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Customization of On-site Assembly Services by Integrating the Internet of Things and BIM Technologies in Modular Integrated Construction

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Abstract

Modular integrated construction (MiC) has attracted considerable attention for accelerating the delivery of public housing projects in Hong Kong. Building information modelling (BIM) serves as a powerful tool in facilitating on-site assembly services (OAS). However, challenges still exist in deploying BIM owing to inefficient data capture methods, inadequate progress monitoring, and lack of automatic decision support. This paper proposes an Internet of Things (IoT)-enabled smart BIM platform (SBIMP) for OAS by integrating IoT, BIM, and computing technologies to address these issues. A trial project located in Hong Kong was deeply investigated and probed to develop the platform. Smart construction objects (SCOs) equipped with STT and GPS sensors are defined and configured to enable an efficient and reliable data collection process. The smart gateway system prompts seamless and timely information sharing and interchange among different stakeholders to support the decision-making process. The application scenarios have demonstrated the effectiveness of SBIMP.

Keywords: Internet of Things (IoT), Building Information Modelling (BIM), Modular Integrated Construction (MiC), On-site Assembly Services

1. Introduction

The scarcity of residential land supply, along with the increase in the population, has posed significant challenges to the construction industry of Hong Kong, one of the most densely populated cities in the world (Jaillon and Poon, 2009, Li et al., 2018). Hong Kong is a compact city with over 7.5 million people and covers only 1,106 square kilometres of the area with a population density of 6,777 people per square kilometre (Census and Statistics Department, 2019). The congested living environment is intensified because only 24.9% of land areas are buildable, with only 3.8% for residential use (Planning Department, 2019). Due to the limited availability of land and expensive land prices, high-rise buildings with prefabricated construction are prevalent in Hong Kong, with approximately 50% of the population residing in public rental or subsidized housing (Jaillon and Poon, 2008). To address these housing shortages, the Hong Kong Housing Society (HKHS) has developed a total of 89 housing schemes serving 131,692 units for low-income residents (HKHS, 2019). Additionally, the Hong Kong Housing Authority (HKHA) also set up a ten-year construction scheme to offer 315,000 public housing units from 2019/20 to 2028/29 (HKHA, 2019). Despite these efforts, however, the Hong Kong construction industry has been facing increasingly pressing challenges in improving labour productivity, decreasing construction costs, shortening construction schedules, achieving better safety, and environmentally friendly construction (Li et al., 2016, Zhong et al., 2017).

Prefabricated construction as a solution to housing straits has been progressively gaining impetus and widely adopted in the public housing projects of Hong Kong due to its underlying benefits of a more efficient and productive production process and a safer and cleaner working environment (Gibb, 1999, Gibb and Isack, 2003, Tam et al., 2007, Chen et al., 2015, Tam et al., 2015, Li et al., 2017). Over the past two decades, Hong Kong has witnessed an expanding adoption of offsite fabrication construction through public housing schemes. With the aim of raising the prefabrication rate of public housing construction and enhancing site productivity, the innovative concept of modular integrated construction (MiC) was recently introduced in the construction industry of Hong Kong, accompanied by the development of advanced production techniques and equipment (Warszawski, 2003, Jaillon and Poon, 2009, Construction Industry Council, 2019).

Modular integrated construction is defined as a form of innovative offsite construction approach where a building's free-standing integrated components or modules (completed with finishes, fixtures, and fittings) are produced and assembled in the manufacturing plant setting before being delivered to site for installation (Building Department, 2019). Pan and Hon (2018) defined MiC as a game-changing, disruptive groundbreaking method to transform fragmental cast-in-situ construction of a building or facility into integrated value-driven production and fabrication of prefabricated modules. Three categories of offsite construction, nonvolumetric, volumetric, and modular buildings, were demonstrated by Gibb (1999). Nevertheless, he argued that there exists a controversial line of dividing each type. MiC generally involves a higher ratio of prefabricated modules and deploys large numbers of integrated free-standing modules (Zhai et al., 2019). As a solution to the widespread discontent of housing problems in Hong Kong, the MiC drew considerable attention both in industry and academia once it appeared. In an MiC project, efficient collaboration strategies among different stakeholders for on-site assembly service (OAS) should be excessively investigated and improved to facilitate delivery (Pan et al., 2018, Li et al., 2018). Fragmented and burdensome on-site activities typically impede the performance of OAS.

However, a well-formatted information exchange platform needs to be explored and developed to ensure strong coordination and timely communication among cross-interdisciplinary professionals, such as prefabricated module manufacturers, module carriers, and on-site builders. Building information modelling (BIM) is typically deemed an effective implementation to foster information exchange and enhance interoperability from the initial inception design stage to demolition (Lu and Li, 2011). Babič et al. (2010) deployed BIM as a linkage tool between enterprise resource planning (ERP) information systems to integrate the design, manufacturing, and construction processes. Chen et al. (2015) demonstrated the potential to utilize BIM to enhance collaborative working environments and decision-making processes. However, the manually captured data are apt to be incomplete and improper, which cannot provide efficient and timely support for the decision-making process, leading to poor traceability in the OAS. To address these problems, some cutting-edge technologies have been employed to enhance the feasibility of real-time information exchange and decision support activities. The Internet of Things (IoT) was introduced to facilitate information collection and progress monitoring processes, such as radio frequency identification (RFID) and global positioning system (GPS) (Shahi et al., 2013, Li et al., 2017). Cloud computing is another core technique equipped with a shared pool of configurable computing resources that can be quickly provisioned and released with minimal effort or service provider interaction (Xu et al., 2018). The IoT has gradually become a promising technology for connecting various smart devices and objects with self-configuration capabilities to construct a global network (Karunanithy and Velusamy, 2020, Da Xu et al., 2014). Smart devices can be considered a set of standard and interoperable communication protocols with unique identities and attributes (Zhang and Chen, 2020). For example, Li et al. (2018) adopted IoT and cloud technology based on a centralized BIM platform to realize real-time visualization and traceability of prefabricated modules. By applying RFID tags and GPS sensors, information such as the location or status of the prefabricated modules can be easily obtained and shared by different stakeholders. The transferability of three interaction modes that integrated MiC and construction robotics was identified by Yang et al. (2019). The findings laid a theoretical foundation for the government to investigate and facilitate the implementation of innovative building technologies.

