https://doi.org/10.1016/j.jclepro.2017.07.156

Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction

Clyde Zhengdao Li [a], Ray Y. Zhong [b], Fan Xue [c], Gangyan Xu [b], Ke Chen [d], George Guoquan Huang [b, *], Geoffrey Qiping Shen [e, *]

a College of Civil Engineering, Shenzhen University, China b HKU-ZIRI Lab for Physical Internet, Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam, Hong Kong

c

Department of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Hong Kong

d Department of Real Estate and Construction, The University of Hong Kong, Hong Kong

e

Chair Professor of Construction Management, Department of Building and Real Estate, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

Abstract

With its generally recognized benefits of clean and safe working environment and good quality, prefabricated house construction (PHC) as a solution is gaining momentum in the face of various housing challenges in Hong Kong's construction industry. Although prefabrication has its own benefits, its fundamental disadvantages of fragmentation, discontinuity, poor interoperability, and scarce real-time information availability have imposed significant adverse influence on the schedule performance of prefabricated house construction. As a result, despite the promise of the government to provide sufficient houses and harmonious housing, schedule delay problems still frequently beset the industry of PHC. To help address schedule delay problems encountered in the construction of prefabrication housing, this research first identified and analysed critical schedule risk factors that may have significant influence on the schedule performance of PHC. Based on the identified schedule risks, the challenges and corresponding required functions for enhancing schedule performance are determined. Then, a radio frequency identification device (RFID)-enabled BIM platform that integrates various involved stakeholders, information/data flow, offshore prefabrication procedures, and state-of-the-art construction technologies, is developed to handle the critical schedule factors. Smart construction objects and RFID-enabled smart gateway work collaboratively to ease operations within the three echelons of prefabrication manufacturing, logistics and on-site assembly construction, while real-time captured data are used to form a closed-loop visibility and traceability mode in which different end users can supervise the construction statuses, progresses in real time. The developed platform can provide various services, tools and mechanisms to different stakeholders, improve the success of daily operations and decision

makings throughout PHC management, such that critical schedule risks can be mitigated and the schedule performance of PHC can be enhanced to ensure timely project delivery.

1. Introduction

Limited availability of land and expensive land prices have resulted in the prevalence of high-rise building construction in Hong Kong. Only a small percentage of the people can afford the high prices of the dwellings of private housing, with about 50% population resides in public housing (Census and Statistics Department, 2015). Widespread discontent is expressed over housing issues, and the calls for harmonious housing in this society are increasingly heard. To meet the high demand of public housing, the Hong Kong Housing Authority (HKHA) planned to supply 91,900 public flats in the following fives year as of the end of 2016, while achieving such an ambitious housing plan in a short timeframe is doubtful (Hong Kong Housing Authority 2016). Besides, the construction industry is also facing a serious labor shortage and the labor cost in Hong Kong is skyrocketing (Li et al., 2017). The execution of an ambitious housing plan may further affect the environment because of problems such as increasing noise pollution, greenhouse gases, dust, construction waste, and high consumption of non-renewable natural resources. Hong Kong needs to balance between the housing production demand and constraints construction, such as safety, environment protection, time, and labor shortages. With its generally recognized benefits of fast process, clean and safe working environment, and good quality, prefabricated house construction (PHC) is gaining momentum as a solution to the various housing challenges in Hong Kong's construction industry (Li et al. 2014a, 2014b; Hong et al., 2015; Hong et al., 2016; Wang et al., 2015; Zhang et al. 2011, 2015).

However, the above-mentioned benefits of using prefabrication cannot be achieved without envisaging its problems. Building design, precast components production, logistics, and prefabrication installation processes are still mostly discontinued and fragmented. Current PHC conditions exhibit poor data interoperability and lack of capacity of visualizing and tracing information in realtime manner (Li et al., 2016b). A relatively new initiative has seen the transfer of the entire prefabrication sector in Hong Kong to offshore areas (Zhongshan, Huizhou, Dongguan, Shenzhen, and Shunde) in the Pearl River Delta (PRD) region. This move helps exploit the cheap labour and abundant material supplies available in that area, but it also exacerbates the drawbacks of using prefabrication. As a result, despite the promise of the government to provide sufficient houses and harmonious housing, schedule delay problems still frequently beset the industry of PHC.

To help alleviate schedule delay problems encountered in the construction of prefabrication housing, this research develops a radio frequency identification device (RFID)-enabled multidimensional building information modelling (BIM) platform. This research investigates and identifies the technical and managerial challenges in Hong Kong's prefabrication construction industry. An innovative RFID-enabled real-time BIM platform that integrates offshore prefabrication processes, technologies, information flow, and people is then developed. The construction project of public rental housing in Tuen Mun, Hong Kong is adopted to demonstrate the feasibility of this platform. Several perspectives are significant for this study. First, smart construction objects (SCOs) enabled by IoTs (Internet of Things) technologies are created to build upon an intelligent construction environment along the prefabrication construction in Hong Kong. The SCOs and RFID-enabled smart gateway work collaboratively to ease operations within three echelons, namely, prefabrication production, logistics, and on-site assembly construction. Second, a multidimensional BIM platform is established using cutting-edge technologies to leverage the realtime captured data from SCOs to form advanced decisions. This platform can provide various services, tools, and mechanisms to different stakeholders to fulfil their daily operations and decision makings to improve the efficiency and effectiveness by enhanced information sharing and advanced models. Third, in this platform, real-time captured data are used to form a closed-loop visibility and traceability mode in which different end users can supervise the construction statuses, progresses in real time. Thus, different parties can focus on different aspects during a prefabrication construction life cycle; in case of problems or unexpected deviations, they can work cooperatively through real-time visibility tools. This research extends traditional 3D BIM application in prefabrication construction into nD by using RFID-enabled real-time visibility and traceability tools, and key concerns are integrated seamlessly into BIM to achieve multidimensional applications. The effectiveness of the platform is evaluated through simulation provided by the hybrid dynamic model.

2. Research framework

To enhance the schedule performance of PHC project, this research develops an RFID-enabled real-time BIM platform that integrates various involved stakeholders, offshore prefabrication processes, information flow, and state-of-the-art construction technologies to mitigate the influence of critical schedule risks identified in PHC project. The latest innovations and technologies in the construction industry in Hong Kong are integrated. The general steps for this research include: (1) determination of critical schedule risks, challenges and required functions; (2) development of RFID-enabled BIM platform; (3) application of RFID-enabled BIM platform; and (4) evaluation of the effectiveness of RFID-enabled BIM platform through simulation. Fig. 1 illustrates the methods adopted and he general steps in this research. The generated outcomes in each step are also highlighted in the figure.

