembly confirmation and quality checking

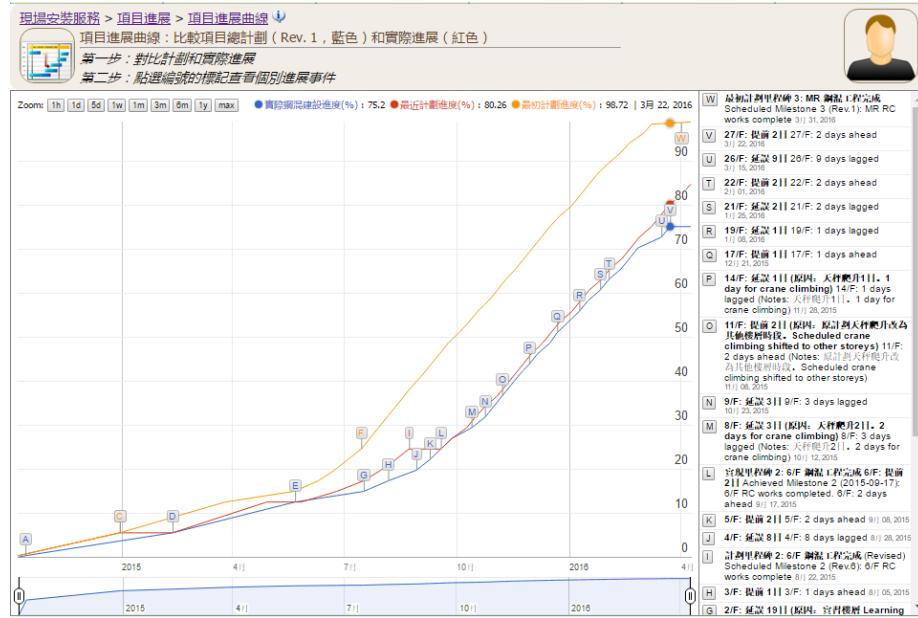
529 This function captures the real-time data of the precast element assembly upon site
530 installation in such a manner that allows meaningful and useful information to be
531 extracted. Once the required precast elements arrive at the site, these are assembled
532 onto the floor and are quality checked.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

538 (4) Real-time progress monitoring

539 The cumulative quantity of precast elements erected based on real-time data collected
540 and the contractor’s master program can be compared using a line chart to identify any
541 delay in site construction progress, as shown in the Figure 11. This service provides a
542 Gantt chart or a 3D virtual reality presentation that uses RFID assembly data to reflect

543 the construction progresses in real-time in terms of prefabrication assembly status,
 544 material consumptions and workers' assignments. The main users are HKHA and on-
 545 site supervisors responsible for controlling the construction objects and reporting to
 546 various stakeholders on the progress, current challenges or barriers.

547



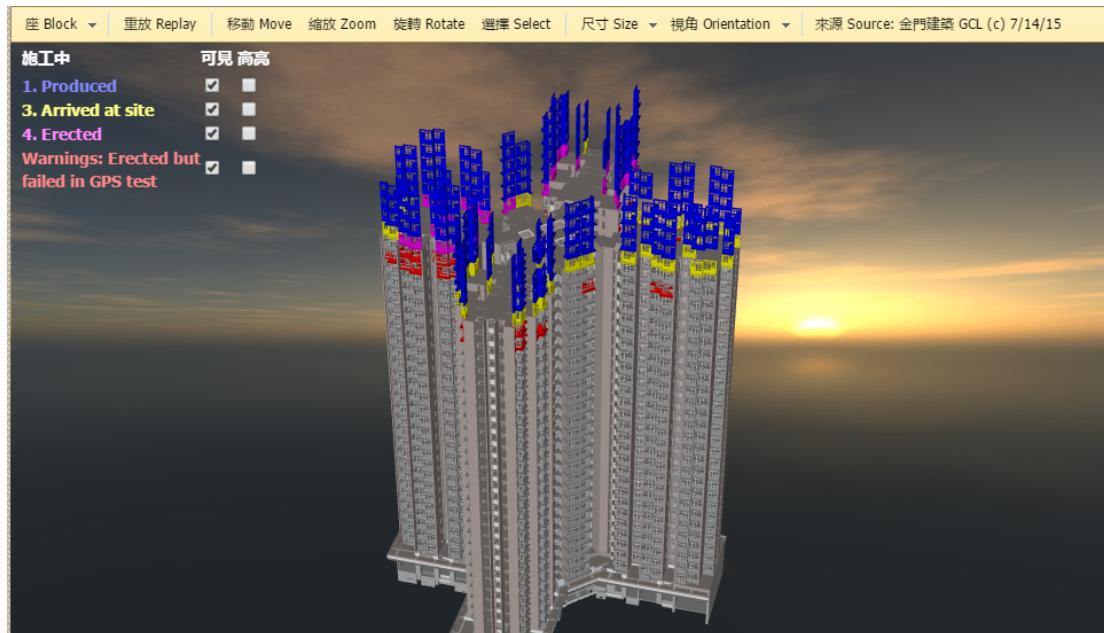
548
549 Figure 11 Function for real-time progress monitoring

