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AN INTERNET OF THINGS-ENABLED BIM PLATFORM FOR MODULAR INTEGRATED CONSTRUCTION: A CASE STUDY IN HONG KONG

Yue Zhai[a,*], Ke Chen[b], Jason X. Zhou[c], Jin Cao[d], Zhongyuan Lyu[e], Xin Jin[c], Geoffrey Q.P. Shen[c], Weisheng Lu[d], George Q. Huang[e]

[a] *Department of Logistics Management, School of Economics and Management, Beijing Jiaotong University, Beijing, PR China*

[b] *Department of Construction Management, Huazhong University of Science and Technology, Wuhan, PR China*

[c] *Department of Building and Real Estate, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hunghom, Hong Kong*

[d] *Department of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Pokfulam, Hong Kong*

[e] *HKU-ZIRI Lab for Physical Internet, Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong*

[*] Corresponding author.

E-mail addresses: zhaiyue@bjtu.edu.cn (Y. Zhai), chenkecm@hust.edu.cn (K. Chen), jason.zhou@connect.polyu.hk (J.X. Zhou), caojin@hku.hk (J. Cao), u3004917@connect.hku.hk (Z.Y. Lyu), verna.x.jin@connect.polyu.hk (X. Jin), geoffrey.shen@polyu.edu.hk (G.Q.P. Shen), wilsonlu@hku.hk (W. Lu), gqhuang@hku.hk (G.Q. Huang).

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Abstract

In recent years, Building Information Modelling (BIM) has been acting an important role in the delivery of Modular Integrated Construction (MiC) project. However, the full potential of BIM to MiC project cannot be realized without accurate information collection, timely information exchange, and automatic decision support throughout the project life cycle. In order to fulfil such requirements, this paper aims to develop an Internet of Things-enabled BIM platform (IBIMP) for the MiC project. A real-life project located in Hong Kong were deeply explored for developing the platform. The IBIMP consists of smart construction objects (SCOs) equipped with smart trinity tag (STT) and GPS sensor, smart gateway system, data source management service, location-based service, rule-based progress control service, as well as decision support services for prefabrication production, transportation, and on-site assembly processes. With the combination of advanced Internet of Things (IoT) technology and BIM technology, the barriers that hamper the possible functions of BIM can be overcame. By using application scenarios of a subsided sale flats MiC project in Hong Kong as examples, this study demonstrates how problems of inconvenient data collection, lack of automatic decision support, and incomplete information can be addressed by the IBIMP.

Keywords: Building Information Modelling (BIM); Modular Integrated Construction (MiC); Prefabrication; Internet of Things

1. INTRODUCTION

Modular Integrated Construction (MiC) is a game-changing disruptively-innovative approach that transforms fragmented in-situ construction of buildings into integrated value-driven production and assembly of prefabricated modules. In a MiC project, free-standing modules (completed with finishes, fixtures, and fittings) are manufactured in a prefabrication yard and then transported to the construction site for assembling (Buildings Department, 2018). It improves the traditional construction method by removing cast-in-situ to a remote prefabrication factory for taking advantages of mass production. Also, it differs from a prefabrication housing project by adopting a higher ratio of prefabricated modules. This innovative approach can largely shorten the construction period, increase cost-effectiveness, uplift productivity and quality of works, enhance site safety, reduce wastage, and improve sustainability (Lu, Chen, Xue, & Pan, 2018; Zhai, Zhong & Huang, 2018). These benefits of MiC make it extremely suitable for regions confronted with housing shortage. For example, in Hong Kong, the Hong Kong Housing Society (HKHS) has been using MiC in its subsidized sale flats projects in order to address its housing problem and take advantage of the firm collaboration of the great bay area. Up to now, over 71,000 units have been built and 2,500 flats are working in progress and scheduled to be completed on or before 2020 (HKHS, 2018).

Deliver a MiC project at the right time in the right location with the qualified quality needs several prerequisites, which include but not limited to consistent information model throughout the entire delivery process, timely information communication and integration, and well coordination among stakeholders (Zhai, Zhong, Li, & Huang, 2017; Zhong *et al.*, 2017). Many new technologies thus are adopted in recent years with the aim to facilitate the delivery of MiC projects. Among them, building information modelling (BIM) was considered a helpful tool for MiC projects due to its capacity of facilitating information exchange and interoperability in the project design, construction, and operation phases (Eastman, Teicholz, Sacks, & Liston, 2011; Davies & Harty, 2011). BIM is defined as the digital representation of physical and functional characteristics of a facility (National Institute of Building Sciences, 2015; Gao & Pishdad-Bozorgi, 2019). The information contained in BIM includes, but not limited to, building geometry, spatial relationships, quantities and properties of building components. It serves as a useful platform for facilitating the prefabrication production, prefabrication transportation and on-site assembly of a prefabricated housing project for its benefits of providing collaborative working teams and decision makers with the physical and functional representations of prefabricated modules (Chen, Lu, Peng, Rowlinson, & Huang, 2015). For example, the status of prefabrication components could be visualized and traced in a BIM platform for facilitating progresses control.

Some cutting-edge technologies have been used to facilitate information collection and decision support in construction project. Internet of Things (IoT) is one of the core technologies, equipped with smart tags and sensors such as: RFID (Radio Frequency Identification) tag, NFC (Near Field Communication) tag and GPS sensor (Zheng, Lin, Chen, & Xu, 2018). The spatial-temporal information of prefabricated modules can be collected for supporting supply chain management, project management, facility management, safety management, and construction process monitoring (Park & Kim, 2013; Shahi, West, & Haas, 2013; Zhong *et al.*, 2015; Li *et al.*, 2017). Cloud computing is another core technology, which based on the information in a centralized BIM platform to optimize production, transportation and on-site assembly schedules in a collaborative manner. It is considered to overcome the shortages of a traditional BIM platform, where decision in different stages are made isolated and only local optimal (Wong, Wang, Li, & Chan, 2014; Xu, Li, Luo, Chen, & Huang, 2019).

Several researches have been found to integrate these advanced technologies into a BIM platform. For example, the linkage between BIM and enterprise resource planning (ERP) is introduced by Babič, Podbreznik, and Rebolj (2010). By jointly visualizing construction processes, this integration enhances information sharing between different stakeholders. Also, a confined space monitoring system is designed and integrated in a BIM platform to improve the visualization and safety of a construction site (Riaz, Arslan, Kiani, & Azhar, 2014). Besides, Dave, Kubler, Främling, and Koskela (2016) developed a communication framework by adopting IoT to facilitate the use of lean construction management and tracking technologies such as RFID, NFC and GPS. In the proposed framework, the status of materials, machines, and crews throughout entire construction process can be tracked. Recently, Li, Xue, Li, Hong, & Shen (2018) incorporate information and communication technology (ICT) enhances smart construction objects

(SCOs) to a centralized BIM platform. By integrating the real-time location information of prefabricated modules in a construction site with the information in previous stages, different stakeholders can easily communicate and coordinate.

Despite these studies provide useful references when integrating the BIM with other core technologies, some challenges still exist that hamper the working efficiency of a construction project and the potential functions of a BIM platform. R&D outlook publications by Council for Research and Innovation Building and Construction (CIB) point out a further need to overcome possible failures in information collection processes and to avoid delayed problem detection (CIB, 2010). Also, literature calls for more research into comprehensive information collection (Shen *et al.*, 2010), fast and accurate decision making(Watson, 2011;Merschbrock & Munkvold, 2012), and automatic emergency alarm (Rebolj, Babič, Magdič, Podbreznik, & Pšunder, 2008). We contribute to this discussion by investigating the problems and challenges exist in a real-life MiC project. Especially, three major challenges are found. The first challenge is the ineffective information collection. At present, the information collection from prefabrication factory to the construction site relies on manual operations, dominated by paper. Thus, the information collection is time-consuming and error-prone. Associated with the first challenge, the second challenge is incomplete information. The well-formatted information of prefabricated modules at the right time at the right quantity in the right place is still insufficient to support efficient decision making and collaborative working among stakeholders. Involving a mass of prefabricated modules handled by different stakeholders, a smooth MiC project largely relays on timely information sharing, accurate and comprehensive information of related construction objects, such as, a prefabricated module, on-site buffer level, condition of working space and so forth. However, it is different to manually maintain all kinds of information updated in the BIM model. Besides, the re-entered information is usually untimely, inaccurately and incompletely, which fails to support reasonable, precise and scientific decision-making. The third challenge is the lack of automatic decision support and error report. The use of BIM alone cannot provide optimal schedule decision and proper guideline for the manager under a dynamic environment in a timely manner. In actual practices, managers may rely on the information shown in the BIM model to manually assign tasks to both upstream and downstream stakeholders via various isolated systems. However, confronted with a variable project environment and constrained by the efficiency of managers, the task assignment is inefficient and might fails to keep up with a changing environment. Also, if any unforeseen events happened, the BIM platform only records these events instead of finding the unusual events and automatically send notification to the managers. This requires the manger to be very careful in supervising the project and be very experienced in the construction project. Unfortunately, failure to detect the problem in-time and tardiness decision making always lead to project error, heavy rearrangement operations and project delay (Li *et al.*, 2016).

In order to address the above-mentioned challenges, a platform integrates BIM and Internet of Things (IoT) technologies is developed in this research. IoT refers to the networked interconnection of objects, which are equipped with ubiquitous intelligence, in order to enable highly distributed network of objects communicating with human as well as other objects via embedded systems (Xia, Yang, Wang, & Vinel, 2012; Manavalan, & Jayakrishna, 2019). It has been increasingly adopted in industries such as manufacturing and automation to facilitate data collection, communication, and decision support (Atzori, Iera, & Morabito, 2010; Trappey, Trappey, Govindarajan, Chuang, & Sun, 2017), but has not been widely used in the construction industry yet. Therefore, this study aims to develop an IoT-enabled BIM platform (IBIMP) for a MiC project. The IBIMP consists of several key technologies, including smart trinity tag (STT) and GPS sensor attached to construction objects (e.g., prefabricated modules, workers, machines and vehicles) for automatic information collection; smart gateway system and data source management service (DSMS) for efficient information management and communication; and cloud-BIM platform, with location-based service (LBS) and rule-based progress control service (RBPCS), for informed decision making. The specific objectives of this research are: (1) to investigate and analyse business process, requirements and shortages exists in a MiC project; (2) to propose an architecture design and develop the IBIMP; (3) to show the application of the proposed platform to a practical project and demonstrate the efficiency of the proposed platform.