3. Determination of schedule risks and required functions

The first step of this research is to identify and analyze major risks that affect the schedule of PHC with consideration of involved stakeholders. These major schedule risks lay the foundation for the determination of challenges and corresponding required functions for enhancing the schedule performance of PHC projects. Per social network theory, PHC is a complex system that comprises various relationships with various stakeholders involved. Network analysis investigates those schedule risks with consideration of associated stakeholders in PHC along with corresponding cause-and-effect relations. Three steps are needed to identify critical schedule risks with social network theory. First, initial list of schedule risk and associated stakeholder that have direct influence on the schedule performance of PHC are identified. Second, the interrelationships among the identified risk factors are determined. Third, the adjacency matrix of link and node lists are introduced into NetMiner 4, which is a professional software for social network analysis, as key input data to visualize and analyze the network. The network analysis produces a list of critical stakeholder-associated schedule risks based on the node- and link-level metrics of social network analysis (SNA). The identification process of critical schedule risks depends on the outcomes of the SNA indicators, including status centrality, betweenness centrality, brokerage and the degree of nodes. Those risk and interrelationships with high status centrality, betweenness centrality, brokerage and the degree of nodes values are identified as critical risks have significant influence. In consolidating the results of SNA indicators, a list of 12 critical schedule risks and relationships is listed as shown in Table 1. Please be kindly noted that given limited length, the detailed identification processes and the analysis of critical schedule risks can be referred to the published article by the authors (Li et al., 2016a), while this research mainly focuses on illustration of the development of the RFID-enabled platform.

After the identification of the critical schedule risks, the actual meanings of these critical risks are comprehended in detail. Based on interviews toward managers involved in PHC, the major challenges faced by stakeholders involved in PHC are summarized. For example, two critical schedule risks, installation error of precast elements and delay of the delivery of precast element to site both describe risks about inefficient management of on-site installation activities, which would cause delay problems in the process of delivering precast elements to the site. As a result, the two schedule risks are placed under the same category, and the corresponding challenge to be handled is determined: "inefficient installation management because of compact space". Following the same principle, a total of seven major challenges encountered by stakeholders in the management of PHC project are summarized as

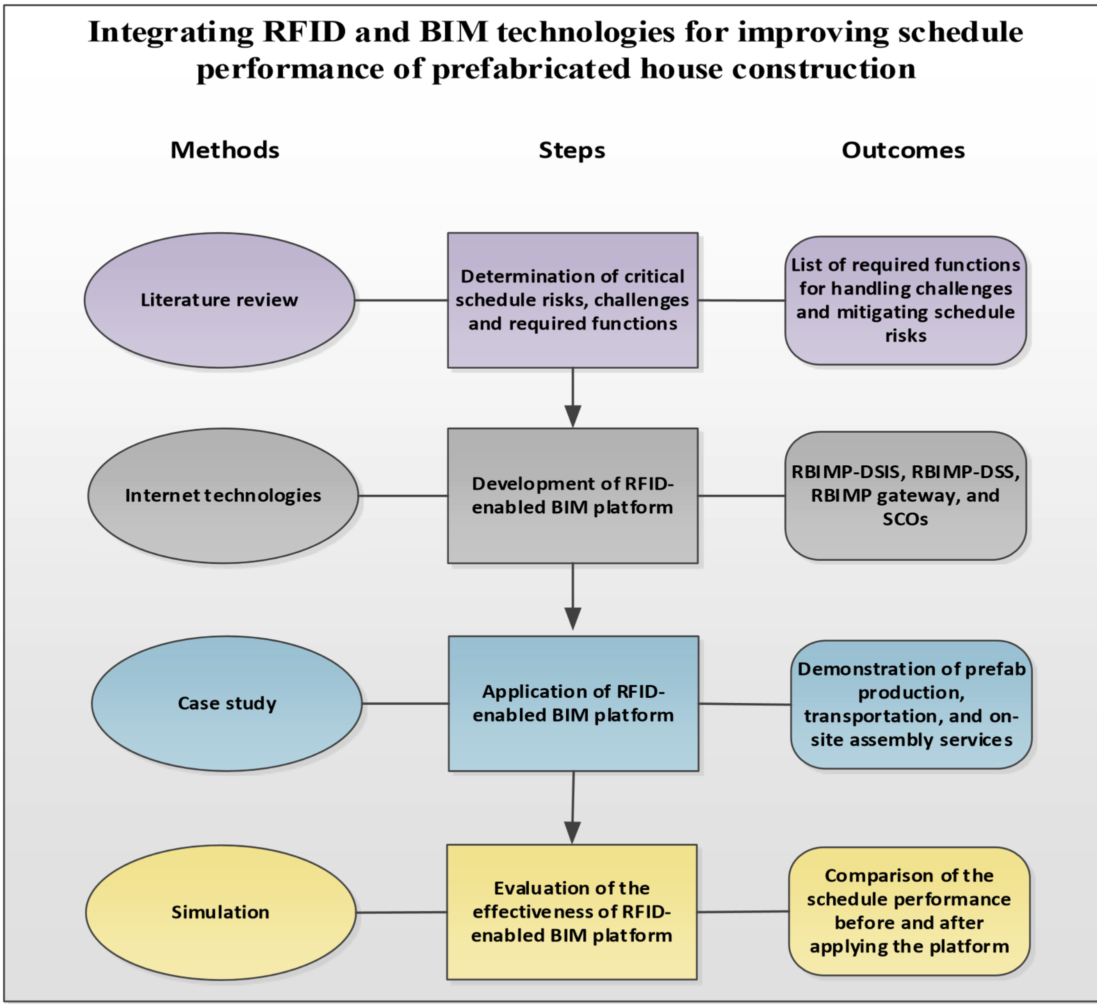


Fig. 1. Research flow.

Table 1

Required functions to handle challenges and mitigate schedule risks in PHC (Li et al., 2016a, 2016b).