550

551 (5) Progress visualization

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

559



560

561 Figure 12 Function for Progress visualization

562

563 (6) Error alert

564 This function is developed to detect the rightness of the assembly of precast elements.
 565 Every precast component has a unique serial number that binds with a specific RFID
 566 tag and is assembled at a specific location. Coordinates of the location where the RFID
 567 tag of precast element installed read with a mobile phone based on GPS can be
 568 compared to the design coordinates based on the BIM model, as shown in the Figure
 569 13. The deviation in position can be shown in meters. Any deviation larger than the
 570 reasonable tolerance in GPS can be identified manually as an error in precast element
 571 installation. Please be noted that because the layout of one typical floor of the studied
 572 building is quite large, with about 5,000 m² per floor, the minor deviation of GPS
 573 position data will not affect the error alert analysis of precast facades and the real-time
 574 data collection.

575



576

577 Figure 13 Function for precast component tracing and error alert

578

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

589 **4.3 Facts on mobile apps and OAS web application**

590 **4.3.1 OAS RFID data gathering APP**

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

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

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

606 Also, some challenges not addressed yet:

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

612 **4.3.2 WeChat OAS add-in**

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

618 **4.3.3 OAS web application**

619 The OAS web application is the main media of use the functions of OAS. It is designed

620 on HTML5 for modern browsers, so the technical issues listed below are about using
621 on PC browsers.

- 622 • The *nD*-BIM model related: (1) At the beginning stage, only façades were
623 displayed on the *nD* model: Later, the full precast model of Block 5 was provided,
624 and all reinforced concrete items were imported; (2) Model size too large (about
625 8MB for real-time frame). The size caused the slow loading: The WebGL data file
626 was redefined. Concrete belongs to the same family was referred to a data class.
627 The heavy class data file was cached as local storage of browser. In this way, the
628 model size was reduced to about 80KB; (3) 4D play-mode still too large (about
629 9MB) redefined “storey” classes (about 1MB).
- 630 • Menu: (1) The first version of menu appearance is plain style, CSS animation was
631 added in the later versions; (2) Menu items were regrouped by objects or functions.
- 632 • Progress curve: (1) The (Adobe Flash-based) chart is not working on iOS. It was
633 later changed to a Java script version; (2) Clues for days of delays were added. The
634 tip texts were converted from manual comments of master plan.
- 635 • 2D floor map / *nD* BIM only display latest frame: Filters were added on to the
636 toolbar for history data and full-screen / windowed form.
- 637 • RC volumes, important dates and plan revisions of each storey were included in
638 master programs (administration) management.
- 639 • A calendar based setup GUI was developed for delivery orders (administration)
640 management.
- 641 • A GPS data based location test was implemented for a coarse but automatic ways
642 of location checking.
- 643 • Hong Kong holidays and special non-working days such as black rain signal were
644 implemented for an automatic delay summary (administration) comments.
- 645 • Factory supply status is now available in both chart and text summary.
- 646 • Google Maps® was used for display of positioning and GPS.