The remainder of this paper is organized as follows. Section 2 describes the general business process of MiC project delivery, identify the requirements and details the challenges to be addressed. Section 3 introduces the proposed IBIMP. Section 4 gives a glance at the application scenarios of IBIMP in order to demonstrate how IBIMP can help address the challenges. Also, both quality and quantity improvements are analyse in this section. Conclusions are presented in Section 5.

2. BUSINESS PROCESS ANALYSIS OF MIC PROJECT

The research team visited several MiC projects located in Hong Kong to investigate the business process and identify the problems faced by the primary stakeholders involved in MiC projects before designing and developing the IBIMP for enhancing MiC project delivery. Considering the feasibility and rationality of implementing the new system, a subsidized sale flats project at Tseung Kwan O (Area 73A) was chosen for this study.

2.1 Background of the target project

The surveyed project proposes to construct one residential tower of 32 stories, which provides 330 flats (1 to 3 bedroom) with 1020 units, including one basement (car park, plant room), 4-level podium for commercial shop, car park, landscape area, plant room, podium garden, and multi-function room (Fig. 1). In this project, nine different kinds of modules were incorporated to form 25 different types of prefabricated façades. Fig. 2 below provides detailed information regarding the typical layout of prefabricated façades in a typical floor.

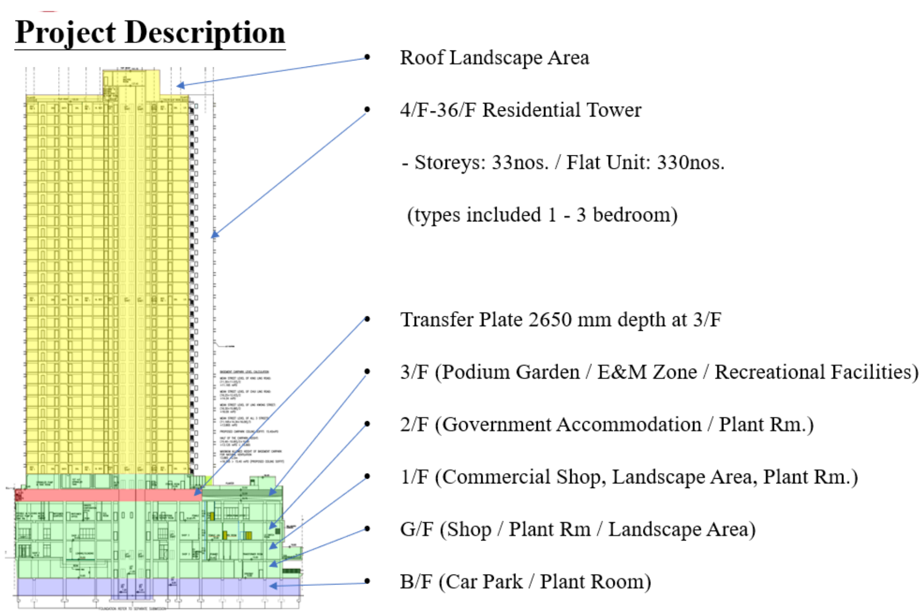

Fig. 1. The description of subsidized sale flats project

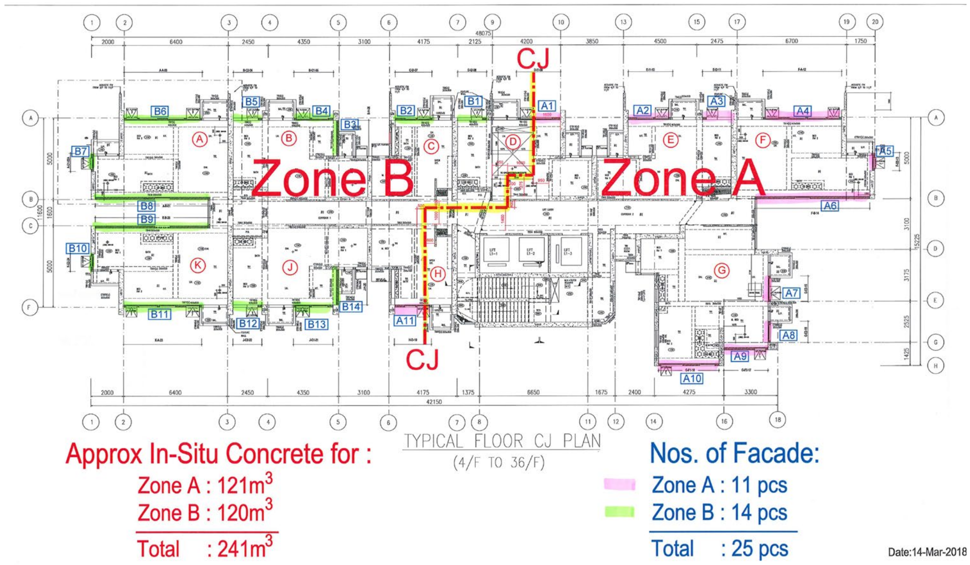

Fig. 2. Layout of prefabricated façades in a typical floor

2.2 Business process analysis and problems identification

The purpose of this section is to analyse the business processes, identify business requirements and summarize problems regarding to the whole MiC project. The research team conducted six times of field studies and interviews between March and September 2018. Fig. 3 shows the related business processes in the construction phase of the target project, which include three main phases namely prefabrication production, prefabrication transportation, and on-site assembly. The main stakeholders involved in this phase include the HKHS as the designer and client, a local company A as the main contractor, an off-shore manufacturer located in Huizhou, Guangdong Province, China, and a third-party cross-border logistics company.

2.2.1 Prefabrication production in MiC project

(1) Production process analysis

The objectives of this stage are: (1) to make production scheduling according after receiving the order from the construction site; (2) to purchase raw materials and to prepare production; (3) to produce the required prefabricated modules according to the design drawing; (4) to store the finished prefabricated modules at the buffer area and to prepare for transportation. The following parts describe these processes in detail.

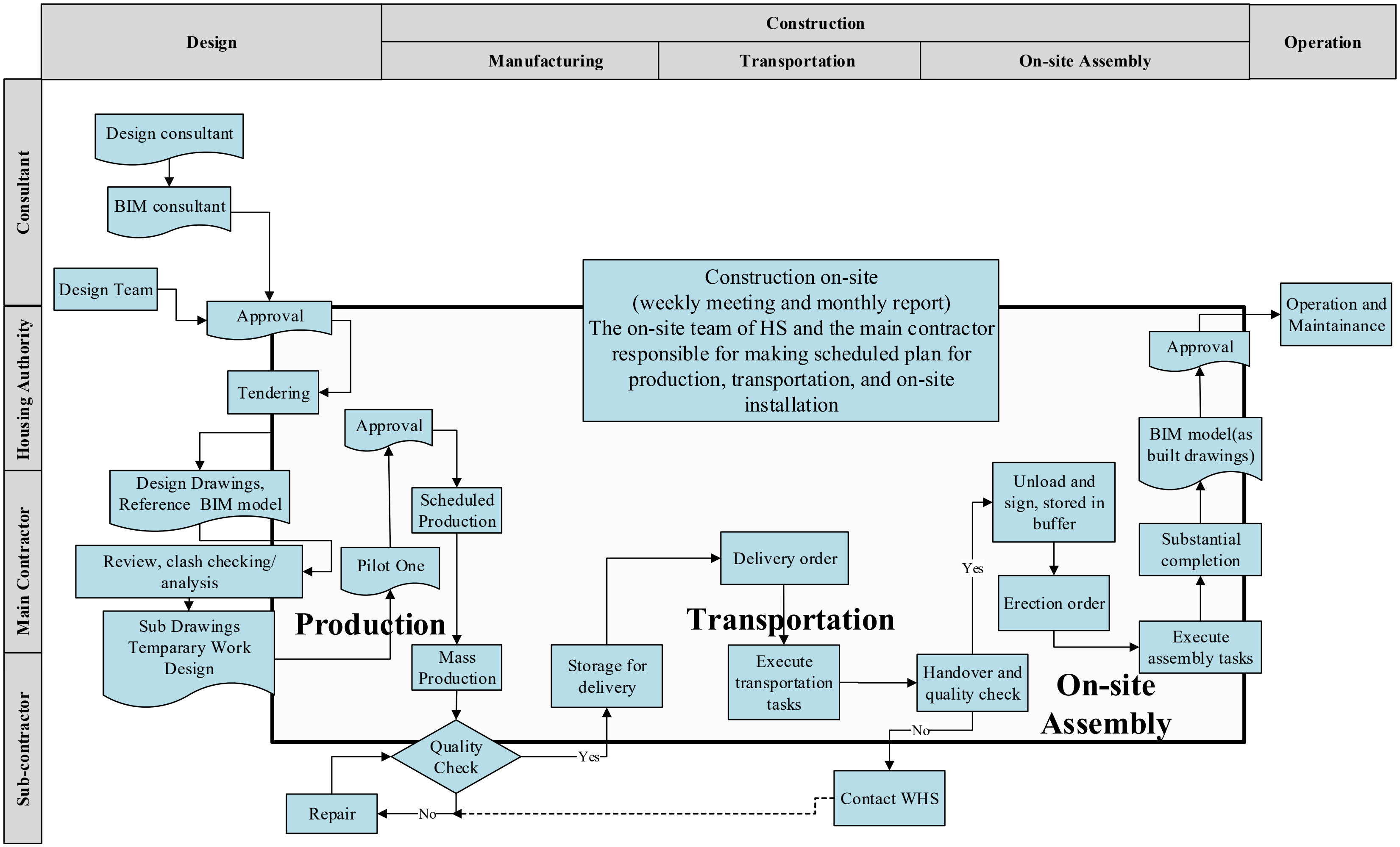

Fig. 3. Business process of modular integrated construction of the selected project

- ***Prefabricated module production scheduling***

After the tender stage, the general contractor will coordinate with prefabricated module manufacturer to work out the master plan and prefabrication production plan. During this period, the design department of the prefabrication manufacturer develops the production drawings based on the design drawings within two months. Once the prefabrication production drawings are developed, they need to be submitted to the general contractor, who is act on behalf of client, for approval before production. After the confirmation of production drawings, the production manager makes the overall production schedule and material list. During the construction of the project, the on-site assembly manager would make order of prefabricated modules based on the master plan and actual project progress. A project manager, (i.e., an on-site representative of the prefabrication factory) will confirm the customer order. If there is no problem, the customer order will be sent to the factory by email or fax.