Required Functions	Challenges in PHC	Critical Schedule Risks
Just-In-Time (JIT) delivery and assembly in compact site area	Inefficient installation management because of compact space	Delay of the delivery of precast element to site (DDPES)

		Installation error of precast elements (IEPE)
Production information sharing between Prefabrication manufacturer and logistics and assembly companies that lead to extra negotiation time	Inefficiency in transportation and high cost of crossborder logistics	Logistics information inconsistency because of human errors (LIIBHE) Low information interoperability between different enterprise resource planning systems (LIIBDERPS)
Embedding the design information in the prefabrication components for further use	Lack of interoperability between various stakeholders and their heterogeneous enterprise information systems (EIS)	Tower crane breakdown and maintenance (TCBM) Slow quality inspection procedures (SQIP)
Efficient communication among stakeholders and managers	Inefficient information transmission between the design and prefabrication stages	Design change (DC) Inefficiency of design approval (IDA)
Passing the design information to the manufacturers without any ambiguity	Information gaps among stakeholders, technologies, and processes	Inefficient design data transition (IDDT) Design information gap between designer and

		manufacturer (DIGBDM)
Efficient identification and verification of proper precast components	Insufficient information storage method of precast elements	Inefficient verification of precast components because of ambiguous labels (IVPCBAL)
	Lack of real-time information visibility and traceability	Misplacement on the storage site because of carelessness (MSSBC)

shown in Table 1. The required functions for dealing with the developed to handle the identified challenges and mitigate the challenges are then determined, and the corresponding managerial impact of critical schedule risks on the schedule performance of and technical solutions provided by the RFID-enabled platform are PHC project.

4. Development of the RFID-enabled BIM platform

4.1. Overall architecture of the RFID-enabled platform

The above findings regarding the challenges for developing the proposed platform are observed and examined through extensive contacts and preliminary studies with public bodies, such as the HKHA, business associations, such as the Hong Kong Construction Industry Council and the Hong Kong Construction Association and individual businesses and companies involved in the field. Over the years, the HKHA has taken a leading role in developing and promoting the application of information and communication technology (ICT) in general and BIM/ERP/RFID in particular among construction stakeholders. Fig. 2 shows the visionary roadmap of the HKHA for ICT application throughout the construction project life cycle (Zhong et al., 2015). At the right is HOMES, an ERP system purposefully developed in-house within the HKHA. HOMES has been used for more than 10 years. At the left of Fig. 2 is BIM, which the HKHA has been pioneering in recent years among Hong Kong construction businesses. The extending usage of HOMES and BIM has resulted in significant benefits for major stakeholders involved in public house production. Recently, the HKHA carried out preliminary pilot studies on extending the HOMES and BIM efforts through innovative uses of GIS and RFID technologies to address special challenges occurring in different stages of the construction project life cycle. The platform is especially developed to play a systematic role in achieving the ICT vision of the HKHA.

Focus has been placed on seven innovative technical components to be developed from research as shown in Fig. 4. The critical technical components developed are categorised using the convention in the service science literature as follows: (1) Software as a service (SaaS): this category represents three sets of serviceoriented decision support (software)

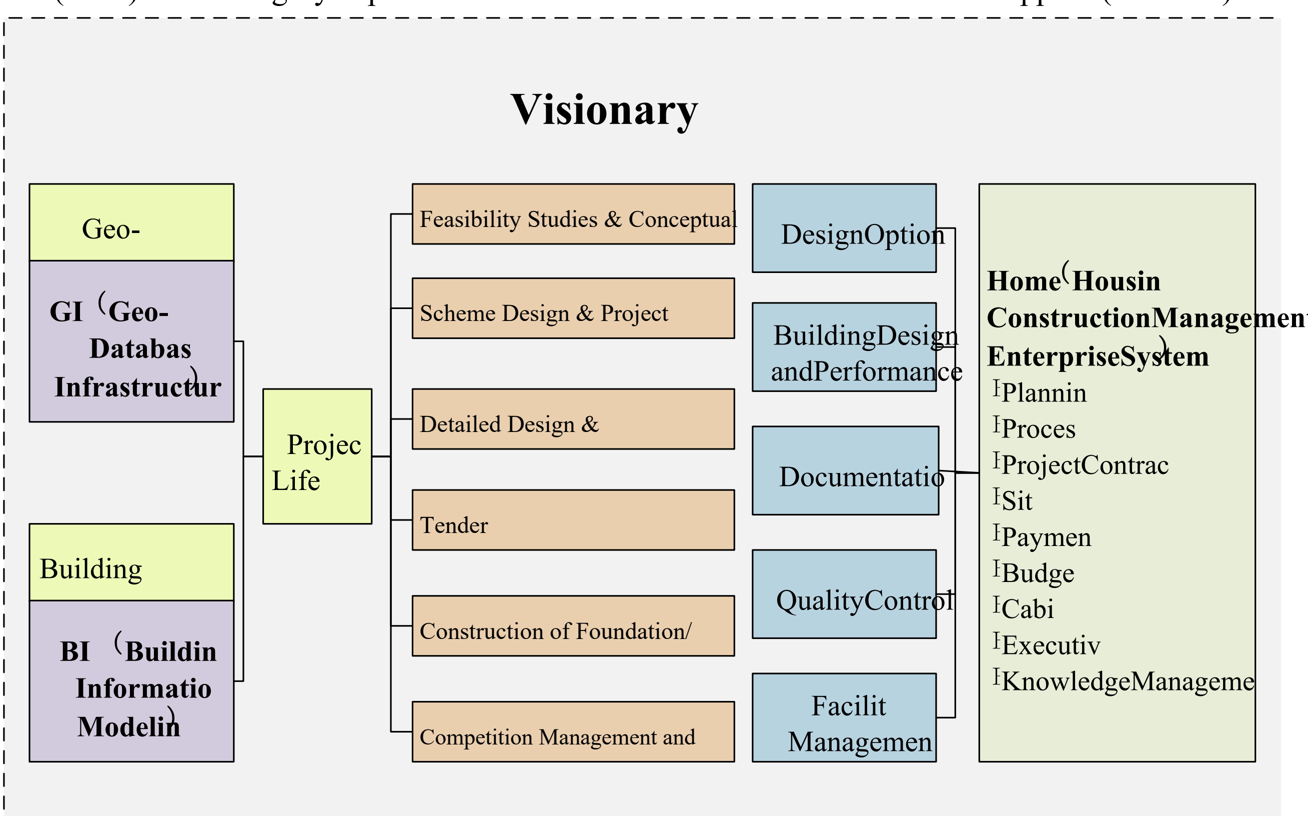


Fig. 2. Visionary framework for ICT applications (Zhong et al., 2015).