Although the preceding efforts can be supportive references for integrating BIM and other core techniques, challenges still exist that deteriorate site productivity and hinder the performance of the IoT-enabled BIM platform. In addition, scholars advocate that more studies should be investigated into the quick and accurate decision-making process (Chen et al., 2010), systems integration and collaboration (Shen et al., 2010), and comprehensive information collection approaches (Lu and Lee, 2017). Arising from the literature, we conduct several investigations into practical MiC projects, probing the difficulties encountered by construction practitioners during the on-site assembly process. It was found that construction professionals typically suffered from poor site productivity, insufficient supervision towards progress, insignificant labour-consuming activities, duplicated work, and tardy reactions facing emergences. In general, three primary challenges are identified to be the major causes of previous hardships, namely, inefficient data capture methods, ineffective progress supervision, and lack of automatic decision support. First, on-site operators mainly rely on paper-based and hand-operated approaches to collect and share data, which is time consuming and error prone. Large quantities of project data, such as specific information on prefabricated modules, available storage space, rectification and inspection records, are involved and supposed to be addressed in the MiC project. As proposed by Li et al. (2018), the embedded tag would cause information loss due to the likely failure of a single type of auto-ID tag. The hand-held RFID reader is cumbersome and hard to use for an on-site foreman in a compact space. The second challenge is ineffective progress supervision. As proposed by on-site end-users, four-stage supervision (Li et al., 2018) may not adequately present the real progress of the MiC process. The management of buffer control should be incorporated into the system to better manage the limited site buffer. Thus, just-in-time delivery with close monitoring is vitally essential for a project with a small buffer space and high tardiness cost. The third problem refers to a lack of automatic decision support and an information-sharing system. On-site managers are restrained owing to the deployment of conventional communication tools such as phone calls, MSG, or email to share information and assign tasks among different practitioners (Zhong et al., 2017). When any unexpected events occur, such as the delay of delivery or mislocated modules, managers might fail to perceive them and make quick decisions within a dynamic and fragmented working environment. The implementation of BIM technology can only record these events but fails to afford automatic decision support and send notifications to the involved parties.

To address these issues, an IoT-enabled smart BIM platform (SBIMP) is developed in this research by applying advanced technologies. Several tracking and sensing techniques are employed in the SBIMP. First, automatic and complete information collection is realized by smart construction objects (SCOs) (e.g., prefabricated modules, machines, workers, on-site buffers, and vehicles) equipped with smart trinity tags (STTs) and GPS sensors. The STT tag integrates the QR (quick response) code, RFID tag, and NFC (near field communication) tag into one smart tag. Second, the smart gateway system and data source management service (DSMS) are developed and utilized for information storage, exchange, communication, and management. Third, the location-based service (LBS) and rule-based progress control service (RBPCS) are assumed to provide value-added applications and automatic decision-making support. The cloud-based BIM is employed by integrating BIM and computing technology to allow end-users to monitor and alter the BIM model in real time. This paper aims to 1) survey and analyse the business process of on-site assembly and demonstrate the customized features of OAS systems in MiC projects, 2) design the architecture system and exploit the Internet of Things-enabled smart BIM platform, and 3) deploy the smart platform in a real-life project to demonstrate its performance and efficiency.

Following this introduction, Section 2 outlines the business process analysis of the MiC project and identifies the problems and requirements through field interviews during the customization of the OAS management system. Section 3 proposes the development of the SBIMP system and the OAS decision support system. Section 4 describes the real project to present and demonstrate practical application. Feedbacks collected from end-users are described in Section 5. Conclusions are displayed in Section 6.

2. Business process analysis and customization of SBIMP

This section aims to explore the business process, ascertain the requirements and problems confronted by on-site practitioners, and propose possible solutions and customization plans. After investigating several MiC projects in Hong Kong, the Subsidized Sale Flats Project at Tseung Kwan O Area 73A was selected as the target project due to the rationality and feasibility of developing the SBIMP system and conducting pilot implementation. The research team conducted four rounds of field study and interviews during January and December 2018. The interviewees included major stakeholders, namely, the client, the main contractor, the offshore manufactory, and the cross-border logistics company. The associated findings can lay a solid foundation for developing and customizing the IoT-enabled smart BIM platform.

2.1 Background of the target project

The Housing Society has been regarded as a devoted housing provider, aiming at continuously demonstrating and solving the housing requirements of the public and probing housing strategies coordinated to their needs. To date, a total of over 71,000 units have been built upon various housing schemes, including Rental Estate, Rural Public Housing, Urban Improvement Scheme, Flat-for-Sale Scheme, and Subsidized Sale Flats Project. The housing department is responsible for managing public housing estates that are built by HKHS, which is a non-government organization aiming to afford the resources of housing and relevant services in Hong Kong. The target project is the Subsidized Sale Flats Project at Tseung Kwan O Area 73A, as presented in Table 1, which aims to build one residential tower of 33 stories that provides 330 flats (1 to 3 bedrooms) with 1020 units, including one basement (car park, plant room), 4-level podium for commercial shops, car parks, landscape areas, plant rooms, podium gardens, and multifunctional rooms. The prefabricated modules are adopted in HKHS's project, which incorporates nine different kinds of modules to form 26 different types of modules, as shown in Table 2.

Table 1 Description of the target project

Project Title	Subsidized Sale Flats Project at Tseung Kwan O Area 73A
Project Scope	Basement (Car Park, Plant Room) G/F (Shop/Plant Room/Landscape Area) 1/F (Commercial Shop, Landscape Area, Plant Room) 2/F (Government Accommodation/Plant Room) 3/F (Podium Garden/E&M Zone/Recreational Facilities) Transfer Plate 2650 mm depth at 3/F 33 Storeys Residential Tower 330 Flats (1 to 3 Bedroom) Roof Landscape Area
Contract Commencement Data	10-Oct-17
Completion Date	29-Nov-19
Project Duration	780 Calendar Days + 1 Day EOT
Contract Sum	Approx. HK$477,700,000
Green Area	530 m^2
Building Height	117 m

Table 2 Summary of prefabricated modules in the target project

Elements Name	**Type**	**Flat**	**Floor**	**Quantity**	**Subtotal**
Prefabricated Modules	A-B-01	A	4F-36F	1	33
	A-G1-02	A	4F-7F	1	29
	A-G2-02A	A	8F-36F	1	4
	A-A-03	A	4F-36F	1	33
	B-C2-04	B	4F-36F	1	33
	B-C1-05	B	4F-36F	1	33
	B-H-06	B	4F-36F	1	33
	C-D-07	C	4F-36F	1	33
	D-I2-08	D	4F-36F	1	33
	D-I1-09	D	4F-36F	1	33

	E-I1-10	E	4F-36F	1	33
	E-I2-11	E	4F-36F	1	33
	F-A-12	F	4F-36F	1	33
	F-G2-13	F	4F-36F	1	33
	F-B-14	F	4F-36F	1	33
	G-E2-15	G	4F-36F	1	33
	G-E1-16	G	4F-36F	1	33
	G-F2-17	G	4F-36F	1	33
	G-F1-18	G	4F-36F	1	33
	H-D-19	H	4F-36F	1	33
	J-H-20	J	4F-36F	1	33
	J-C1-21	J	4F-36F	1	33
	J-C2-22	J	4F-36F	1	33
	K-A-23	K	4F-36F	1	33
	K-G2-24	K	4F-36F	1	33
	K-B-25	K	4F-36F	1	33
Total				**26**	**825**

2.2 Business process analysis

The related business processes of the whole target project are presented in Fig. 1. It starts with the design stage, which produces the design drawings with the BIM model, and finally, the scheduled master plan. Three primary phases are involved in the process after the approval of design drawings and completion of the scheduled master plan, namely, the production stage, logistics stage, and on-site assembly stage. The responsibilities of the production stage are mainly for 1) making a production plan based on the master schedule and actual project progress, 2) preparing the required materials grounded on the production schedule, 3) producing the prefabricated modules with conformed quality, and 4) appropriately storing the finished products for transportation. Cross-border logistics is the linkage between the production phase and the on-site assembly phase, which fulfils the tasks of delivering the manufactured modules from the manufacturing plant to construction sites for installation. The tasks include 1) making transportation schedules based on the delivery order, 2) assigning delivery orders to trunk drivers, and 3) monitoring the delivery process and arriving on time. On-site assembly is the last step for the MiC project. After the production of prefabricated modules in the manufactory and then delivered through cross-border logistics to the construction site, the field operators set out to perform the installation work.