- ***Prefabricated module production preparing***

Based on the prefabrication production plan, the material list will be made. At the same time, the order of steel formwork will be sent to the formwork producer around 45 days in advance. After the material list is made, production managers will make the monthly and weekly production plans, and the purchase staff will organize the purchasing process. Materials will be inspected and only be used if they pass the inspection. Reinforcement bars of the prefabricated façade would be purchased earlier than other materials since the inspection of the reinforcement bars needs additional one month. The inspection results will be marked on the reinforcement bars. After the inspection, samples of prefabrication will be made and checked. Production manager will organize the production if there are no problems found in the pre-made samples of the module.

- ***Prefabricated module manufacturing***

Quality control (QC) check should be conducted to check whether the steel formwork and concrete are suitable for prefabrication production. After the QC check, concreting and vibration will be conducted for natural curing. Once the required strength is reached, de-molding can be carried on. The production information including project code, floor, module type, weight, and production date will be marked on the surface of the prefabricated modules for identification purpose (See Fig. 4). Then, the prefabricated facade will be transferred to the finished product warehouse for laying the mosaic tiles. The warehouse information is recorded in paper show in Fig. 5. At this stage, QC check will also be conducted to make sure the product is well-formed. Repairing works must be carried out if there are some defects found. After that, the prefabricated modules are prepared and packaged, waiting for the delivery order issued by the main contractor mostly via email or paper-based documents.

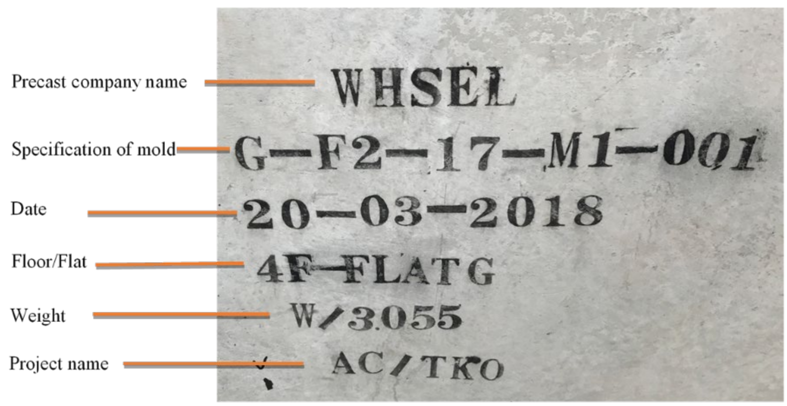

Fig. 4. Information printed on the surface of the prefabricated modules

Fig. 5. Inventory information of prefabricated modules

- ***Prefabricated module transportation preparing***

Due to the adoption of the 4-day construction cycle for a typical floor construction with formwork system installation, the order for prefabrication delivery should be issued at least 4 days in advance to ensure the in-time delivery of the prefabricated façades for the on-site assembly. According to the delivery order from the construction site, the prefabrication production manager will make transportation plan. Before the tractors arrive the factory, the workers would load the required prefabricated façade on the trailer according to the delivery docket. The workers will take the photos for record.

(2) Requirement analysis

The critical findings and observations are summarized as bellows:

- The workers rely on paper documents to carry on prefabrication production;
- Production department has its own production coding system;
- The methods for receiving production order and delivery order include e-mail, telephone and fax;
- Take a long time to response to any emergency; and
- The HKHS shows extreme concern about whether the ordered prefabricated façades have been produced on time.

The requirement analysis of prefabricated module production is summarized in Tab. 1.

(3) Problem identification

Three major problems in prefabrication production stage are summarized. First, traditional methods still dominate data collection. For example, once a prefabricated module is finished, a worker will record the status and information of this component in a paper and then submit this paper to the production manager. Second, the communication within the production system majorly relay on inefficient, incomplete and untimely means, such as phone call and email. For example, if the production manager wants to check the inventory level of prefabrication modules, he should dispatch labours for manually counting and then get the number via a phone call. By this means, the useful data fails to be captured in timely, accurate and complete manner and thus hampers efficiency of a production system and quickly response once any changes and interruptions happens. Third, the dynamic production optimization decisions are made manually, based on untimed, inaccurate and incomplete data. For instant, when a machine breakdown sudden happens, the production manager should reassign the production tasks to other machines and workers. However, relay on non-real-time and incomplete information, the decisions made by the production manager might not be the optimal one.

Tab. 1. Requirements analysis of prefabricated module production

No.	Type	Requirement	Priority
Functional Requirements			
1	Production preparation	Display production progress by different phase	Preferred
2	Production preparation	Display production plan	Must-Have
3	Production	Standardized QC record	Preferred
4	Production	Production testing, demolding, maintenance records	Preferred
5	Production	Must be aware of when prefabricated modules are finished	Must-Have
6	Production	Must be aware of when products are qualified	Preferred
7	Transportation planning	Automatically generate transportation plan	Preferred
8	Transportation preparation	Loading records	Must-Have
9	Transportation preparation	Departure records	Must-Have
Non-Functional Requirements			
1	Performance	Real-time access to data	Must-Have
2	Security	System administrator rights	Must-Have

2.2.2 Prefabrication transportation in MiC project

(1) Transportation process analysis

The objectives of prefabrication transportation process are: (1) to make transportation schedules according to the transportation tasks; (2) to assign the delivery order to drivers; (3) to finish the transportation task and monitor the shipping processes. As the connection of the production stage and on-site assembly stage, the prefabrication transportation process needs to be efficient and timely. The following parts describe these processes in detail.

- ***Prefabricated module transportation scheduling***

The transportation schedule is made by the transportation contractor based on the master plan and actual project progress, generally one week in advance before each assembly cycle. According to the transportation schedule, the required prefabricated modules are loaded on the trailers three or four days in advance before dispatching. Besides, the transportation contactor will report the transportation schedule to the custom for declaration. Usually, the type, weight, number of prefabricated modules, the license number of transportation vehicles (including trailers and tractors), and the identity information of the driver should be reported 7 days in advance.

- ***Delivery order assigning***

After evaluation, the transportation tasks are divided into several delivery orders and allocated to different trailers according to specific requirements and status of the trailers for achieving trailer workload balancing. The prefabricated modules are delivered in batches according to the real-time requirements of each building cycle. The transportation manager will assign each delivery order to a specific driver and inform the driver by telephone. After receiving the delivery order, the drive should go to the transportation manager's office to get the paper-based order detail, denoting the assigned trailer, tractor and the prefabricated modules details.

- ***Prefabricated module shipping***

According to the assigned order tasks, the drivers will first get the tractor and then pick the trailer loaded with prefabricated modules. The transportation starts from the prefabrication factory in Mainland China to the construction site in Hong Kong. One thing to be mentioned here is that if the construction site is congested and difficult to hold these bulky and heavy prefabricated modules, the drives will temporally store these prefabricated modules in an intermediate warehouse, which is usually located near custom. After arriving the construction site, the site manager will confirm the right prefabricated modules to be delivered at right time in right quantity at right quality and sign the delivery docket.

(2) Requirement analysis

The critical findings and observations are summarized as bellows:

- Very few trailers or tractors are equipped with GPS device;
- The driver just looked at the car number and drove away. It should not have been a

very careful check (a double check process is needed);

- After get the trailer based on assigned tasks, only the tag in the trailer was scanned, but there is lack of inspection towards its contained prefabricated modules;
- Transportation scheduling and task assigning are based on personal experience;
- The critical information is record in paper;
- Labor intensive;
- Tardiness rearrangement decision-making for responding unforeseen events; and
- There is a lack of trackable and visible tool for monitoring the transportation process in a real-time manner.

The requirement analysis of prefabricated module transportation is summarized in Tab. 2.

Tab.2. Requirements analysis of prefabricated module transportation

NO.	**Type**	**Requirements**	**Priority**
Functional Requirements			
1	Transportation scheduling	Automatic transporation task scheduling	Must-Have
2	Transportation	Must be aware of the process of transportation tasks	Preferred
3	Transportation preparation	Electronic prefabrication transportation order and docket	Must-Have
4	Transportation	Digital signature	Optional
5	Transportation	The system needs to exchange information with its upper lever (i.e., HS)	Must-Have
6	Transportation	The system needs to be sensitive to any emergencies	Must-Have
Non-Functional Requirements			
1	Performance	Location and status can be traced in a real-time manner	Must-Have
2	Availability	Access out-of-office, in transit	Must-Have
3	Security	System administrator rights	Optional
4	Security	Individual and role-based authorizations	Must-Have

(3) Problem identification

Three major problems in prefabrication production stage are summarized. First, traditional methods such as manual scan still dominates data collection, which causes inefficiency in some critical steps. Also, the location and quantity information of prefabricated modules, drivers, trailer and tractors is difficult to collect in-time. Second, if any interruption or emergency occurs, it is difficult for the transportation managers to notice unforeseen events in the first place and thus fails to response immediately. Unfortunately, tardiness response increases the difficulty of problem solving and costs more. Third, efficient coordination and cooperation among different stakeholders are hampered by delayed and incomplete information sharing. Optimizing both local and global decisions as well as providing quick response to emergencies, relays on critical information such as inventory level, tractor location, occupancy of crew and machine, and site condition. However, these information does not present in a real-time, precise and comprehensive manner and thus difficult to support reasonable, considerable and scientific decision making.

2.2.3 On-site assembly in MiC project

(1) On-site assebmly process analysis

The objectives of on-site assembly stage are: (1) to make assembly schedule on behalf of the client to ensure the project can be finished on-time; (2) to establish the construction site for providing a safety, environmentally friendly and convenient building place; (3) to finish building tasks and supervise entire building process. The following parts describe these processes in detail.

- ***On-site assembly scheduling***

The site manager acts on behalf of the client to supervise the whole building process. A master plan for guiding on-site assembly workflow is made before a MiC project carry out. Especially, four main stages are included in the on-site assembly workflow: site facilities setup and operation, RC structure construction, electrical and mechanical works, and architectural finishing works & external landscaping works. Three stages, apart from the first stage, can be put into practice concurrently based on the schedule. The prefabrication assembly is mainly involved in the second stage. The site manager gives the master plan to the prefabrication production manager 6 months in advance. Confronted with space limitation, the prefabricated module order for each building cycle are released 15 days in advance. According to the master plan, the foreman makes the floor plan and informs the specific tasks to the corresponding crew. The foreman supervises the building activities, records the progress in paper, and reports to the site manager. If some non-critical unexpected events happen, the foreman can use feeding buffer or project buffer to absorb these uncertainties. If critical disruptions or emergency happens, the foreman should report to the site manger by phone call. Then, the site manager should reschedule the project plan, make decisions for responding the emergency, and inform other stakeholders.