647 **4.4 Summary of the application**

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

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

661 **4.5 Scalability testing of the platform**

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

672 **4.5.1 Overview**

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

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

678

679 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

680

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

686

687 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

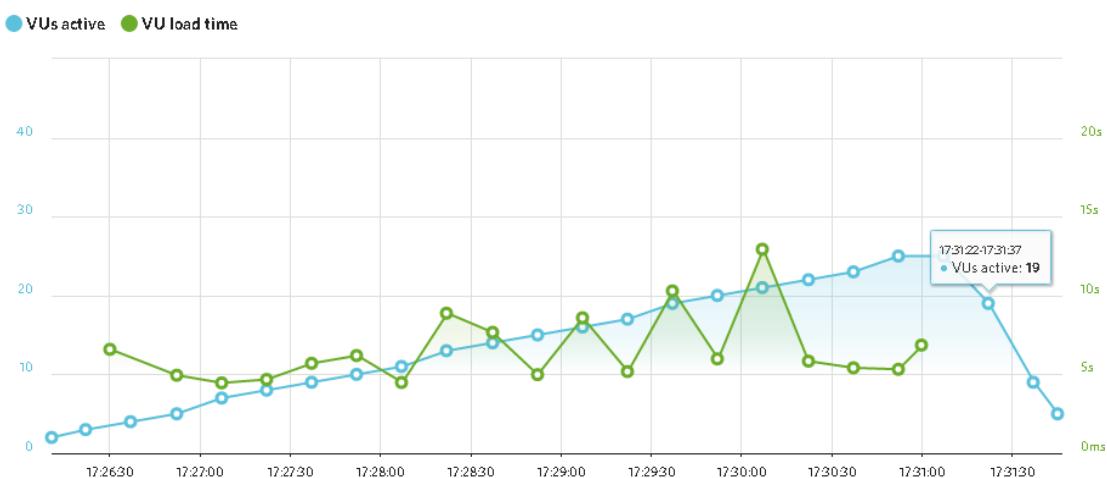
688

689 **4.5.2 Scale testing for different scenarios**

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

694 (1) Scenario 1 - Client 1 + shared server

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



698

699 Figure 14 Scale testing result from scenario 1

700

701 (2) Scenario 2 - Client 1 + shared server

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

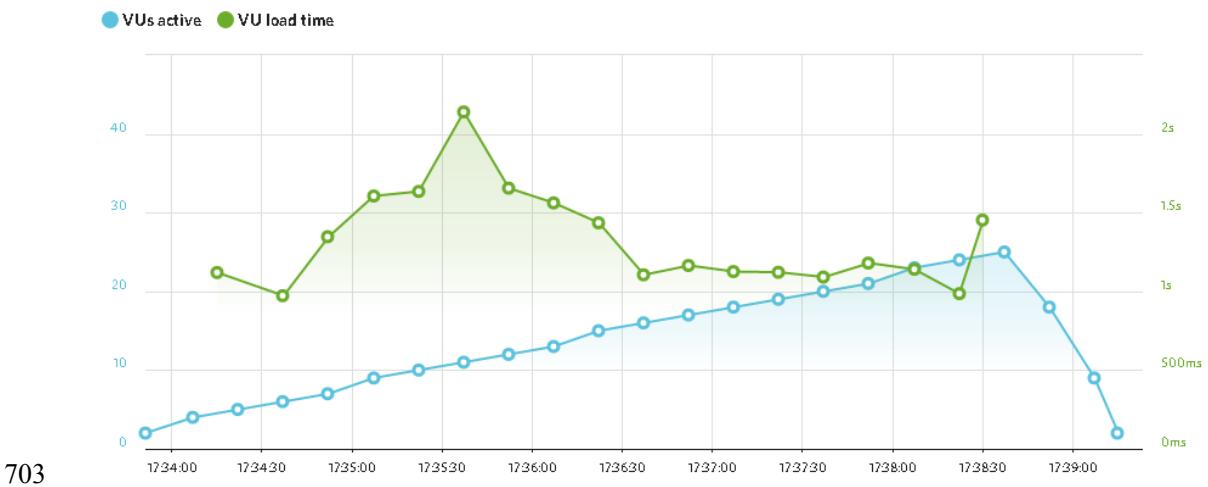


Figure 15 Scale testing result from scenario 2

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

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

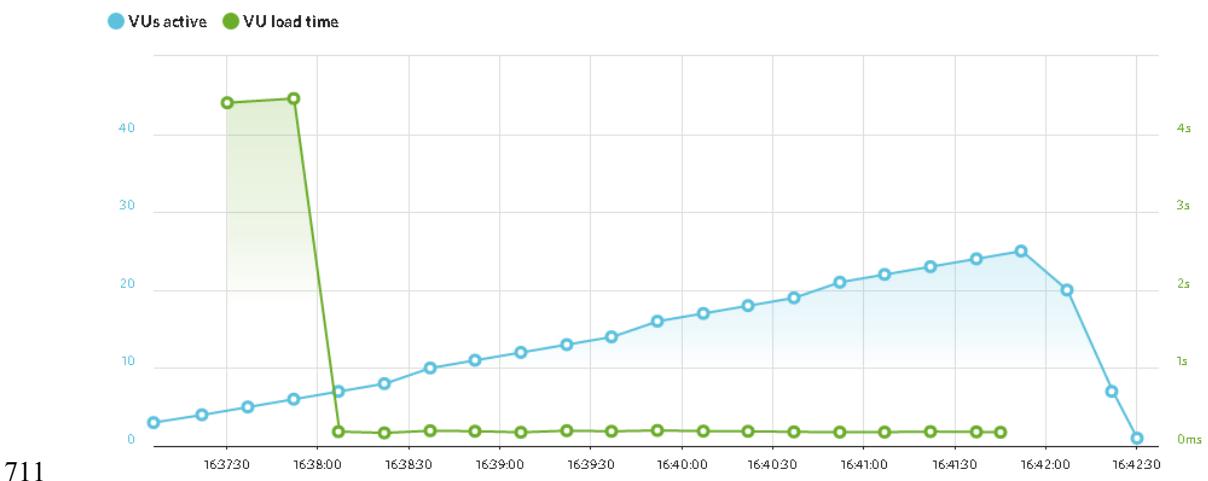


Figure 16 Scale testing result from scenario 3

713 (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.

719 **4.6 Technology integrity and scalability**

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

742 **5. Conclusions**

743 Over the years, HKHA has taken a leading role in developing and promoting the
744 application of ICT in general and BIM/ERP/RFID among construction stakeholders.
745 The architecture of the IoT-enabled platform has considered the business processes, the
746 stakeholders, the information flow, and the real-time information visibility and

747 traceability. It uses the service-oriented open architecture as a key innovation to enable
748 the platform as a service. Given its potential to manage building information throughout
749 processes of OAS, IoT-enabled platform is considered as significant part of the
750 HKHA's overall ICT architecture, which aims to reengineering the OAS of
751 prefabricated construction in Hong Kong.

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

770 Despite the various benefits, the limitations of the developed platform in the research
771 should be also outlined for its further development and broader application. Due to the
772 limitations of resource, this research only applies the developed platform to only one
773 practical project for testing its effectiveness. Besides, this research focus more on the
774 development of the functions related to schedule and cost management, while
775 management of safety, quality and construction environment are also important for
776 prefabricated construction project. Despite of the above limitations, the research not

777 only pioneers on developing a platform for on-site assembly services of prefabricated
778 construction with integration of Internet of Things and BIM from a new perspective,
779 but also serving as a solid basis for further research, which may include: improving and
780 extending the applicability of the platform to more practical project to enhance its
781 effectiveness; improving the platform by incorporating more functions related to the
782 management of safety, quality and construction environment.

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789

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