systems that are particularly developed as plug-ins to the BIM/HOMES by HKHA for three important phases of prefab production, prefab logistics and construction assembly site throughout the project lifecycle. (2) Infrastructure as a service: this category represents three sets of serviceoriented facilities that combine hardware and software components for building up the infrastructure to create an intelligent construction environment. These infrastructure include smart objects and gateway technology. SCOs are typical construction resources, such as tools, machinery, and materials, which are converted into smart objects by binding them with different RFID devices (Niu et al., 2016), as shown in Fig. 3. The purpose of SCOs is to create an intelligent construction environment within typical prefabrication production sites, such as shopfloors, warehouse, logistics and supply chain and construction sites. The RFID-enabled BIM platform (RBIMP) gateway works as a host to connect all SCOs and provides a suite of services to manage their operations and construction logistics. This gateway collects real-time information on prefabrication production, logistics, supply chain, and on-site assembly, and sends information to upper-level decision makers according to the predefined workflows. Traceability and visibility tools: these tools use real-time RFID-enabled construction data for precise decision making, such as prefabrication production planning and scheduling, logistics optimisation, real-time visualability and traceability, JIT delivery and smooth on-site assembly. They provide a rich set of sub-services for facilitating the operations of various end users in prefabrication production, logistics and on-site assembly. Data source interoperability service (DSIS): this service is designed to integrate different EISs to ensure that data sharing, system interconnection and interoperability can be improved. This service uses an agent-based technology capable of accomplishing construction tasks in an autonomous manner with minimal human

Fig. 3. Example of applying SCO.

intervention. Different data sources with high heterogeneities, such as communication protocols, information presentations, and unformatted engineering data information system, should be standardised. (3) Platform as a service (PaaS): this category denotes the service-oriented open-architecture platform called RBIMP incorporating key hardware and software settings for other technical deliverables.

This platform covers stakeholders, capacity of visualizing and tracing information in real-time manner, production processes, and information flow, including four main components: RBIMP-DSIS, RBIMP decision support service (RBIMP-DSS), RBIMP gateway, and SCOs. The PaaS is divided into several parts to smoothly integrate the RBIMP into the current HKHA information design. The SCOs are construction objects from the HKHA business partners. Typical construction resources in these sites utilize RFID equipment and are transformed into "smart" construction objects. The RBIMP gateway manages, links, and has control on SCOs by configuring, defining, and implementing the construction logistics. The RBIMPDSS is customized for use in Hong Kong's prefabrication housing construction. Three key phases (i.e., precast components production, transportation and installation) are selected to achieve the vision of HKHA. The RBMIP-DSIS adopts an Extensible Markup Language (XML)-based data-sharing mechanism for interoperability among HOMES, BIM, and RBIMP. Decision-making systems, which include HOMES and BIM in the HKHA, can use real-time information for advanced and effective decision making under PaaS.

4.2. Major technologies and innovations for the platform

The innovativeness of the RBIMP can observed in four aspects, (a) a connected and dynamic nD BIM, (b) a service-oriented architecture (SOA), (c) standard and component-based development of user interfaces and (d) centralised data source management service for heterogeneous EISs. This study introduces an innovative combination of ICT developed in manufacturing and the needs in housing production.

4.2.1. Connected and dynamic nD BIM for reengineering offshore prefabrication construction processes

RBIMP development will involve installing BIM as the basic infrastructure that controls the structure of the system. The innovativeness and successful delivery of this platform can turn Hong Kong into the leader in BIM use for reengineering architecture, engineering, and construction (AEC), specifically for offshore prefabrication construction.

First, the RBIMP underlines the stakeholder incorporation to foster BIM-based communication and coordination. BIM has been implemented in architectural design (e.g., spatial analysis), engineering design (e.g., heating, ventilation, and air conditioning) and construction process rehearsals (e.g., N-day cycle of a standard floor) individually. Nonetheless, integrating them to reduce discontinuity and fragmentation, thereby achieving greater benefits of using BIM, remains a good wish to be realised in Hong Kong, even for some flagship BIM projects (e.g., One Island East). The innovativeness of this platform, which is based on prefabrication housing procedures in offshore areas, does not attempt to address the structural problems of project delivery organizations. Instead, it increases their connectedness by adopting advanced ICTs in BIM.

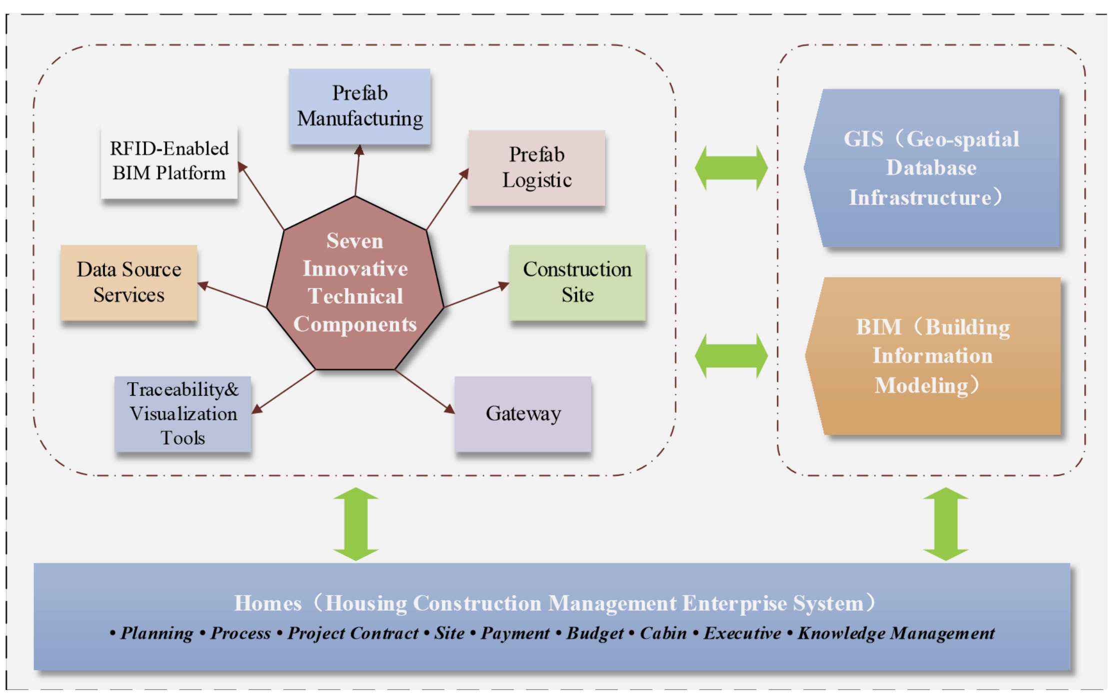


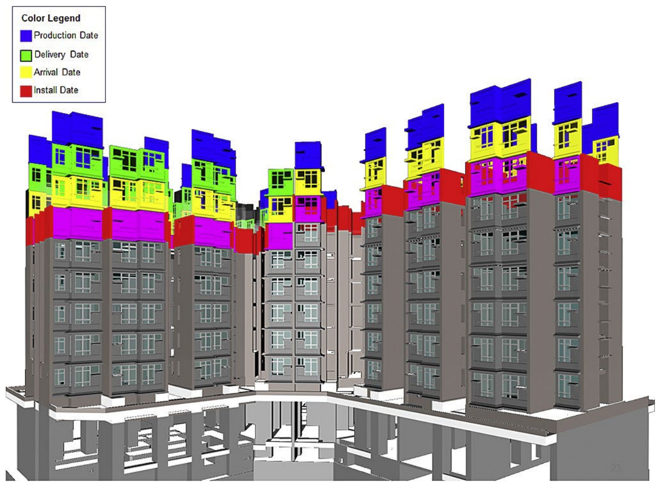
Fig. 4. Seven technical components of the platform for achieving the ICT vision of the HKHA.