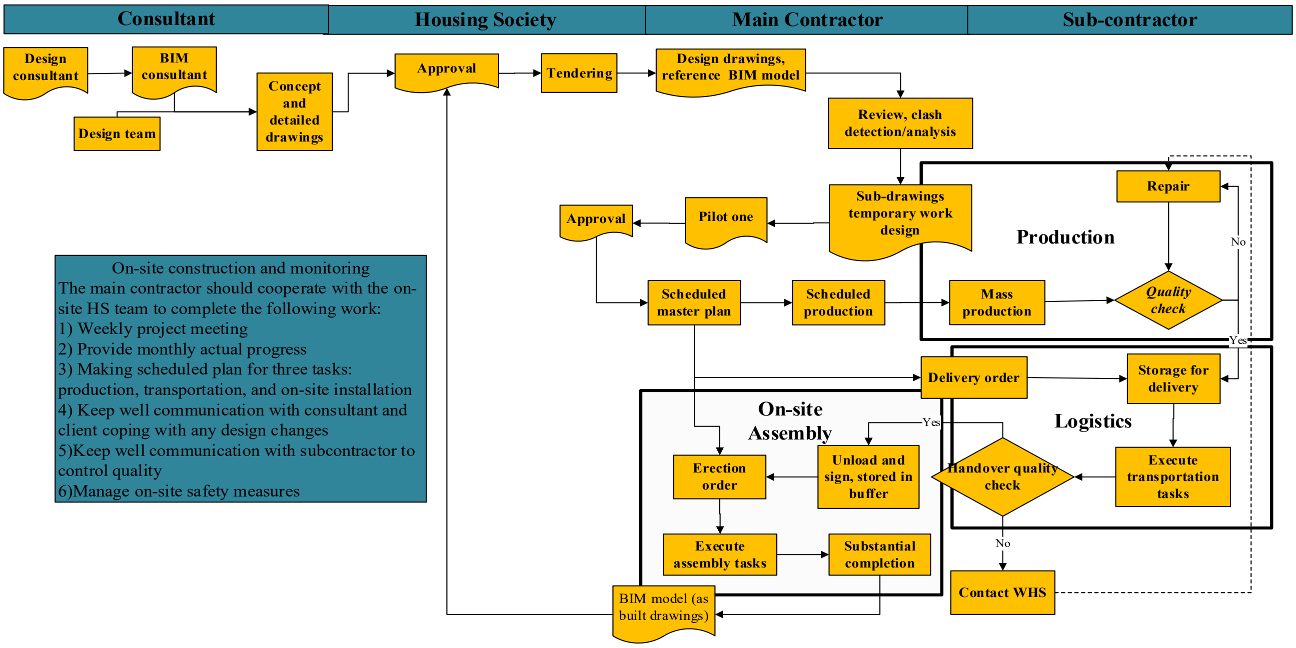

Fig. 1. The business process of the target project

2.2.1 On-site assembly process analysis

To outline the business needs and requirements of the on-site assembly process and to further determine solutions to the identified challenges, a detailed business process analysis should be conducted by group and individual interviews and frequent site observations. The on-site assembly process can be categorized into four main stages by purpose, as described in Fig. 2. The first stage is the site facilities set up and operation, which aims to provide adequate resources and a safe working environment to on-site practitioners, such as establishing accommodations, office rooms, maintaining site security, and setting site boundaries. Temporary works include preparation works such as tower crane erections, material and passenger hoist erections, and other temporary metal working platforms. The R.C. structure construction stage is the main focus of the on-site assembly process. It covers the podium structure (B/F - G/F including basement tanking system; G/F - 2/F; 3/F - 4/F E&M zone and transfer plate) and tower structure (4/F – R/F slab; bamboo scaffolding erection). It should be noted that the tower crane needs to be escalated after the completion of slabs (13/F, 18/F, 23/F, 28/F, 33/F). The construction duration of one typical floor from 5/F to 6/F is considerably longer (23 days and 19 days, respectively) than 6/F above due to the learning storey of deploying prefabricated modules in an MiC project. The third stage is architectural finishing works and external landscaping works, which include tower finish tasks, podium finish works and external finish works. After the R.C. structure construction works and architectural works and building service-related electrical and mechanical works will be installed, mainly including (1) fire service installation work, (2) plumbing drainage installation work, (3) MVAC (podium and tower) installation work, (4) electrical and ELV installation works, and (5) lift shaft and lift machine room installation.