- ***Construction site establishing and preparing***

Before the assembly activities carries out, the working crew should set up a construction site for supporting subsequent activities. The objectives of site facilities set up and operation are: (1) To give maximum security to plant, materials and the works; (2) To protect the public and the environment from the works; (3) To provide adequate facilities to both the clients and the contractors staff, and to give the maximum possible benefit to the site for the duration of the contract; (4) To ensure that upon completion the site is efficiently demobilized and reinstated to everybody's satisfaction.

- ***On-site assembling***

The operator at buffer checks the prefabricated module after unloading and signing in the dockets if it is well delivered. In case there are some flaws or defects when conducting the QC check, the operator should report to the on-site senior manager personally or via call and email, and the prefabrication manufacturer will be contacted via call or email for further actions, and relevant information shall be recorded. Later the module is lifted for erection by tower cranes. In a normal erection, a prefabricated module is adjusted horizontally then vertically. Reinforcement works are carried out after the confirmation of assembly, then inspection. Inspection forms are generated after erection and inspection in written format. Six-day construction cycle is employed in this project for a one typical floor, which requires immediate responses when confronted with fragmented problems.

(2) Requirement analysis

The critical findings and observations are summarized as bellows:

- The buffer on-site is too small, which indicates little tolerance for schedule delays;
- The HKHS requires more efficient and real-time supervision of prefabricated construction process;
- The general contractor shows extreme concern about whether the ordered prefabricated façades are produced or delivered on time;

- If the tag is missed or out of work, it is difficult to record the relevant information; and
- The stakeholders need real-time feedback of any challenges, progress regarding on-site assembly process.

The requirement analysis of on-site assebmly is summarized in Tab. 3.

Tab. 3. Requirements analysis of on-site assembly

NO.	Type	Requirements	Priority
Functional Requirements			
1	SCOs management	The system needs to keep a record of pending prefabricated modules (with or without ID) for the current working day, and next days on one floor (a 6-day cycle and 4-day cycle)	Preferred
2	Buffer	Be aware of prefabricated modules are safely delivered	Must-Have
3	Buffer	Be aware of the distribution of materials and workers	Must-Have
4	Buffer	Be aware of storage of materials on site	Must-Have
5	Erection inspection	Be aware of prefabricated modules are erected successfully	Must-Have
6	Buffer	Be aware of the place where prefabricated modules are held	Must-Have
7	Buffer & erection inspection	When RFID tag is missing or not working, QR code can be used to record information	Must-Have
8	Messaging	Automatic SMS or Android/iOS notifications on prefab delivery/ erection/ unexpected issues for WHS / HS	Preferred
9	Messaging	Automatic SMS or Android/iOS notifications on materials consumption and workers assignments	Optional
10	Erection inspection	Multiple scanners or floor partitioning for RFID scanning	Optional
11	Erection inspection	Random order RFID scanning within one floor after inspection	Preferred
12	Erection inspection & buffer	Batch upload of photos synchronized or synchronized with hand-held scan data upload	Optional
13	Erection inspection & buffer	Able to record operators' GPS locations of delivery & erection as EXIF in JPG images and automatically extractable as supplementary location info	Optional

14	Erection inspection	Digital/ vocal signature of inspector	Optional
15	Buffer, erection inspection, & general management	Electronic files (PDF) sharing of inspection reports and progress reports	Preferred
Non-Functional Requirements			
1	Performance	Data and status are available at real-time	Preferred
2	Availability	Accessible through wireless/wired network out of office/ site	Must-Have
3	Security	One shared input to account for one wing/building	Preferred
4	Availability	Accessible on iOS/Android smart devices	Preferred
5	Security	Binding PC/Phones' IP/MAC ID address for / HS's access	Optional
6	Performance	Feedbacks are available at real-time	Preferred

(3) Problem identification

Several problems in on-site assembly stage are summarized. First, data recording and storage are relays on manual handling. After the arrival of prefabricated modules, the handover process is customarily carried out manually and important information such as prefabricated modules type, floor, quality condition is recorded in paper. When executing erection tasks, the operator scans the target module and manually input data, which is time consuming, error-prone, and incomplete. Second, unforeseen events such as project delay, schedule change, machine breakdown, and material shortage, can not be noticed immediately by corresponding managers once happen. According to the site interview, lag in problem discovery is the major cause of project time overrun. Third, the site manager always fails to response to the uncertainties promptly, which hampers construction site working efficiency and causes project cost overrun. Confronted with tight project schedule and small buffer area, the manager should continuous optimize site resources and coordinate with its upstream stakeholders. However, fail to obtain real-time information and difficult to communicate with other stakeholders result in more non-value-added activities.

Besides the problems and difficulties faced by independent stakeholders, there are some critical challenges plagues the whole system. First, although the Auto-ID technology has deployed in some pilot projects, the application follows a non-uniform approach. For example, the RFID tag is embedded in the prefabricated components for managing prefabrication production and on-site assembly and incorporated in an ERP system. However, in the transportation stage, the vehicle management relays on NFC technology. Moreover, other importation construction objects are equipped with various tags, such as QR code for workers and bar code for standard raw materials. Information fragmentation greatly increase the difficulties of data transferring. Second, the promising potential of BIM models were not fully explored. In current stage, the BIM model is only used for prefabricated module designing and information presenting. Owing to the traditional work habits, some critical design drawings, construction objects statuses are recorded in paper. Without complete and accurate information, the decisions made by managers are based on rule of thumb, which are usually sub-optimal and untimely. Consequently, the benefits of adopting prefabrication technology will be easily wipe out. Third, diversiform systems and data hampers information sharing among different stakeholders. The decisions made by a manager is local optimal and impact the system performance. Besides, owing to the fragmentation, any disruptions and emergencies in one stage is difficult to be noticed by other stakeholders timely, which enhances difficulty of coordination and cooperation.

In order to address the identified shortages discovered in a MiC project, the innovative design aims to propose an integrated IBIMP which is grounded on the Auto-ID, IoT and BIM technology to improve information collection reliability, to realize real-time information visibility and traceability and enable intelligent information transmission, to support decision making, and to facilitate the collaboration among different stakeholders. With the assistance of IoT technology, IBIMP can make information obtained, updated and exchanged more easily and efficiently. In addition, with the help of cloud computing, IBIMP can provide the automatic decision support in MiC projects. Once any exceptional events happen, the IBIMP can automatically send notice to the managers, i.e., send alert, alarm, and action reminder according to the degree of emergency. Automatic notices facilitate the manager to better supervise the processes and to quickly response to these events. On the other hand, based on the real-time, accurate and complete information collected from the entire construction process, the IBIMP is able to make reasonable, precise and scientific decisions.

3. OVERALL SYSTEM ARCHITECTURE

The overall system architecture of the IoT-enabled BIM platform (IBIMP) is shown in Fig. 6. The architecture comprises three key layers, from the bottom to the top, including Infrastructure as a Service (IaaS) layer, Platform as a Service (PaaS) layer, and Software as a Service (SaaS) layer.

3.1 Infrastructure as a Service layer

IaaS of the IBIMP includes smart construction objects (SCOs) and smart gateway system for SCOs. SCOs are construction objects (e.g., prefabricated modules, tractors, trailers, workers, machines, raw materials, inventory, and on-site buffer area) that are equipped with the smart trinity tag (STT) and GPS sensor and thereby converted into "smart" objects. A STT consists of three types of Auto-ID tags, i.e., active radio frequency identification (RFID) tag, near field communication (NFC) tag, and QR code. The reason for the adoption of STT is that, in a harsh, dynamic environment like construction, the use of STT can significantly decrease the chance of information loss due to the failure of one type of Auto-ID tag.

For each STT, the data strings storied in its RFID tag, NFC tag, and QR code for identification should be consistent. Otherwise, the SCO will have two different IDs, causing potential confusion in its identification. In addition, the adoption of STT allows different types of readers to be used. Specifically, active RFID readers can be placed at value-adding points (e.g., gate of the construction site) to sense and detect SCOs automatically. Hand-held NFC or QR code reader can be used by workers to access and record information of specific SCO. Apart from the STT, the GPS sensor can provide the location information of construction objects, especially those critical construction objects. Through the use of Auto-ID device and GPS sensor, each SCO can have its unique identification number and report its real-time location, enabling the location-based service (LBS) in PaaS layer of the IBIMP.