Second, BIM can serve as an information hub that connects SCOs and creates an intelligent construction environment. This scenario is an innovative approach in the structural design of the RBIMP system. BIM currently stores an information hub from designers and engineers. However, the information is less exploited in the downstream processes, such as construction and facility management. A major problem is that BIM is largely a static hub, in which its information cannot be synchronised automatically with the construction process to derive a new "as-built" BIM model. The RBIMP will connect SCOs, which are under fast development, such as the "in-house" BIM Lab in the HKHA, National BIM Lab created in the United Kingdom, and the Google Warehouse. The further development of existing software development kits and application-programming interfaces is expected to connect RFID systems to BIM models. This connection can develop a popular plug-in that integrates RFID technologies with BIM. However, few plug-ins (e.g., clash detection and BQ generation) are available in the industry. Exploring the link between RFID and BIM is poor and disjointed. This scenario also allows to connect BIM and the IoTs because BIM-based materials and available resources worldwide can be purchased.

Third, Fig. 5 shows the innovative use of graphic information generated from the RBIMP to instruct the entire offshore PHC. IKEA furniture and its "assembly instructions" are regarded as highly ground-breaking. Progress is presently indicated by adopting 2D tools, such as the Gantt chart. The RBIMP can innovatively generate graphic "instructions" for resource configuration, precast elements trace and track prefabrication with the supply chain including production, transportation and, and installation.

4.2.2. SOA for RBIMP components and its integration

The RBIMP is a web portal for following a standard SOA. Fig. 6 shows that a complete SOA involves three principal phases:



search, invoke, and publish. Web services are implemented by service developers/providers at designated server sites and publish service details (e.g., location, capability, and interfacial description). Service consumers search and select applicable web services from the published database. Values must be specified and provided before invoking services in a specific application.

These typical phases involve three important web service components, which include web service description language (WSDL); universal description, discovery, and integration (UDDI); and simple object access protocol (SOAP). The WSDL standard offers a standard approach that describes the abstract and protocol of these services. It simply defines the functions of a web service, enumerates its residing areas, and explains the manner of its application. UDDI is a platform-independent, XML-based registry that allows distributed services to be included on the Internet. The SOAP is a platform-independent protocol that applies these distributed web services by exchanging XML-based messages.

The proposed RBIMP extends the SOA concept of service. Services can be different interrelated information sources or application systems. These services can be divided into three categories. The first category, which includes standard optimisation software utilized to develop and deploy planning algorithms, belongs to SaaS in cloud computing. The second category involves a third-party native enterprise information/application platform, such as different BIM, HOMES, ERP, and SCM modules. This category can be considered as PaaS. The third category consist of data sourced from different native database systems directly. Adaptation converts the information sources into standard web services with standard outputs. The database as a service (DaaS) concept in cloud computing is depicted in this category. The proposed RBIMP is a form of hybrid anything-as-a-service SOA, in which SaaS, PaaS and DaaS are innovatively combined.

4.2.3. Standard and component-based development of user interfaces

Fig. 7 shows the web-based user interfaces, called RBIMP explorers. One of the most significant design and implementation considerations for RBIMP is the use of suitable standards at two levels. At the first level, RBIMP explorers are based on standard data models in the domain of construction and logistics. At the second level, RBIMP explorers are developed using standard third-party web controls.

The first level uses many of major data model standards relevant to RBIMP. Such standards have undergone substantial evolution

Fig. 5. Take BIM technologies as virtualization tool for facilitating the management of PHC.

recently. Some of these standards are heavy-weight ones that involve comprehensive coverage and a substantial amount of documentation. Examples include COBie and AEC data exchange standards in construction domain, B2MML following ISA95 in the manufacturing domain and GS1 eCom and GDSN in the logistics and transportation domain. Some are light-weight standards with a focused scope and simple documentation. A light-weight standard is preferred over a heavy-weight standard.

The second level has a set of web-based RBIMP explorers. Thus, various cutting-edge web controls are used. RBIMP has used ComponentArt and DHTMLX, which are client-side AJAX-based user interface (UI) components. Client-side components provide more interactivity between the user interface and the user with less communication between the client and server components.

Component-based development with standard data models represents an important paradigm shift, which is to build software systems from standard components rather than "reinventing the wheel" each time. This approach offers several advantages. First, using components to construct an application is highly productive because the components are ready to use and/or reuse. Second, style sheets can be used to define the styles of components and (re) configure the overall layout of multiple components. Reusable components enable developers to customise solutions without high costs and long development cycles. Third, component-based solutions are of high quality because components are more reliable, interfaces are modularly tested and architectural patterns are standard. Finally, components and their data sources can be defined through component-specific XML documents, which enable seamless binding between XML-standard data contents and component-based presentation.

4.2.4. RBIMP DSISs for heterogeneous EISs

The standard and component-based development of RBIMP is enabled by a DSIS, shown in Fig. 8. RBIMP-DSIS aims to build a bridge for information communication between explorers and heterogeneous EISs in different stakeholders (Pang et al., 2015).

DSIS provides two levels of data management services. One level is the two-way conversion of XML documents between domain data s (e.g., COBie and B2MML) and component standards (e.g., ComponentArt). Once the type of components is chosen for the development, this level of conversion service is relatively fixed in that both domain and component data models are fixed according to the chosen standards.