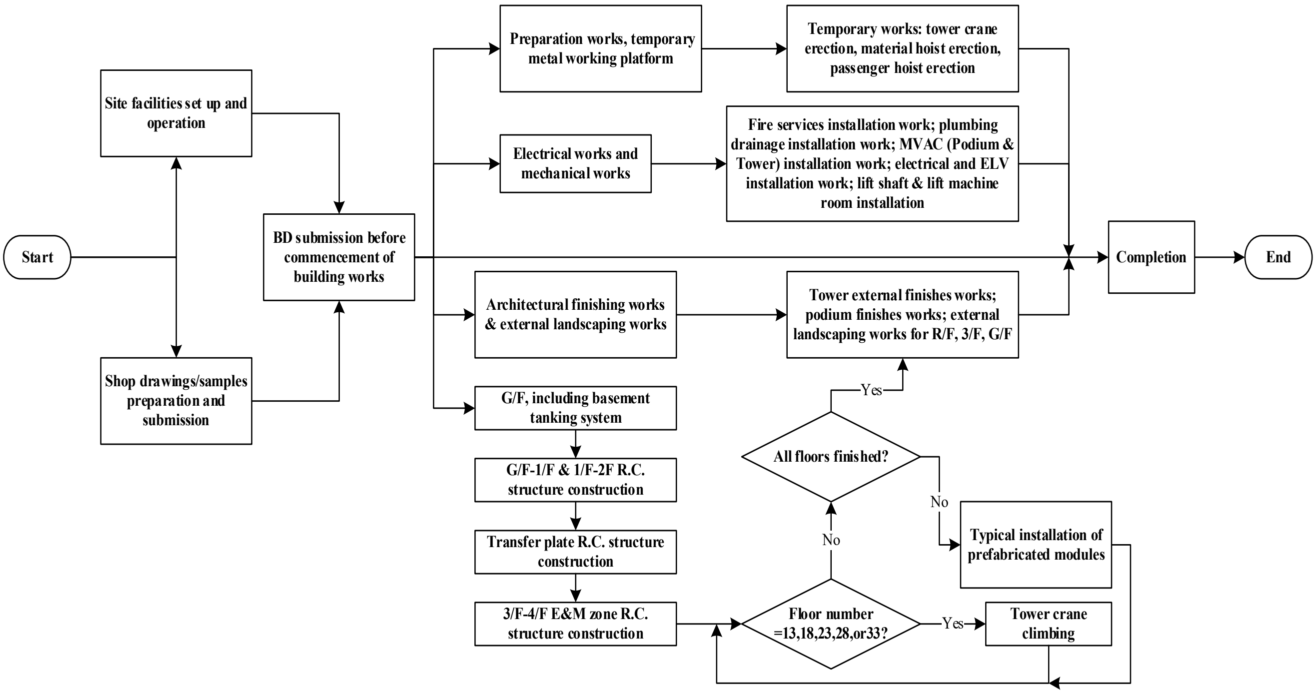

Fig. 2. The workflow of typical floor construction with prefabricated modules

The workflow of the prefabricated module on-site assembly process can be divided into three stages. First, the operator at the laydown yard inspects the prefabricated modules after receiving them. If rectification is needed due to some flaws or defects after delivery, the operator notified the on-site senior managers personally or via call and email. The module manufacturer is contacted using the same methods for further actions, and the relevant process and information is manually recorded. After quality inspection, the qualified modules are stored in the laydown yard, waiting for erection the next day. Later, the prefabricated modules are hauled for installation by a crane tower. In a standard installation, a prefabricated module is adjusted horizontally and then vertically. Inspection is executed after completed assembly and concreting. Thus, this prefabricated module on-site assembly came to an end. The operator uses inspection forms to record the installation and inspection process. In this case, two zones of prefabricated modules are delivered and installed in turn. Two laydown yards are generally located close to the target building for the accessibility of the tower crane and conform to the site layout plan for the erection of prefabricated modules. In general, the construction foremen coordinate the scheduled actions and supervise the whole erection process in case of emergency events.

2.2.2 Problems and challenges identification

Based on the business process analysis, after several rounds of site visits, discussions with major stakeholders, including the client, the main contractor, and the subcontractors, are conducted. There are still some challenges during the on-site assembly process that remain to be solved during the whole installation process of the prefabricated modules. First, upon arrival, conventional manual scans and paper-based records are customarily employed during the handover process. Information on the arrived modules, such as type, location, and quality, is hand-marked with the paper-based format, which is perceived as time consuming and error prone when retrieving or re-inputting the data. If the received modules require rectification, the operator informs the on-site managers and contact the manufacturer and trunk driver via MSG, call, or email, which has an adverse effect on the installation process owing to the inefficient and untimely manner. In addition, the operator cannot retrieve large numbers of modules from laydown yards, such as buffers, when required for efficient assembly. Due to the limited storage space and tight schedule, the modules must be unloaded, stored, retrieved, and hauled promptly. Moreover, the on-site workers of the previous pilot project gave their feedback about the difficulties in scanning the RFID tags accurately and sometimes failed to obtain data due to the broken tag or information loss. Overall, the intrinsic tediousness and tendency towards error and failure associated with the tracking process adversely affected the motivation and efficiency of on-site operators. Second, if any unexpected events occurred, such as delivery delays, schedule changes, and on-site machine breakdowns, they can adversely affect the working efficiency and hinder the installation process. The corresponding stakeholders cannot be notified immediately and make associated decisions in time. Delay response can cause installation lag, leading project duration, and cost overruns, as stated by the on-site interviewees. Third, because of the tight schedule and compact buffer space, on-site managers usually fail to reallocate resources and take prompt actions to coordinate with other upstream or downstream stakeholders in a timely manner. Real-time information exchange and sharing systems need to be improved to streamline the on-site assembly process with enhanced coordination and cooperation.

2.3 Customization of on-site assembly service (OAS)

To address the issues mentioned above, the research team conducted several in-depth interviews and discussions with the primary end-users. Findings and observations are summarized below:

(1) Due to the possible failure or loss of the RFID tag, the smart trinity tag, which includes RFID, NFC, and QR code, is deployed in this project. If the RFID tag is out of work, the QR code could be utilized to capture data and keep track of information. The smart tag is glued on the interior surface of prefabricated modules, and the position is on the left-hand side of prefabricated modules, 1,200 mm above the structure floor level (S.F.L).

(2) After comparing the hand-held RFID reader with the wearable RFID reader and based on the experience of the operators, the wearable reader is deemed more convenient and portable to capture data. The wearable RFID reader reads data stored on the tags and then sends data to the attached cell phone via self-connecting Bluetooth

(3) Considering that the client and the main contractor showed extreme concern about the real-time monitoring of prefabricated modules, a six-stage strategy is employed in the MiC process, namely, producing, produced, delivering, arriving, ready to install, and installation.

(4) Real-time supervision of the storage area is envisaged to enhance the efficiency of resource utilization and installation processes owing to the limited laydown yard space.

(5) A notification service is added to the system to make all parties involved keep well informed and make associated decisions collaboratively. It allows related stakeholders to perceive current progress and status in a dynamic and changing environment.

Based on the requirements of corresponding stakeholders, the proposed features intend to establish an IoT-enabled SBIMP serving OAS. With the assistance of the IoT technique and cloud BIM technology, SBIMP can improve the efficiency and reliability of the information collection process, realize real-time visibility and traceability, support collaborative decision making and rapid action for unforeseen events, and enhance coordination and cooperation among all stakeholders. Details of the customized features of OAS are presented in Table 3.

Table 3 Summary of required customized features of OAS

No.	Category	Designed Features of OAS	Priority
Functional Features			
1	Order tracking	Required to track the prefabricated module delivery (with or without ID) for the current working day, and the next time of delivery on one floor (4-day cycle for typical floor construction)	**Preferred**
2	Laydown yard	Must be aware of whether the modules are successfully delivered	**Must-Have**
3	Laydown yard	Must be aware of the allocation of the corresponding materials and assembly crew	**Must-Have**
4	Laydown yard	Must be aware of the accurate location of on-site materials	**Must-Have**
5	Laydown yard	and able to retrieve the prefabricated modules when required for inspection or installation	**Must-Have**
6	Installation inspection	Must be aware of modules are hauled and installed completely	**Must-Have**
7	Installation inspection	Be aware of the GPS location of installed modules	**Preferred**
8	Rectification	Must be aware of the completion of defect rectification	**Must-Have**
9	Data collection	In case of the failure of the RFID tag, a QR code can be used to collect and record information	**Must-Have**
10	Notification	Automatic SMS, email, website system, or Android/iOS notifications or alerts on modules delivery/installation/unforeseen events	**Preferred**
11	Notification	Automatic SMS, email, website system, or Android/iOS notifications or alerts on the abnormal status of materials and workers	**Optional**
12	Installation inspection	Multiple scanners or floor partitioning for scanning	**Optional**
13	Installation inspection	Random order scanning within one floor after inspection	**Preferred**
14	Installation inspection	Digital or vocal signature of inspector	**Optional**
15	Installation management	Be aware of uploading and synchronizing on-site photos and scanned data	**Optional**
16	Installation management	Able to record operators' GPS locations of delivery and erection as EXIF in JPG images and automatically retrievable as supplementary location information	**Optional**
17	Installation management	Electronic file sharing of related documents or drawings such as shop drawings, material approval forms, inspection reports or progress reports	**Preferred**
Non-Functional Features			
1	Performance	Availability of real-time data and status	**Preferred**
2	Performance	Availability of real-time feedback	**Preferred**

3	Availability	Accessible through wireless/wired network out of office/site	**Must-Have**
4	Availability	Accessible on iOS/Android smart devices	**Preferred**
5	Security	One shared input to account for one zone/building	**Preferred**
6	Security	Binding PC/Phones' IP/MAC ID address for/HS's access	**Optional**

3. Overall system architecture

Three interactive service models are exploited to support the IoT-enabled smart BIM platform for on-site assembly services, namely, the infrastructure as a service layer (IaaS), platform as a service layer (PaaS), and software as a service layer (SaaS). The overall system architecture of the IoT-enabled smart BIM platform is presented in Fig. 3.