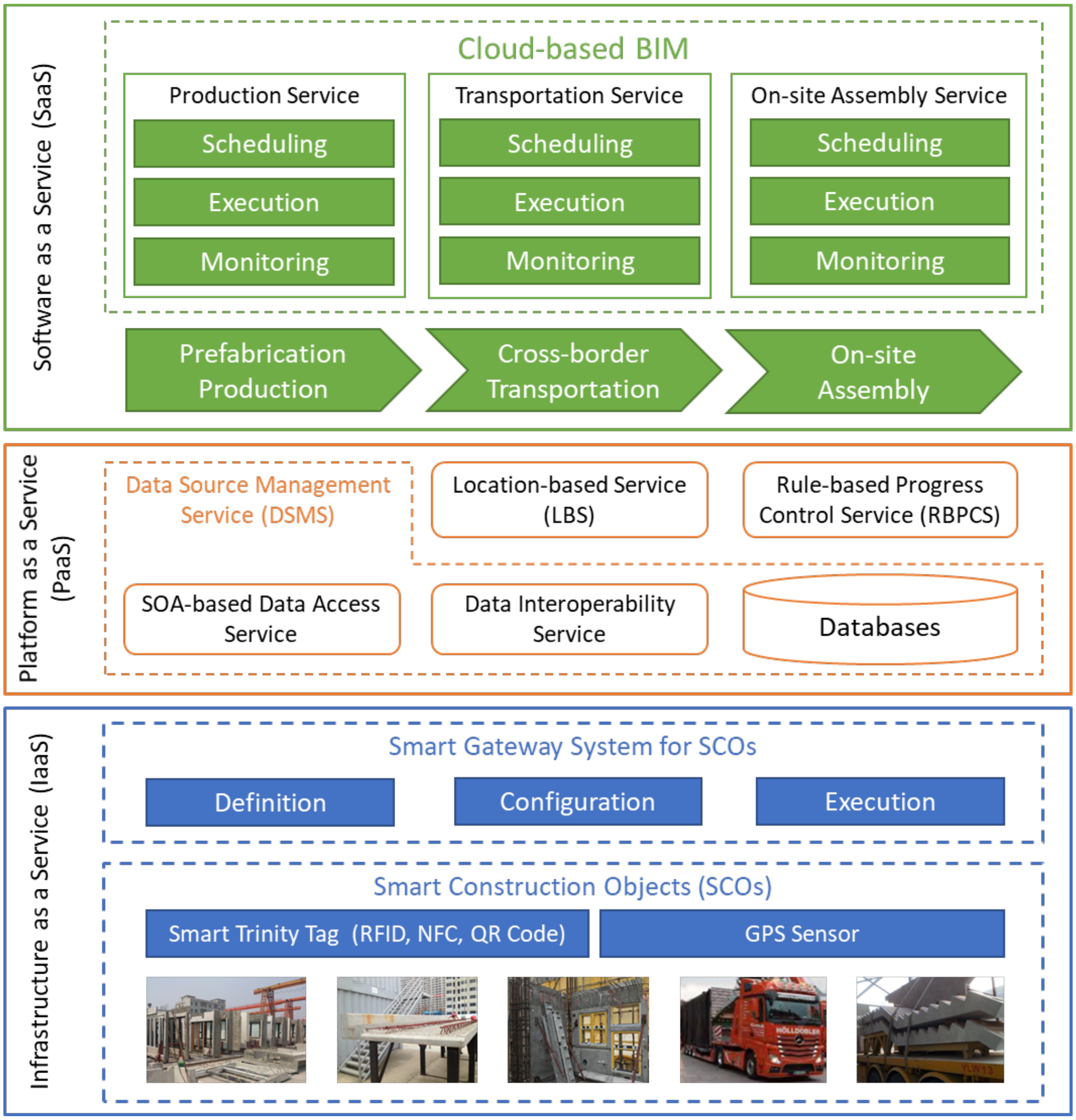

Fig. 6. System architecture of IBIMP

The gateway is a light-weighted middleware system that can run on the fixed workstations or mobile devices (Fang, Qu, Li, Xu, & Huang, 2013; Lu, Huang, & Li, 2011). It will be set up on the raw material buffer area, prefab manufacturing shop, warehouse entry, dispatching area, trailer and tractor, intermediate check point, construction site, on-site buffer area, and crane tower for real-time data collection. The gateway provides several functions for the management of SCOs. First, the gateway connects a set of SCOs through wireless communication standards. Based on standardized connection, operators can define and configure SCO by assigning the tag ID to the tag-attached construction object. Second, the gateway allows operators to access information such as the status of SCO in order to execute their daily tasks. Third, the gateway acts as the bridge that communicates with the upper layers, i.e., PaaS and SaaS, of the IBIMP. Thus, real-time data captured by SCOs can be seamlessly synchronized with the decision support services. Fourth, it can pre-process and cache real-time data locally and temporally in case the communication network is unavailable, which helps eliminate the risk of information loss (Chen, Lu, Xue, Zheng, & Liu, 2018). By combining the Auto-ID technology with gateway, the unique identification of all kinds of construction objects can go through the whole lifecycle of prefabricated module production, transportation, on-site assembly and maintenance. All kinds of activities and status can be easily collected, monitored, controlled, shared and recorded.

3.2 Platform as a Service layer

PaaS layer of the IBIMP consists of Data Source Management Service (DSMS), Location-based Service (LBS), and Rule-based Progress Control Service (RBPCS). DSMS works as an information sharing adapter that ensures heterogeneous data from various sources can be seamlessly integrated. A detailed illustration of DSMS is presented in Fig. 7. Relational databases such as MySQL and Access are used to store the design information of prefabricated modules and the real-time data collected by SCOs. In the database, design information and collected data are stored in different types, like numeric or string types. The service-oriented architecture (SOA) is adopted to integrate the collected data from SCOs into a standardize form. The SOA-based data access service is designed to standardize the data passing through the gateway, enabling the data can be easily shared, transferred and used by various isolate systems (i.e. enterprise resource planning (ERP)). The operator will send a request token to the service. The token is a Structured Query Language (SQL) statement indicating the target data source to query and the filter criteria in "SELECT", "FROM", and "WHERE" statements. Once the data interoperability service receives the token, it will parse the token and retrieve the required data from corresponding databases. The retrieved data is compiled into standardized XML files for further processing by other services of IBIMP.

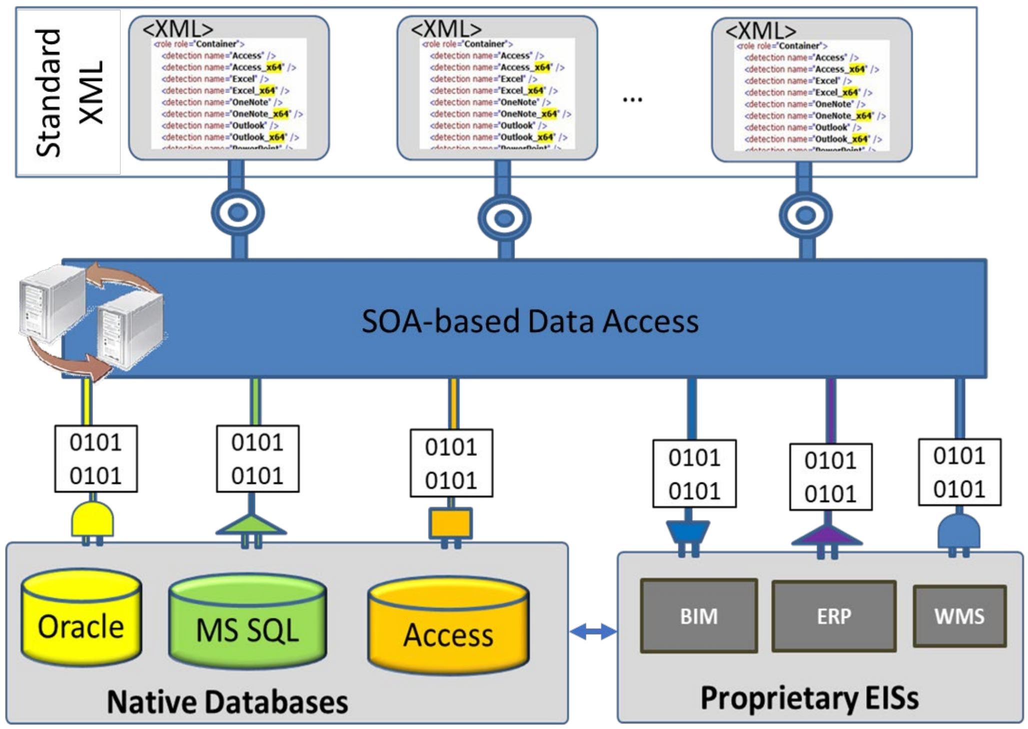

Fig. 7. Details of DSMS

LBS uses the location and time information to provide value-added management applications (Barak & Ziv, 2013, Motamedi, Soltani, & Hammad, 2013). In IBIMP, the location information of SCOs is collected by the GPS sensors, and LBS will integrate the collected location information so that the relevant, up-to-date information about SCOs' surroundings can be reported to end-users (see Fig. 8). Such information integration is completed by adopting both pull and push mechanism. For the pull mechanism, LBS will integrate the location information of the prefabricated modules at the moment that the attached STT is scanned by a reader. For the push mechanism, the location information of the vehicles during the delivery of prefabricated modules will be activity recorded in the database and integrated by LBS. With the help of LBS, different stakeholders can be timely informed of the location information throughout the prefabrication supply chain, and the real-time transportation routine of the prefabricated module can also be visualized according to LBS. Both functions enabled by LBS are important to the achievement of the JIT delivery strategy.

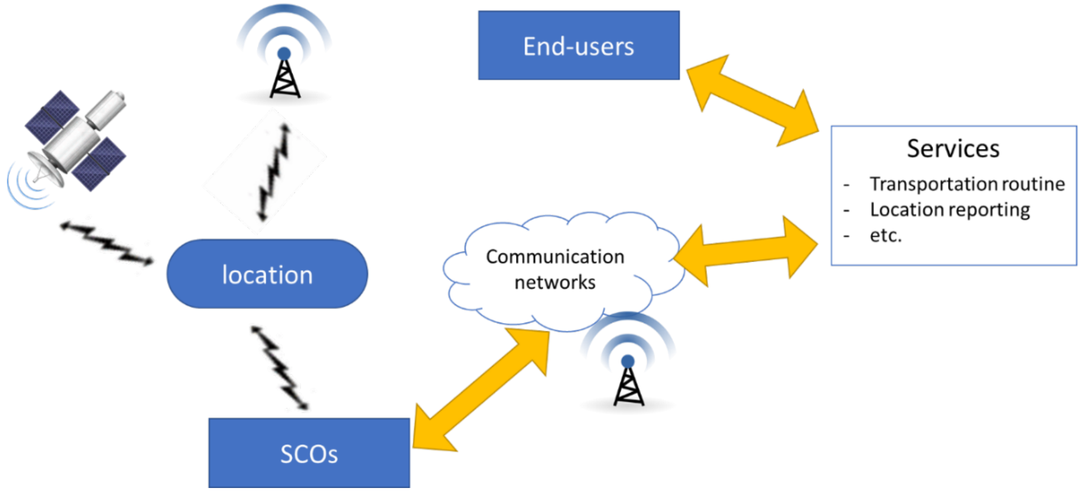

Fig. 8. Illustration of LBS

RBPCS used rule-based approach to make decisions for progress control. The benefits of rule-based approach are that it separates knowledge with the reasoning process to fit various progress control practices and can reflect the best knowledge of experts (Deng, Cheng, & Anumba, 2016). In the rule-based approach, knowledge is represented as rules, and data is abstracted as events (Asadi & Ghatee, 2015). When events meet the conditions of one or more rules, the service will automatically trigger the rules and generate the results in a way that coordinate with the business logics of back-end applications, i.e., suggesting suitable actions for progress control. In this study, all rules are written in Semantic Web Rule Language (SWRL) and will be processed by Stanford Protégé which is an ontology editing environment and directs in-memory connections to description logic reasoner (Musen, 2015). An example of the rule is illustrated in Fig. 9.

```
alarmRule   PrefabircatedComponent (?p)
            ^ ProductionDate (?p, ?d)
            ^ ExpectedDate (?p, ?c)
            ^ Gap (?p, ?g)
            ^ swrlb:lessThan (?g, 14)
            ^ OverFourteen (?g, false)
            ^ Suggestion(?g, ?alarm)
            → NeedAlarm (?p, ?alarm )
```

Fig. 9. Illustration of the rule

3.3 Software as a Service layer

SaaS layer of the IBIMP contains three services, i.e., production service, transportation service, and on-site assembly service, that are centred on cloud-based BIM. The cloud-based BIM refers to an organic combination of the cloud computing technology and BIM, distributing software, computing power, and storage capacity required by BIM in the cloud (Li & Ma, 2016). The emerging cloud computing technology is considered to leverage the benefits of BIM by addressing the standalone nature of conventional BIM and leading to high level of cooperation and collection (Wong, Wang, Li, & Chan, 2014). The development of a cloud-based BIM starts with developing the model in BIM software such as Autodesk Revit. In BIM software, each BIM object is assigned with a unique name following a structure naming convention (Chen, Lu, Wang, Niu, & Huang, 2017). Next, data of BIM objects is converted into JSON format which can be rendered by Web Graphics Library (WebGL) into interactive 3D graphics. After that, interfaces are designed based on Internet Protocols such as HTTP and FTP for information exchange between the cloud-based BIM and databases. Taking advantages of cloud computing technology, the developed cloud-based BIM allows end-users to directly view and modify the BIM model through the browser. The production service, transportation service, and on-site assembly service will make use of the services in the PaaS and IaaS layers of the IBIMP and support the management of prefabrication production, transportation, and on-site assembly separately. Detailed descriptions of these three services will be presented as follows.