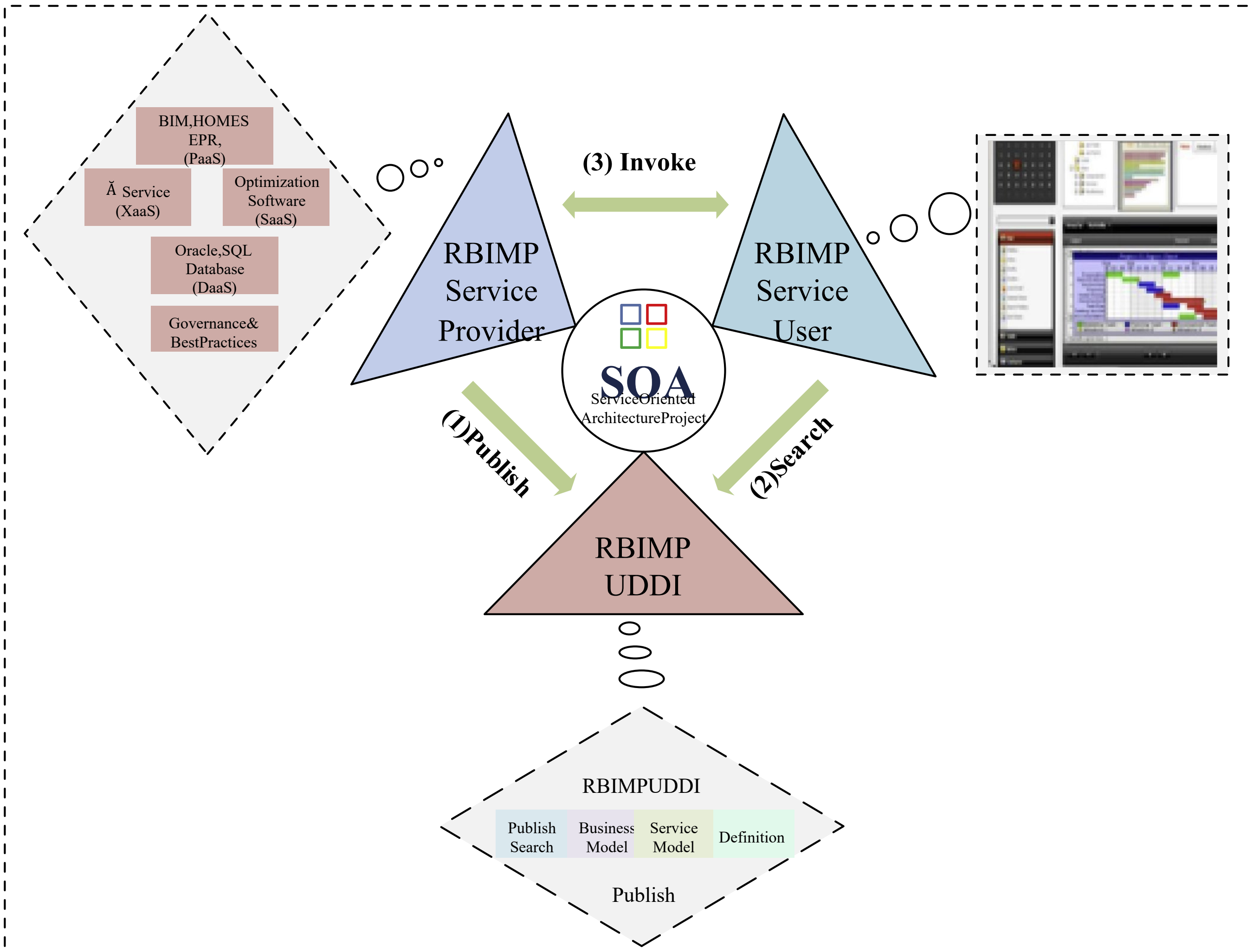


Fig. 6. Service oriented architecture for the platform.

The other level of information service is managing data between heterogeneous EISs and XML-based data models by following some domain standards. This level is highly complicated and involves several operations. Proprietary EISs are first wrapped around the concept of service-oriented agents to become standard web services. These agents provide standard methods, such as Update_Data_Method and Get_Data_Method, which can be utilized by users or systems in updating and obtaining information from and to corresponding EISs, respectively. Because the architecture of web service is adopted, the input parameters of each method are denoted as standard XML segments to facilitate the connection, query and updating operations.

The outputs from DSIS agents follow standard information schemas, such as COBie data structure and B2MML schemas.

5. Practical application of the developed RBIMP platform

RBIMP-DSS works as SaaS to suit the three echelons in prefabrication housing in Hong Kong. These represent three sets of service-oriented decision support (software) systems, which are developed as plug-in to HKHA's BIM/HOMES for three important phases (e.g.,

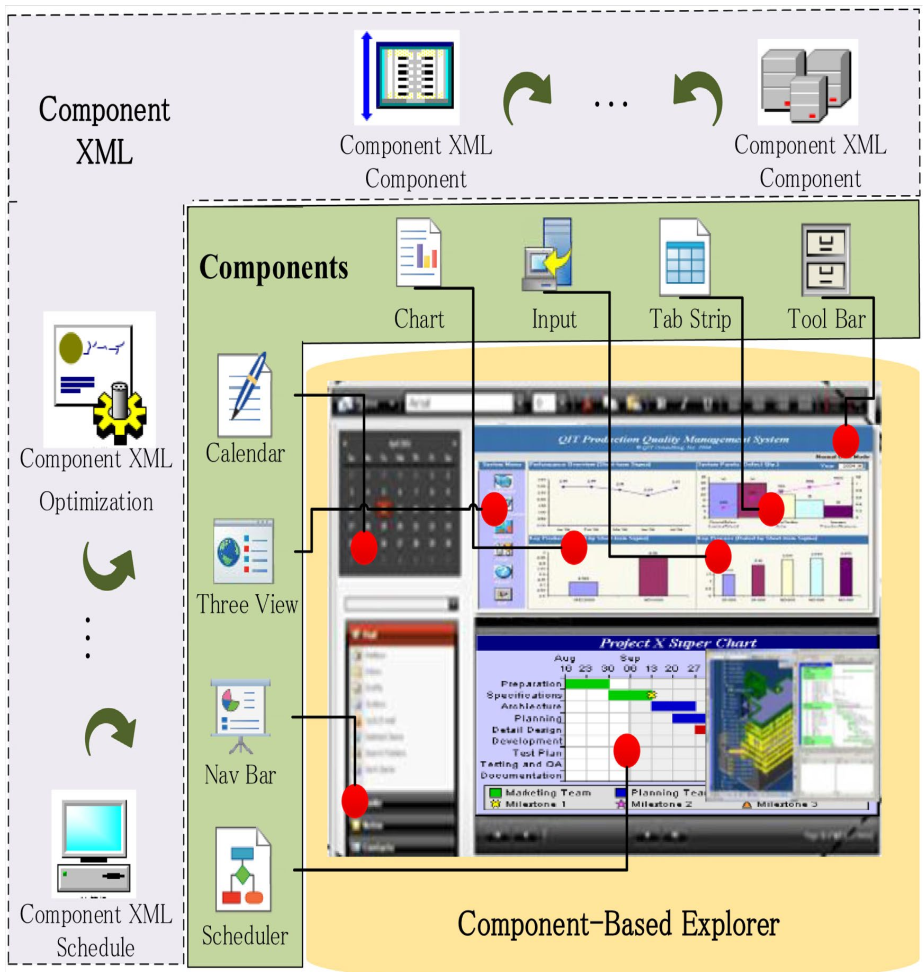


Fig. 7. Standard and component-based user interface.