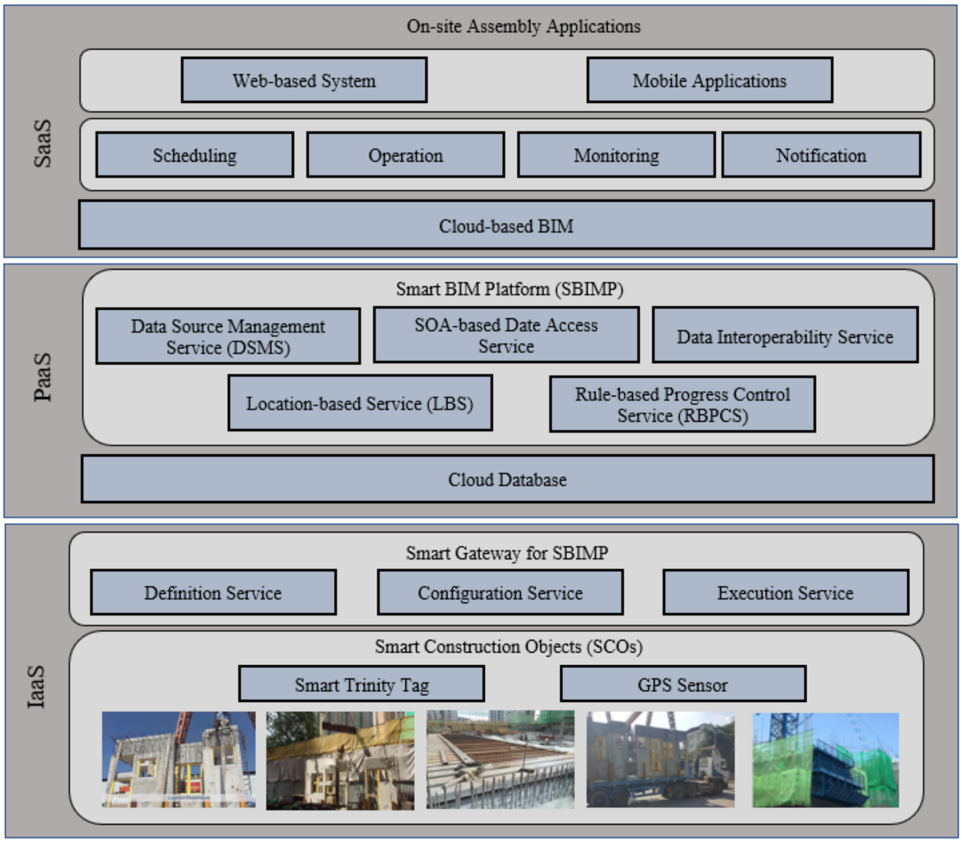

Fig. 3. The system architecture of OAS in SBIMP

3.1 Infrastructure as a service layer

The IaaS layer comprises smart construction objects (SCOs), as shown in Fig. 4, and the smart gateway system. Construction resources, such as prefabricated modules, trucks, operators, machines, and laydown yards, are transformed into IoT-enabled smart objects by labelling with STT auto-ID tags and GPS sensors. Unique data strings and numerics are stored in the STT tags. To avoid possible information loss and obtain reliable information access, three different identification tags (RFID, NFC, and QR code) are utilized in the MiC project. In the case of a single tag failing, the other two will ensure that information is not lost. During the system definition stage, the unique identifiers of each object will be encoded with a unique string of data that is consistent among the three tags. The identification encoding is then sorted into the central cloud database that is now able to recognize attribute data collected from wearable RFID readers and hand-held NFC or QR code readers. Additionally, GPS sensors are employed to capture real-time location-based data of construction objects, leading to the development of location-based services in PaaS.

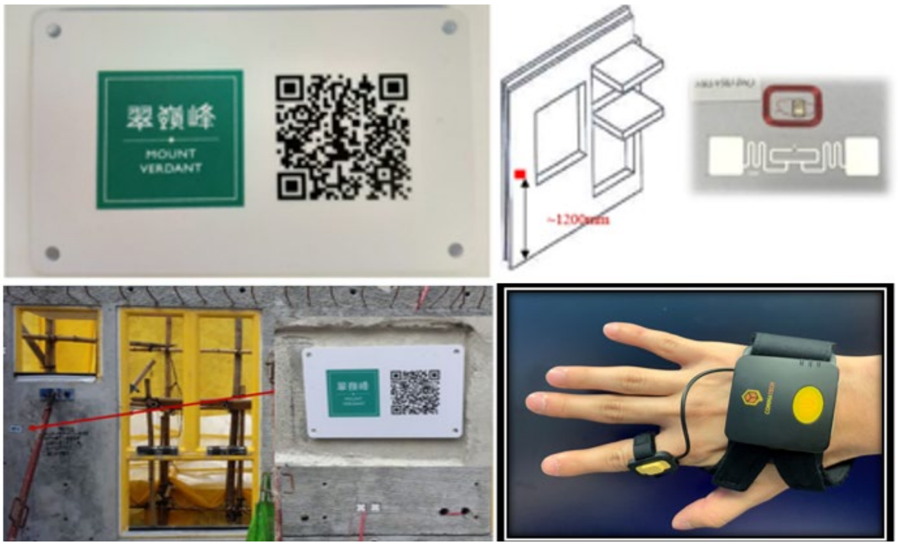

Fig. 4. Smart construction object

A middleware system operates as a smart gateway that runs on fixed workstations or mobile devices. The gateway is an IoT-enabled industrial computer that fulfils several essential functions in SBIMP. First, it links and manages a batch of SCOs via wired or wireless communication standards and allows operators to define, configure, execute on-site assembly tasks in a user-friendly manner. Second, it functions as a bridge that interacts with the defined SCOs and the upper-level cloud-based database and decision support systems in PaaS, enabling seamless synchronization of real-time data captured from SCOs and presented in a standardized scheme. Third, in the case of communication problems with the central system, real-time data can be processed and stored locally and provisionally in the gateway and updated automatically when the connection is secure. The smart gateway system and SCOs perform as a management mechanism to ensure real-time information collection, sharing, exchange, and monitoring, thus supporting decision-making systems. The XML/JSON (JavaScript Object Notation)-based message exchange protocol is deployed to prompt communication and interactions between SCOs and other services of SBIMP.

3.2 Platform as a service layer

The PaaS layer, containing the data source management service (DSMS), rule-based progress control service (RBPCS), and location-based services (LBS), mediates the information between the IaaS and SaaS layers. It provides a level of organization and structure to the multidata streams from different devices, facilitating data integrity, homogeneity, accessibility, and enabling value-added applications. The central cloud database allows a set of allocated computing resources (e.g., servers, services, networks, cloud storage) to be securely and rapidly allocated, coordinated, and released with the least administrative efforts or service provider interaction.

The DSMS facilitates the seamless integration of heterogeneous data collected from the SCOs. Related databases such as MySQL and Access are utilized to reposit design information of prefabricated modules and processed data from SCOs that are reserved in numeric or string forms. With the assistance of the service-oriented architecture (SOA), data streams are integrated and standardized in a type that can be easily shared, transmitted, exchanged, and employed among different isolated systems. To fetch the data, the operator sends a request token in the form of a structured query language (SQL) statement. The data interoperability service is applied to receive the token, parse, and retrieve the target data from relevant designated databases. The retrieval data are then converted into standardized XML files for further handling by other services of the SBIMP.