3.4.1 Prefabrication production service in MiC project

The production service is developed for managers and workers involved in prefabrication production process to better management and supervise the processes. Three key sub-services are provided. First, the production scheduling and planning service receives the orders from the contractor and breaks them down into individual production task. The information about each production task, including order ID, module type, module ID, and date of requirement, is presented to the production management in a table format. The production manager can make the production plan, i.e., setting the planned production date and assigning the specific operators to each prefabricated module according to the urgency of these orders. Second, the production execution service is used by workers when executing the production task. Through the production execution service, workers can view the production tasks assigned to them and record the production information by scanning the STT of prefabricated modules. Third, the production monitoring service shows the real-time status of production task, based on which the production manager can clearly monitor the progress of individual production tasks and can even re-prioritize the production task dynamically.

3.4.2 Prefabrication transportation service in MiC project

The transportation service is developed for the logistics company that is responsible for delivering the prefabricated modules from the manufacturing factory to the construction site. Three key sub-services are provided. First, the transportation scheduling service helps make the optimal decision about the delivery of prefabricated modules. This service can automatically develop the transportation plan for each bunch of prefabricated modules according to the date that the modules should reach the construction site. The manager of the logistics company is also allowed to manually assign driver and transportation vehicle to each transportation task and adjust the automatically-generated schedule. Second, the transportation execution service is used by drivers to view their transportation tasks and deliver the prefabricated modules according to the plan. The transportation execution service uses STT and GPS sensors to track transportation status. In addition, the transportation execution service will bind the tag IDs of the transportation vehicle and prefabricated modules. Therefore, when the status of transportation vehicle changes, the status of prefabricated modules can change simultaneously. Third, the transportation monitoring service will show the real-time status of individual transportation tasks to the manager. Based on the precise, actual situation, the manager can make coordinating decisions and operations in a smooth manner.

3.4.3 On-site assembly service in MiC project

The on-site assembly service is developed for the contractor to manage and supervise the assembly of prefabricated modules at the construction site. Three key sub-services are provided. First, the construction scheduling service optimally establishes the assembly plan based on the current construction progress and available resources. Second, the construction execution service is used by workers when carrying out the assembly of prefabricated modules. Workers can view the assembly task and retrieve relevant information such as the designated location of the module to be installed. Similar to the transportation execution service, the construction execution service uses STT and GPS sensors to record the assembly information. In the meantime, the LBS helps automatically check whether the prefabricated module is installed at the correct location. Such real-time feedback enables improved accurate of the assembly work. Third, the construction monitoring service is developed to monitor the construction progress. Key information such as progress, current status, and on-site situations will be retrieved from the databases and shown in a cloud-based BIM model where the digital prefabricated modules were marked in different colours to indicate their real-time status. Analytical charts, such as S-curve of the project progress, will be presented to the manager. Both the cloud-based BIM model and the analytical charts improve the information visibility and traceability. Additionally, based on the real-time construction progress, the RBPCS allows several management issues being finished automatically. For example, if the construction scheduling service identifies one prefabricated module is not produced 21 days in advance, the service will generate an alert warning to the project manager. If the prefabricated module is still not produced 14 and 7 days in advance, the service will generate alarm and action warnings, respectively, to the project manager. Based on the warning received, the project manager can take immediate actions to avoid potential delay.

4. APPLICATION SCENARIOS

Our research follows a leading, real-life project to develop and implement IBIMP for use in design, construction, operation and management of subsidized sale flats. The period of case study starts from 15th January 2018 to 8th December 2018, including 32 stories. To deploy the IBIMP and to collect data, a series of site visits, interviews and training courses are carried out. Managers and engineers operate the developed IBIMP for facilitating management, decision-making, and real-time monitoring in a MiC project.

4.1 IBIMP application in prefabrication production

Objects, such as raw materials, prefabricated modules, machines and workers are equipped with STT and GPS sensor for real-time, accurate and complete information collection. Smart tag readers are installed at fixed positions or held by workers facilitating data collection. Several services are exploited to facilitate material management, production planning and scheduling, production execution management, and process monitoring. The application of IBIMP in prefabrication production is shown in Fig. 10.

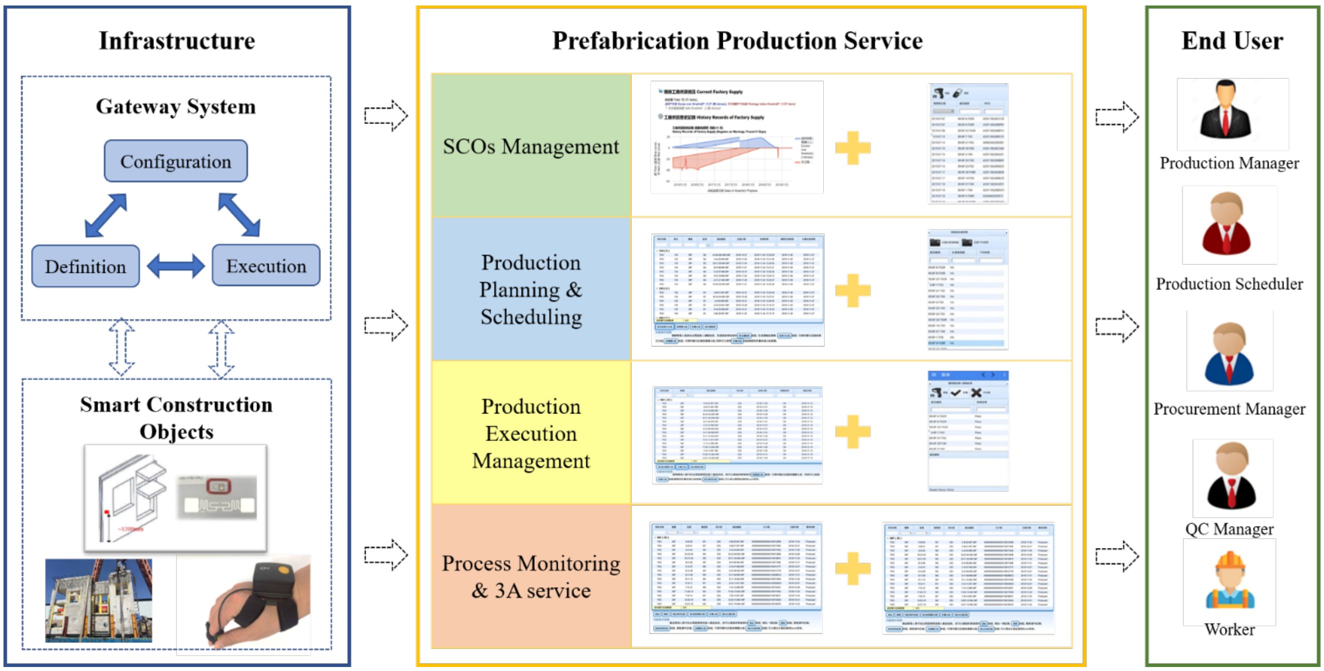

Fig. 10. Application of IBIMP in prefabrication production

- ***SCOs Management***

In the prefabrication production stage, the STT connects the prefabricated modules with IBIMP. An exclusive identification number, regulated by the pre-defined naming protocol, is set in the STT to register the prefabricated modules in the dominant database and combine its information with the IBIMP. The STT attached to the prefabrication modules facilitates collection of real-time production information, including generating a materials list for production, de-molding, quality control, and availability for logistics preparation. After the prefabricated modules are stored in the outbound area, the status of the module from "Manufacturing" to "In storage" and therefore update such information in the database automatically. The inventory level of raw materials and prefabricated modules can be easily get accessed. Since the physical prefabricated modules are linked with the digital representation in IBIMP, the production manager and scheduler can remotely monitor the status of the prefabricated modules, which enables real-time information visibility and traceability.

In addition to the STT, the GPS sensors will help collect information about the real-time location of prefabricated modules. Through the IBIMP, the location of all the modules is displayed based on synchronously GPS data transmission from time to time. The status of the modules can be determined based on the location-based services and the on-going progress.

- ***Production Planning & Scheduling***

The production scheduler input the production plan in the “production management” page. A production plan specifies the type, number, quality requirements, and delivery due date of the prefabricated modules. Once a new production plan is entered, the system will upload the data to the database. The web system allows searching a specific item by keywords, such as, production date and type. If a hardcopy is required, the web system can export the selected information as an Excel file for printing.

- ***Production Execution Management***

After producing, the prefabricated component should be equipped with a STT. Then the worker opens the “binding” page in his mobile app to write in the prefabricated module information (e.g., type, floor, produced date, project, and weight) to the STT. Meanwhile, the binding date and GPS data will be automatically collected by the app and uploaded to the database. QC After that, the QC manager open the “quality check” page in the mobile app to record the quality-checking results. Instead of recording in papers, the QC manager only need to read the STT and touch the button. The qualified modules will be loaded on a trailer in the outbound area and waiting for transportation. The production manager should confirm the delivery order in the “delivery management” page and assign the loading tasks to the workers. After loading, the workers open the “delivery” page in the mobile app to collect the loading time of each prefabricated modules. This information will be transferred to the database in a real-time manner.

The status and location of prefabricated modules changes with the activities automatically and simultaneously. The production manager can supervise the production process (i.e. unbound, demolding, producing, and produced) in his office. With the help of location-based service, finding a prefabricated component takes little time. Flow chart of production process not only supports efficiency decision-making but also records history data for facilitating productive improvement.