prefab production, prefab logistics and construction assembly site) throughout the project lifecycle. RBIMP-DSS acts as key decision support parties in RBIMP and works as an interface for different end users in prefabrication production, logistics and construction site assembly. Fig. 9 shows three key services in RBIMP-DSS, which are prefab production service, prefab transportation service and on-site assembly service. Each service contains a rich set of sub-services for facilitating the HKHA's decisionmakings at different stages of the prefabrication housing construction. The technical framework indicates that three key services are developed under Java Runtime Environment 7.0 utilizing the Java programming language. Tomcat 7.0, which is stable, light, and widely recognized by many enterprise applications, is adopted as the web application server. Moreover, the database utilizes SQL Server 2012 because of the present database systems in the case company. Three Android applications are also developed for each of the three key services to enable the daily driver operations and compile their operational information throughout PHC.

Three pilot studies are conducted in the management of prefabrication construction supply chain to test the proposed platform. Wing Hong Shun Ltd. (WHS) located in Huizhou, Guangdong Province manufactures prefabricated components. Yingyun Logistics Co., Ltd (Yingyun) ships prefabricated components from WHS to the assembly site. Tuen Mun A54 S2b conducted by Gammon Construction Limited (Gammon) uses manufactured prefabricated components for building public housing. The following sections will present each pilot in detail.

5.1. Prefab production service

The major purpose of the developed prefabrication production service is to generate best schedules and tactics for operational convenience of HKHA and corresponding prefabrication manufacturers. Various cutting-edge models and algorithms, which include particle swarm optimisation, colony algorithm and genetic algorithm are adopted in the development of the service. Several major sub-services, such as planning service, scheduling service, internal logistics service and production execution, are exploited to facilitate operations of manufacturing precast components. The operational flow of the developed service is shown in Fig. 10.

5.1.1. Production plan development

The deployment of the web system starts with receiving the order from Gammon. The staff of WHS inputs the production plan in the “production management” page. The production plan includes the description (e.g., target location and type) of the components to be produced and the planned production date. The system uploads the data to the database whenever new data are added. The web system also allows the use of keywords to search information of a specific item. The web system can also export selected information as an Excel file for printing if a hardcopy is required.

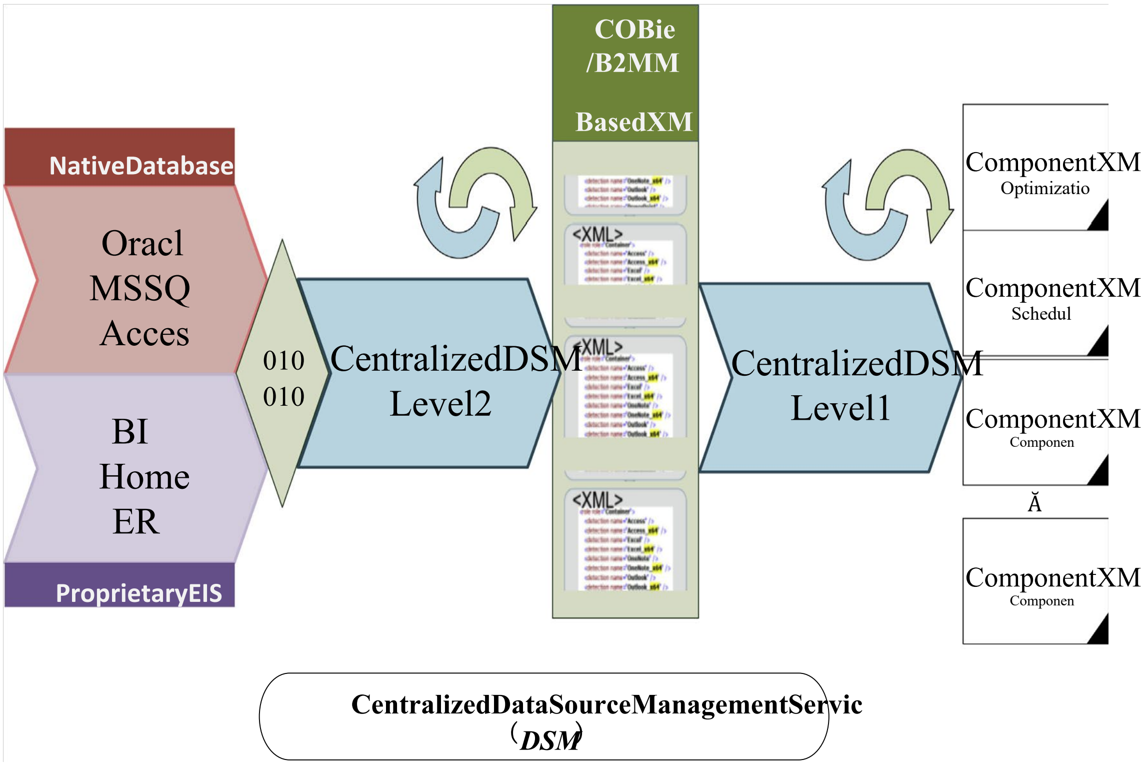


Fig. 8. RBIMP-DSISs.