The LBS collects locational and time information by applying GPS sensors attached to the SCOs to afford value-added services. It aggregates captured location information from heterogeneous sources and facilitates real-time information access for end-users. The pull and push functions are utilized to realize up-to-date information integration. While the reader scans the SCOs to record information, the pull function integrates the location information of the prefabricated modules. The push function is adopted in the delivery process by actively recording and integrating the location information of trunks. It is especially powerful in tracking the real-time movement of specified and tagged objects. Just-in-time delivery and transportation routine of prefabricated modules can be achieved by deploying both mechanisms of LBS.

The RBPCS gives rise to decision-making support for progress monitoring through rule-based computations. The rule-based approach, written in semantic web rule language (SWRL), is envisaged to isolate knowledge with the inference process to adapt diversified progress control scenarios and present the best knowledge and experience of experts. By applying SWRL, knowledge is programmed as rules, and data are abstracted as events. Once the rules are triggered, the RBPCS generates optimal and logical solutions automatically to meet the requirements of back-end applications, such as proposing possible actions for installation delay.

3.3 Software as a service layer

The SaaS layer incorporates the final applications for OAS, namely, OAS web applications, OAS mobile applications, and software development toolkits. Web-based OAS applications are envisaged for frequently used browsers (e.g., Safari and Chrome), which are compatible with HTML 5, JavaScript, and WebGL. The WebGL data file converted from the cloud-based BIM model is redefined into 3D interactive graphics to display and visualize the on-site assembly progress. By using JavaScript, the real-time progress curve can be presented on Windows or iOS. With the aid of cascading style sheet (CSS) animation, menu items are reorganized by objects and services. The OAS mobile app is designed to read and write data collected from STT tag readers through the smart gateway and transmit time and location information to the server. Multilevel menu, waterproof function, and switchable English/Traditional Chinese version are designed for the system UI. The integration of cloud-based BIM technology supports information transmission and exchange among the web-based system, mobile app, and gateway. Cloud computing technology enables a higher level of collaboration and cooperation and enhances the transparency and accessibility of information.

4. Application of SBIMP for on-site assembly services

This section presents a real-life project (Subsidized Sale Flats Project) that deploys the developed SBIMP for the on-site assembly process. The implementation period began in January 2018 and ended in December 2018. A total of 32 stories of prefabricated modules were installed successfully with the assistance of SBIMP. Two training courses, several rounds of interviews, and regular site visits were executed, aiming to make good use of the system and collect corresponding data. The developed SBIMP for on-site assembly service is presented in Fig. 5 and Fig. 6.