- ***Process Monitoring & 3A service***

All the collected real-time information from STT and GPS sensor are linked with BIM in the developed IBIMP. Traceability and visibility of the production information, including the overall progress and status of individual prefabricated modules are always available throughout the entire production process. The paper-based records are subsequently freed for many processes and only reserved for a few key verification processes. Relying on the real-time information, the management of the prefabrication production becomes more efficient. The sharing of real-time data and the status of the virtual models can also be used in proactive ways. For example, SMS and pop-up notification of imperative events are used to guide the relevant workers. Additionally, the production manager and workers would be alarmed once on-time production is hampered by any uncertain events or a tardiness has taken place. Actions should be carried out to reschedule the production plan or to adjust the transportation plan and assembly plan.

4.2 IBIMP application in prefabrication transportation

Various construction objects, such as trailers, tractors, drivers and vehicle parking lot, are equipped with STT. Several services are exploited to facilitate fleet management, transportation planning and scheduling, transportation execution management, and process monitoring. The application of IBIMP in prefabrication transportation is shown in Fig. 11.

- ***SCOs Management***

Attached with the STT and GPS sensor, the tractors, trailers, and drivers are changed into SCOs which can achieve information tracking, updating, and monitoring. After each prefabricated module is loaded on the trailer in the outbound area, a transportation order is generated, denoting which trailer contains which prefabricated modules. The transportation orders will become accessible and imported into the prefabrication transportation (PTS) system. In the order page, all transportation orders waiting for handling are listed. Information of order such as ID, customer, project, origination, and destination are all encompassed in the list. Orders is editable before the scheduling starts, in case some urgent changes come out, such as increasing, decreasing or replacing. In fleet management page, basic information of the vehicle includes license, capacity, and type. Status information is shown according to real-time collected from these SCOs and can be edited and modified according to the actual requirement. Driver's status and information can also be tracked and managed in the driver management tool.

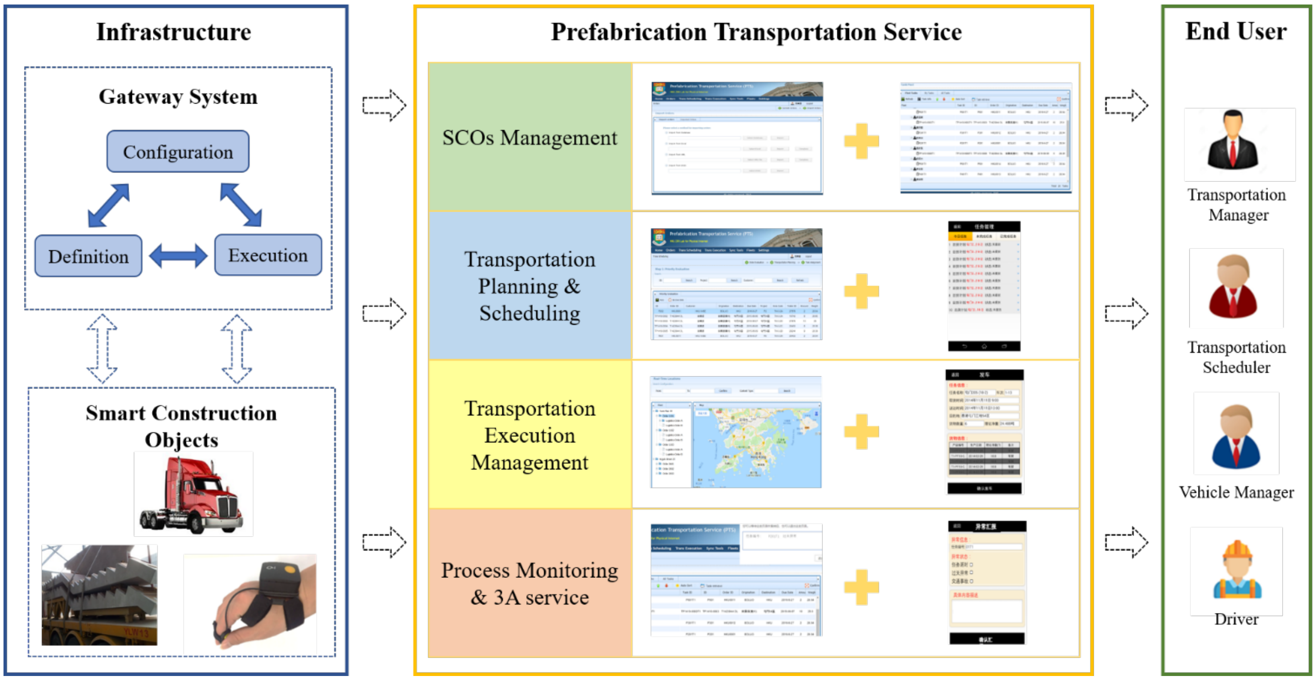

Fig. 11. Application of IBIMP in prefabrication transportation

- ***Transportation Planning & Scheduling***

In this function, the transportation mode will be decided with the direct to on-site or through the intermediate warehouse. Then the transportation information such as due date and status will be analyzed and evaluated with built-in sorting rules to automatically decide the sequence of orders handling. After confirmation by the transportation manager, orders will come to the scheduling step. The transportation manager can manually assign transportation tasks to drivers or the order can be automatically divided into several sub-orders while taking the site requirements and trailer workload balancing into consideration. Then the system assigns the task to drivers automatically according to real-time drivers' status. PTS manager can also manually assign orders to drivers with specific requirements.

- ***Transportation Execution Management***

The driver logins to the task management application in the mobile app with his user ID and password. After drivers received the transportation task, five steps will be executed:

pick up the tractor, pick up the trailer, departure, passing the customs, and finish the delivery. First, the tractor driver will come to get the tractor and scan the STT to confirm and to record the right tractor has picked. Second, he drives the tractor to the outbound area get the trailer loaded with prefabricated modules. After checking the information, the driver updates the task status and starts the transportation process. Real-time information of task execution status, and vehicle location will be updated in the system automatically and accurately. When passing to the custom, a status denoting whether the custom clearance goes well will report to the transportation manager. Then after the prefabricated modules are shipped to the construction site, the site manager will confirm the number, types, quality of prefabricated modules with the driver. If all the information is correct, the site manager will unload these prefabricated modules to the on-site buffer area and the driver can finish the task.

- ***Process Monitoring & 3A service***

For the real-time trace services, the real-time transportation status can show the whole transportation time and distance, as well as the speed. Any delays regarding the transportation process within a certain period of time will be recorded on the map and reported to the transportation manager. If the shipping process is slower than expected based on historical data, alert information will be sent to the driver. Transportation operators can timely upload the emergency status when driving such as no signal, customs clearance delay, or traffic jam. With the alarm information, the transportation manager can quickly response to the emergency and inform the driver. Actions such as withdraw tasks or temporarily change shipping destinations will be implemented according to the actual situation. Automatic decision support is also integrated to the PTS, with the collected and recorded information, the transportation scheduling can be further optimized according to the history data.

4.3 IBIMP application in on-site assembly

Objects, such as building materials, on-site buffer, crane tower, machines, on-site vehicles and workers are equipped with STT and GPS sensor for data collection. Several services are exploited to facilitate construction object management, assembly planning and scheduling, assembly execution management, and process monitoring. The application of IBIMP in on-site assembly is shown in Fig. 12.

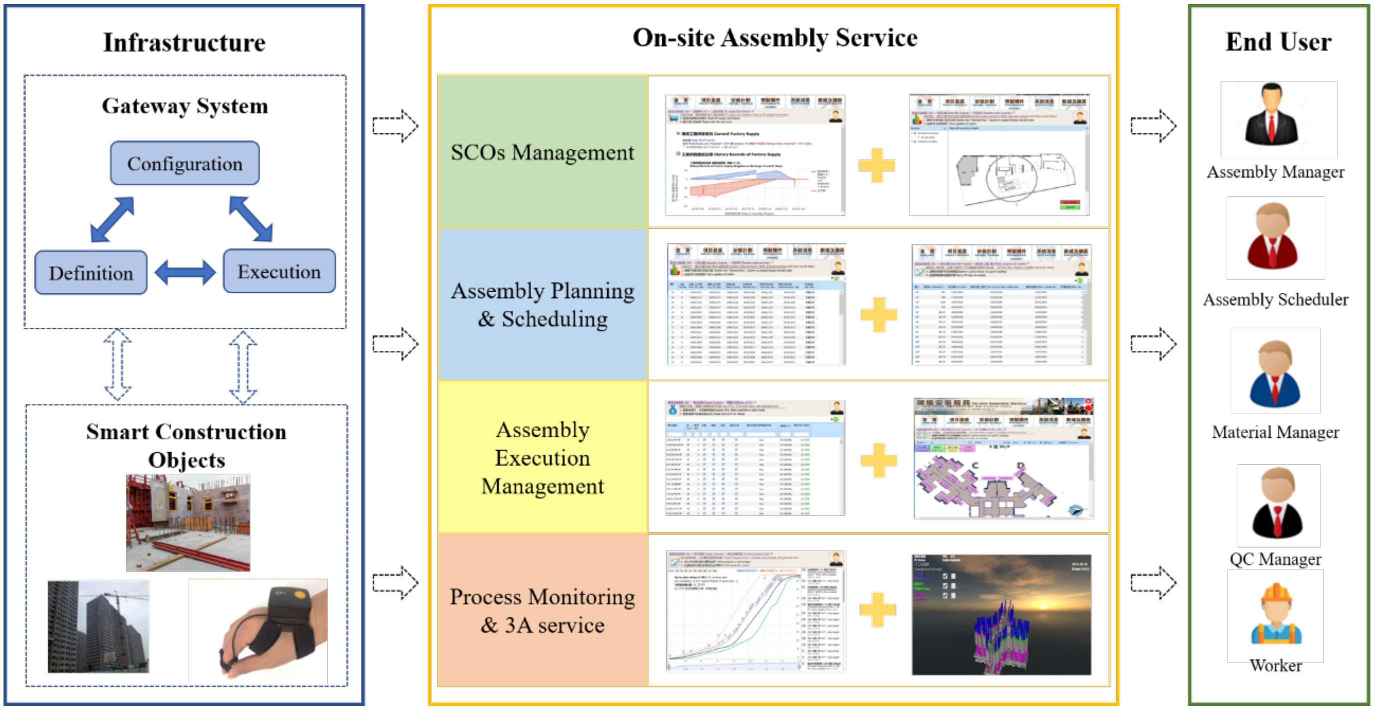

Fig. 12. Application of IBIMP in on-site assembly

- ***SCOs Management***

Once the prefabricated modules arrive on-site, the worker scans the STTs to confirm the arrival of required modules. Then, the workers at buffer checks the prefabricated modules after unload and signs if it is well delivered and click the “confirm” button on the mobile app. If some flaws or defects are found, the workers should click the “reject” button. The qualified modules are placed in the on-site buffer for further erection and the status of prefabricated modules become “ready to install”. The on-site asset can also be managed and controlled effectively and efficiently with the aim of optimizing the efficiency of resources utilization and streamline the on-site assembly process of the project. The IBIMP allows to monitor the status of on-site buffer area (occupied or empty), which is displayed in different colours to signify the status of the buffer. If the status of the prefabricated modules is at ‘ready to install’ stage, the buffer indicates occupied; If the status of façade is at ‘erected’ stage, the buffer shows available.

- ***Assembly Planning & Scheduling***

Based on the master plan, real-time assembly progress, and status of prefabricated modules, the assembly manager revises the assembly schedule before each building cycle in the “assembly program” page of IBIMP. Simultaneously, the up-to-date assembly schedules are synchronized to the mobile app. The foreman and workers can plan their activities and working sequences according to this schedule.

- ***Assembly Execution Management***

Based on the assembly schedule, the assembly operator gets job and assembly instructions by scanning STTs. Also, the mobile app will provide assembly workers the demonstration videos to visualise the assembly work. After erection completed, the assembly workers scan the targeted module and click ‘confirm button’ on the mobile app to confirm the actual erection time of prefabricated modules. The real-time information will be transferred to the IBIMP for facilitating further assembly scheduling.

- ***Process Monitoring & 3A service***

Real-time supervision refers to monitor the assembly process, the availability and consumption of building materials, and the positioning of prefabricated modules. The actual progress regarding the master program of RC structure construction can be compared with the planned ones by using a line chart to monitor construction progress visually and identify any delays directly. Any delay events, and total delay days are displayed in the system. The cumulative quantity of prefabricated modules erected is recorded by real-time assembly data, displayed in percentage of total consumption.

Real-time progress visualisation aims to monitor prefabricated construction progress in a virtual environment with real-time information, under six crucial stages, like producing, produced, delivering, arrived at the site, ready to install, erected. In the developed IBIMP, the digital prefabricated modules are displayed in different colors to signify the current status of prefabricated modules. six stages marked with discriminative colors are involved in the process of prefabricated construction to realize real-time supervision of project progress. When clicking on a certain color, modules in that status will be highlighted. Additionally, real-time prefabricated construction progress can be visualized grounded on the 2D floor plan, which contains more concrete and precise information in terms of prefabrication assembly status of each prefabricated module of each typical floor.

Real-time feedback is the prerequisite to realize 3A function. Real-time feedback aims to report the current status of the on-site assembly process to different parties involved and other interested associations. It allows different stakeholders to get access to the up-to-date status. The real-time feedback model is developed by using critical information so that those related parties could make associated decisions on production or logistics in line with the current assembly requirements. Assembly notification services for facilitating in reminding and notification for subscribed users, as shown in Fig. 13. Any exceptional event, like production or transportation delays, will be recorded and issue alert dialog on the website and mobile app. The site managers will receive the alert or alarm immediately. In reverse, once there is any delay regarding on-site assembly process, the production and transportation company will receive schedule delay alarms. Additionally, the notification service is realized by sending email alerts for managers and engineers who work in the office, SMS notification service.

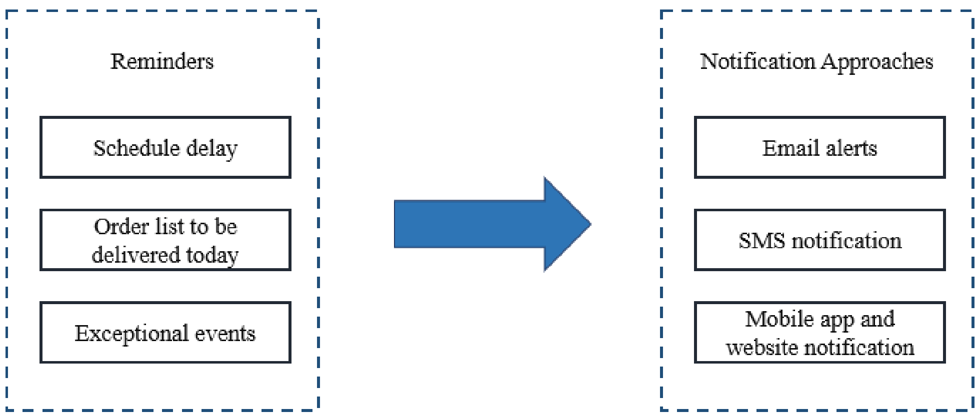

Fig. 13. Assembly notification service

Real-time progress is deployed to achieve real-time traceability and visibility of the whole prefabricated construction process, which provides the main contractor powerful toolkit to efficiently and effortlessly monitor and control the on-site assembly process. Moreover, the main contractor can be aware of any delays in the production or delivery stage, carrying out schedule adjustment or exception handling to cope with any deferred events promptly. By applying real-time information, the IBIMP will reflect real-time prefabricated construction progress with related line chart. Therefore, all involved stakeholders can be aware of real-time situations and make associated decisions collaboratively.

4.4 Discussion of implementation

The proposed IBIMP solves the problems faced by the MiC project, overcomes the barriers which hamper the working efficiency and convenience of a construction project, and explores the potential of BIM platform. Attaching construction objects with STTs largely decrease the chance of information loss due to the failure of one type of Auto-ID tag. The manual work and paper based working approach can be further reduced owing to the reliability of the STTs. With the assistant of IoT technology, the IBIMP enables flexible and seamless connection between SCOs with its upper layer. Besides, the information transfer among different stakeholders becomes timely, accurately and complete, which supports managers to make reasonable, scientific and comprehensive decisions and enables real-time coordination among different parties. The whole construction cycle can be monitored in a real-time manner. All the involved parties are benefit from the proactive notification (i.e, 3A service), for any emergency or process changes will not be missed. Real-time feedback largely shortens the response time and thus reduces MiC project time and cost overrun.

Besides qualitative approach, quantitative approach is also carried out. KPIs are collected before and after deploy the IBIMP in the selected case project. Tab. 4. illustrates the definition of KPIs and presents comparative results. By integrating the 3A service in the IBIMP, the time for realizing unusual events is reduced by 85% in production stage and 80% in transportation and assembly stages respectively. With the assistant of reliable information collection and automatic decision making, the order releasing time and the drivers idle time are reduced by 66.7%. Also, the rescheduling time for coping with emergencies are reduced by 92.8%. Besides, visibility and traceability tools facilitate project supervision, it can be observed that the on-time delivery rate in production, transportation and assembly stage are improved more than 12.5%, 7.3%, and 25% respectively. These significant improvements demonstrate the efficiency of the proposed IBIMP. The challenges faced by the real-life MiC project are largely reduced by the propose IBIMP.

Tab. 4. Requirements analysis of prefabricated module production

Stages	*KPI*	*Definition ,*	*Before*	*After*	*Improvement*
Production	Paper work	NO. of paper used to record as complement to digital documents	10-20 papers	≤ 9 papers	More than 10%
	Production time	Time requires for finishing the production process	8-10 days	<7 days	More than 12.5%
	Emergency detecting time	Average time to notice an emergency event in production process	10-30 mins	3 mins	Average 85%
	Emergency response time	Time requires for adjusting the production plan if any emergency happens	7 days	0.5 days	92.8%
Transportation	Transportation task scheduling time	Time requires for scheduling transportation tasks according to the transportation order	1 day	10 mins	99.3%
	Driver idle time	Drivers wait at the factory before the delivery	3-6 hours	1-2 hours	Average 66.7%
	Task releasing time	Time to get the task	5-10 mins	2-3 mins	Average 66.7%
	Vehicle locating time	Time spent on locating a trailers or tractors in a warehouse	5-10 mins	2-3 mins	Average 66.7%
	Transportation time	Time to transport the manufactured prefabs from production factory to construction sites	3-4 hours	2-3 hours	Average 28.6%
	On-time delivery rate	Probability to deliver the prefabricated modules to the construction site before the due date	92.5%	99.8%	7.3%
	Emergency detecting time	Average time to notice an emergency event in transportation process	5 mins	1 min	80%
Assembly	4-days assembly cycle	The target assembly time for building one floor is 4 days	5-7 days	4 days	Average 33.3%
	6-days assembly cycle	The target assembly time for building one floor is 6 days	7-9 days	6 days	Average 25%
	Emergency detecting time	Average time to notice an emergency event in on-site assembly	10 mins	2 min	80%
	Prefabricated module information collection	Time requires to collect the status and location information of a prefabricated module	2 mins	<1 min	More than 50%

5. CONCLUSION

This paper presents an Internet of Things-enabled BIM platform (IBIMP) that facilitates the delivery of MiC projects through enabling real-time information collection, autonomous decision supports and emergence alarm. Application scenarios from a subsided sale flats project in Hong Kong are presented to demonstrate the benefits of this platform. First, the smart construction environment is built by equipping conventional construction objects with smart trinity tag (STT) and GPS sensor. This IoT-enabled technology not only transfers these construction objects to smart construction objects, but also provides a compatible way to capture information of SCOs so as to hedge against information loss owing to the possible failure of a single type of Auto-ID tag. Combining the smart gateway technology, the data can be timely and conveniently transferred and operated among stakeholders. Stakeholders in the MiC project can easily track a prefabricated module's status, location, quality, and cost in a real-time manner. Second, with the help of advanced information management and process technologies, the IBIMP is able to automatically provide various value-added services, such as 3A function. Rule-based process control service automatically informs emergencies to the end-users in a certain order and quickly provides optimal guidelines for the managers. Third, this platform integrates complete real-time information which expands the scope of automatic decision-making and facilitates both horizontal and vertical collaboration. Information of construction objects, working crew status, inventory level, and working space condition are accurately captured by IoT technologies. Base on this comprehensive, real-time data, any construction activities can be easily supervised and controlled.

Despite the various significances, the IBIMP can be further improved and extended by carrying out future research from several aspects. First, even this research pioneers on transferring a passive construction environment to an active one, the automatic decision making only focus on rescheduling after any uncertainty happened. The functions of operational hedging decision can also be integrated into the IBIMP for preventing potential risks. Second, the performance and working efficiency of a construction project can be further improved by processing and analysing the collected data. In this way, the advanced technology such as Big Data can be adopted and integrated to the IBIMP (Bilal *et al.*, 2016;

Zhong, Newman, Huang, & Lan, 2016). Third, in order to improve and extend the applicability of the IBIMP in other projects and regions, more practical testing should be carried out. By this means, not only the generalizability of IBIMP can be verified, but also a list of optional functions required by more end-users can be identified.

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