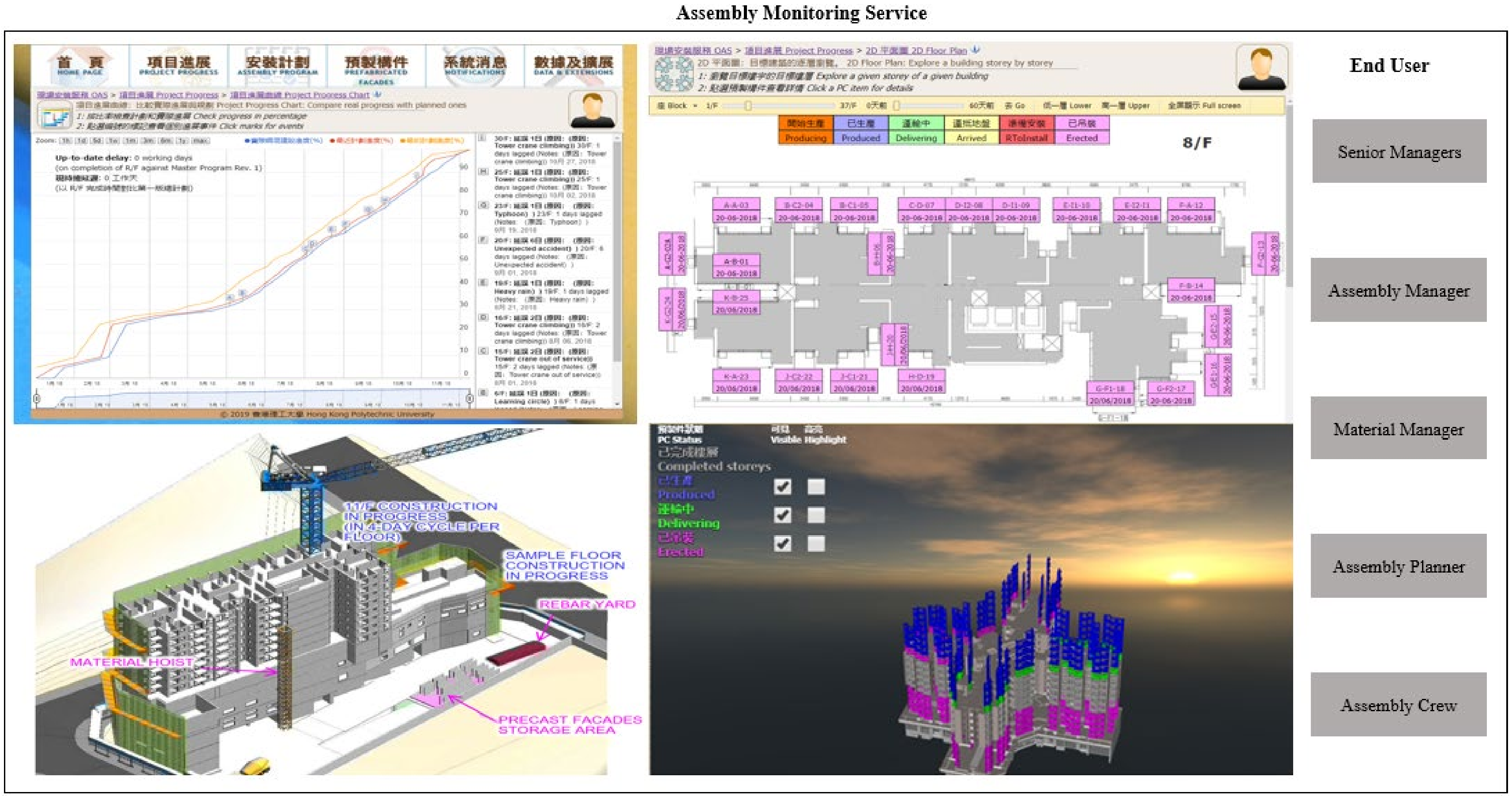

Fig. 6. Application of SBIMP for on-site assembly monitoring service

OAS > Assembly Program > Erection order summary

Erection order summary: Notify planned erections and trace overall status

1: Double click "Planned Erec." column to assign/change erection date

2: Trace updates of orders

樓/F	Portion	Prod. (Ed. day)	Log. (St. day)	Ready to Erec.	Planned Erec.	True Erec. Day	Confirmed Erec. Day	GPS Test
36	A	2018/11/23	2018/11/23	2018/11/24	2018/11/06	2018/11/23	2018/11/23	[illegible]
36	B	2018/11/23	2018/11/23	2018/11/27	2018/11/06	2018/11/23	2018/11/23	[illegible]
35	A	2018/11/01	2018/11/15	2018/11/19	2018/11/01	2018/11/20	2018/11/20	[illegible]
35	B	2018/11/01	2018/11/17	2018/11/21	2018/11/01	2018/11/23	2018/11/23	[illegible]
34	A	2018/10/30	2018/11/10	2018/11/14	2018/10/27	2018/11/15	2018/11/15	[illegible]
34	B	2018/10/30	2018/11/12	2018/11/16	2018/10/27	2018/11/17	2018/11/17	[illegible]
33	A	2018/10/28	2018/11/06	2018/11/07	2018/10/23	2018/11/10	2018/11/10	[illegible]
33	B	2018/10/28	2018/11/06	2018/11/11	2018/10/23	2018/11/13	2018/11/13	[illegible]
32	A	2018/10/12	2018/10/31	2018/11/02	2018/10/18	2018/11/03	2018/11/03	[illegible]
32	B	2018/10/12	2018/11/10	2018/11/03	2018/10/18	2018/11/06	2018/11/06	[illegible]
31	A	2018/10/09	2018/10/26	2018/10/28	2018/10/12	2018/10/30	2018/10/30	[illegible]
31	B	2018/10/09	2018/10/28	2018/10/31	2018/10/12	2018/11/14	2018/11/14	[illegible]
30	A	2018/10/06	2018/10/19	2018/10/23	2018/10/08	2018/10/24	2018/10/24	[illegible]
30	B	2018/10/06	2018/10/21	2018/10/25	2018/10/08	2018/10/27	2018/10/27	[illegible]
29	A	2018/09/28	2018/10/14	2018/10/17	2018/10/03	2018/10/19	2018/10/19	[illegible]
29	B	2018/09/28	2018/10/16	2018/10/20	2018/10/03	2018/10/22	2018/10/22	[illegible]
28	A	2018/09/21	2018/10/11	2018/10/11	2018/09/27	2018/10/13	2018/10/13	[illegible]

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TKO73A Past Event Summary

過去 24 小時	過去 7 天	過去一個月
確認吊裝: 0 件	確認吊裝: 0 件	起運: 0 件
生產: 0 件	生產: 0 件	運抵: 0 件
起運: 0 件	起運: 0 件	確認吊裝: 0 件

The modules of zone A 10th floor has been erected!

The delivery of the modules (11floor) was delayed

PC Tracing: Check geolocation distribution by storey

1: Select criteria from toolbar

2: Click "Go" button

Producing | Produced | Delivering | Arrived | RToInstall | Erected

Fig. 6. Application of SBIMP for on-site assembly scheduling and notification service

4.1 On-site assembly scheduling and operation service

The on-site assembly service is designed to support on-site scheduling, operation, and management during the installation process of prefabricated modules, as shown in Fig. 6. It provides the critical information and analysis results of the on-site assembly process for end-users involved to monitor the progress in real time, better manage the on-site SCOs, and make associated decisions to dispose of unexpected events promptly. The assembly plan is created and altered based on the construction master programme. Any unforeseen circumstances causing assembly delay is recorded in the platform, automatically generating a modified schedule for on-site managers. The master programme and assembly schedule are adjusted accordingly. The on-site operators follow the latest plan and working sequences to execute their installation tasks.

The flowchart of the on-site assembly process by deploying IoT technology is demonstrated in Fig. 7. Two groups (zones A and B) of prefabricated modules are delivered and erected in turn. Upon the arrival of prefabricated modules, the on-site operator scans the STT tag to confirm the arrival of specified modules. The operator at the laydown yard inspects the prefabricated modules after receiving them upon good delivery and presses the 'confirm inspection' button on the mobile app to record the "ready-to-install" status. Then, the qualified modules are stored on the laydown yard for further installation. If modules need rectification after delivery, the operator should click the "reject" button. Senior managers such as the on-site foreman, on-site project manager, superiors from logistics company and module manufacture are immediately and simultaneously received "quality alerts" through mobile app and website notification, which can help relevant stakeholders take immediate actions when some unexpected events occur. Following the scheduled installation date, the operator receives tasks and installation instructions by scanning the QR code. The dynamic video demo is also provided for operators to visualize the assembly work through the OAS mobile app. Once the installation work completes, the operator scans the STT attached to the module and clicks the 'confirm installation' button on the mobile app to record the actual installation time of prefabricated modules. The system provides a more convenient data capture method by utilizing a wearable reader, which is more convenient and portable than the hand-held reader. The collected data is integrated and synchronized into SBIMP immediately for further processing.

Additionally, due to the compact buffer space and tight assembly schedule, the laydown yard should be operated efficiently to realize just-in-time delivery and catch up with the assembly schedule. With the implementation of SBIMP, effective operation of the laydown yard can be achieved by presenting different colours to denote the status (occupied/empty) of the laydown yard. After inspection of the received modules, the laydown yard displays occupied; once the modules are erected, it indicates empty.

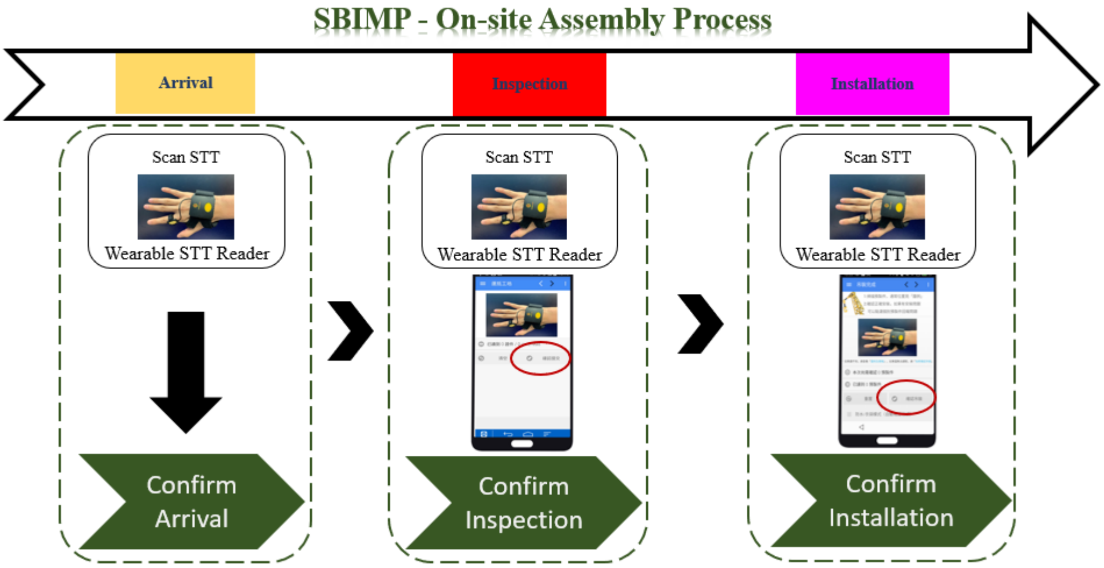

Fig. 7. Flowchart of the on-site assembly process by deploying IoT technology

4.2 On-site assembly monitoring service

Six critical phases are deployed to realize real-time monitoring of the status of prefabricated modules during the whole construction process of the MiC project. The on-site assembly process contains real-time progress monitoring, real-time progress visualization, and real-time clash detection. The Gantt chart is utilized to display the real-time assembly progress by using the total consumption (volume) of prefabricated modules. It allows the comparison between the planned schedule and the actual installation date. Any delay events (e.g., production delay, delivery delay, tower crane climbing, machine breakdown, violent typhoon, etc.) are recorded and revealed in the right-hand column, as shown in Fig. 5.

Real-time progress visualization proposes to supervise the construction process in a virtual and digital environment by importing and processing real-time information. The prefabricated modules are marked with discriminative colours to indicate the current status, enabling real-time supervision of the assembly process. Modules can be retrieved and highlighted while clicking on a particular colour. In addition, the 2D floor plan is deployed to visualize the real-time assembly progress of each module on each typical floor. It provides more detailed and complete information in light of a single prefabricated module. Real-time clash detection refers to 3D BIM animation usage to simulate the real site situation to probe any discrepancy, disruption, or safety issues. It provides a virtual environment to investigate and resolve all (interface check/clash detection) potential risks on critical issues.

4.3 On-site assembly notification service

The real-time feedback model's development lays a necessary foundation for alarm, alert, and action (3A) notification services, aiming at reporting the current status of the on-site assembly process to various stakeholders and other associations of interest. It allows project stakeholders to perceive the current situation (real-time progress, challenges, or barriers) and make associated decisions collaboratively. Collected essential information is used to develop the real-time feedback model, enabling interrelated parties to make associated decisions and adjustments to cope with the latest assembly schedule. The notification services are achieved by retrieving the intended schedule data from the OAS database and tracking the day difference between the present day and the planned day regarding the assembly work. By using a notification JavaScript library, alerts are generated using SQL data retrieval requests and visualized as browser alerts shortly after the operator logs into the system. The notification shows concise information as a pop-up window on the web-based system and mobile app, as shown in Fig. 6. For example, any unexpected events such as delivery delays would be marked and sent out alert dialog on the website and mobile app. On-site managers and operators receive delay notifications and rational solutions immediately. The notification service is also designed to detect the GPS locations of prefabricated modules. If any modules are mislocated, the system sends an error alert by comparing the actual GPS location with the designed location. In addition, email and SMS notification approaches are employed by this system to notify the corresponding managers working in the office or out of site.

5. Discussion

MiC is a novel paradigm that is rapidly gaining ground in the construction industry of Hong Kong. The above sections present an Internet of Things-enabled smart BIM platform (SBIMP), which integrates the Internet of Things (IoT), BIM technologies, and computing techniques. It facilitates real-time information capture, processing, display, and sharing among various stakeholders, thus supporting their decision-making process during the on-site assembly process. Problems in the business process of MiCs are identified, and the customization requirements of stakeholders are analysed. The usage of STT substantially decreases the possibility of information loss due to a single ID tag's potential failure. Additionally, it enhances the assembly efficiency by effectively retrieving a large number of modules in the laydown yard and improving the rightness of the installed location. With the help of SCOs and smart gateways, accurate and complete information is seamlessly and simultaneously synchronized in the system to realize real-time monitoring service, enabling cooperation and collaboration among different parties to make rational and optimal decisions. Proactive notification services significantly reduce the emergency detection time and the response time with immediate and appropriate actions.

The statistical analysis of KPIs is implemented before the pilot study (February 2018 to March 2018) and after the deployment of SBIMP (October 2018 to December 2018). As shown in Table 4, the on-site assembly process efficiency was dramatically enhanced by deploying the SBIMP. By implementing the platform, the unloading time and number of inspection crews decrease by 50%. Reliable and completed information collection approaches allow information collection time and retrieval time to be reduced by more than 80% and 50%, respectively. The assembly crew could easily follow the assembly instructions on the mobile phone and record the installed components by using mobile devices and STT readers, which were executed by the extra recorder in the previous project. Thus, the assembly crew was reduced by one. Additionally, due to fast track and fewer errors, the average time to install modules in the right location was reduced by one hour. With the assistance of notification services, the error and emergency detection times are largely improved by accelerating the perception of exceptional events. Alone with the enhancement, the feedback time also increases by more than 86.7%. Due to the above improvements, the assembly time and assembly cycle are improved by 40% and 33.3%, respectively. Substantial improvements demonstrate the efficiency of deploying the SBIMP and imply higher productivity with time and cost savings.

Table 4 KPI comparisons for the on-site assembly process

KPI items	Description	Before (Average)	After (Average)	Enhancement
Unload time	Average time to unload modules from the truck to the laydown yard	40 min	20 min	50%
Number of inspection crew	Number of crews required for inspecting and unloading received modules	2	1	50%
Information collection time	Average time needed to capture complete time and location information of modules for one zone	5 min	< 1 min	More than 80%
Retrieval time	Time required to retrieve specific modules for installation	2 min	< 1 min	More than 50%
Number of assembly crew	Number of crews required for assembly work	5	4	20%
Error detecting time	Average time to identify the misplaced prefabricated modules	5	< 1 min	More than 80%
Assembly time	Average time to erect modules in the right location for one zone	2.5 h	1.5 h	40%
Emergency detecting time	Average time to notice the urgency regarding the on-site assembly process	10 min	2 min	80%
Feedback time	Average time to make responses and take actions	15 min	2 min	86.70%
Assembly cycle	Time required to complete the assembly and R.C. structure work for one typical floor	5-7 days	4 days	Average 33.3%

6. Conclusion

The proposed SBIMP, especially for addressing the specific problems of an inefficient data capture approach, ineffective progress monitoring, and lack of automatic decision support, is developed to streamline the successful delivery of the MiC project. The real-life subsided sale flats project in Hong Kong is selected as a trial project to demonstrate the underlying benefits of this platform. The SCOs are outfitted with STT and GPS sensors, enabling an efficient and complete data collection process with timely, accurate, complete information. The smart gateway system prompts seamless and flexible information sharing and transmission among the different stakeholders involved. The service-oriented open architecture is utilized as an essential innovation to enable the platform as a service. The objective of the on-site assembly service is to collect and extract valuable and reliable information from an extensive data set to format real-time and useful information to enhance the visibility and traceability of the whole on-site assembly process and coordinate different parties involved. Moreover, SBIMP enables notification service by employing the RBPCS. It allows subscribed stakeholders to be aware of any exceptional events and make reasonable responses to cope with the dynamic working environment to support decision making. Additionally, the platform will provide optimal and rational solutions to corresponding end-users, aiding them in perceiving the actual situations and making associated decisions collaboratively. With the assistance of a higher level of cooperation and collaboration, the information collection time, retrieval time, assembly duration, and feedback time have been dramatically shortened by deploying this platform.

Despite these benefits, the limitations of this study should be presented for further research. First, the SBIMP is only adopted in one real-life project to demonstrate the effectiveness owing to the availability of applicable projects in Hong Kong. More practical project trials should be executed to test the operational and economic efficiency of this platform. In addition, the SBIMP should be further explored and developed for extensive and comprehensive deployment in a standardized approach, which can be widely adopted in diversified construction projects. Second, the developed platform is mainly concentrated on exploring the features efficient for scheduling and cost, ignoring the quality, safety, and sustainability issues in the MiC project. Therefore, more advanced technologies and functions need to be exploited and extended to achieve a higher level of applicability and serviceability of SBIMP, dealing with the increasingly complex and fragmented construction project.

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