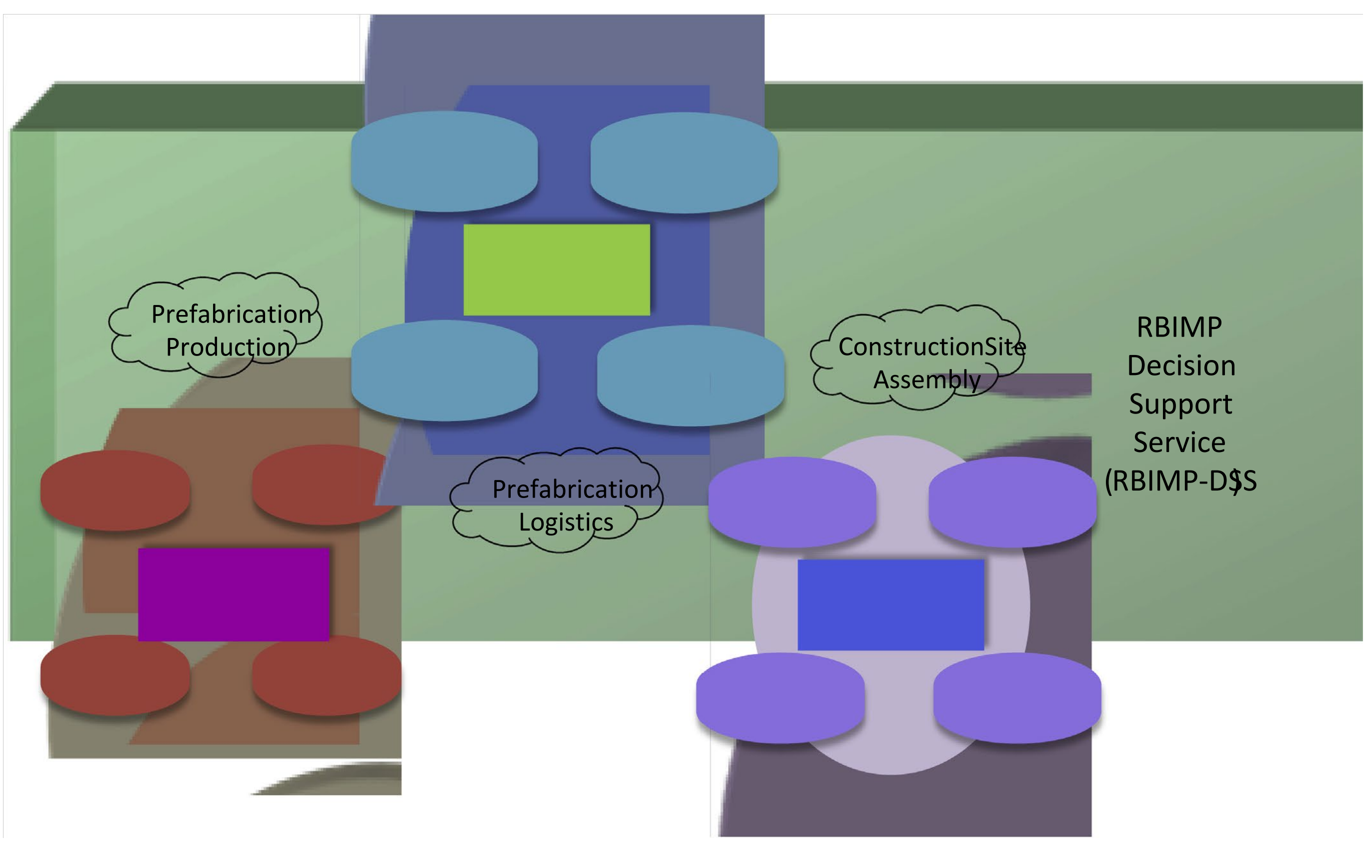


Fig. 9. Key services in RBIMP-DSS

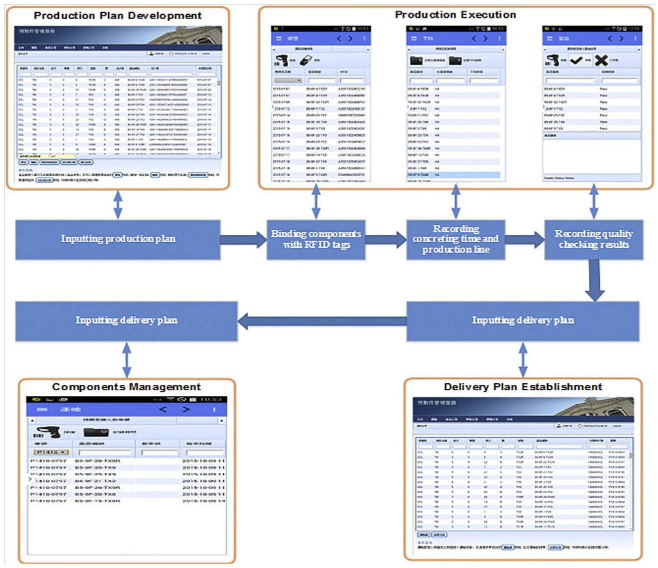


Fig. 10. Workflow of PPS.

5.1.2. Production execution

A smartphone and RFID reader connected to each other through Bluetooth are deployed. A smartphone app is programmed to collect the information on the production and delivery. The first step is to bind the prefabricated component with the RFID tag. After the tag is fixed on the reinforcement cage of a component, the worker opens the “binding” page in the smartphone app, which lists the components from the database arranged by the planned production date. The worker selects the right one and scans the RFID tag using the reader. The tag is linked to the component it is attached. The binding date and GPS data are collected by the app automatically and uploaded to the database. Workers can also open the “concreting” and “QC” page in the smartphone app to record the production line and quality-checking results, respectively. Information on the corresponding product is shown on the screen by scanning the RFID tag. Workers then input the required information.

5.1.3. Delivery plan establishment

The staff opens the "delivery management" page in the web system to input the delivery plan. The information of products stored in the database is listed automatically. The staff only needs to set the delivery order number of each product.

5.1.4. Components management

When loading prefabricated products on trailers for delivery, workers open the "delivery" page in the smartphone app and use the reader to scan the RFID tag. The loading time of each prefabricated product is collected by the smartphone app. All information is transferred to the database in real-time.

The web system, smartphone app and RFID device help collect and record information in real-time. A type of information is inputted, stored in the database, and shown on all relevant pages of the web system and smartphone app. Information synchronisation is automatic. Therefore, workers do not need to first record the information on paper and then type it in a digital Excel file. Double input, which is a waste of time and manpower, is significantly decreased. Moreover, this study's system facilitates information management compared with traditional paper-based method, wherein information is managed fragmentally. First, all information is stored in the central database. Only authorised staff can edit the information through the web system. Second, the time when a new piece of information is transferred to the database is recorded automatically, which is convenient for the staff to identify the latest information. Third, the web system provides a keyword search function if the staff wishes to view information on specific product. Thus, the staff can obtain the desired information within seconds. Finally, the contractor previously had a limited idea on the status of the prefabricated product (e.g., whether it is produced or loaded on the trailer for delivery). Using the system, the status information of each product stored in the central database is transferred automatically to the On-Site Assembly Service System for the contractor to review.

5.2. Prefab transportation service

The major purpose of the developed prefab transportation service is to real-time management and control of the logistics of the precast component from manufacturer to assembly site, which includes cross-border logistics between Mainland China and Hong Kong. Cloud asset is implemented to collect real-time transportation data, and Advanced Ant Colony Algorithm is applied to use the best strategies in the development of the service (Xu et al., 2015). Several major sub-services, such as transportation planning and scheduling, fleet management, real-time transportation monitoring, and cross-border logistics execution, are exploited to facilitate operations of manufacturing precast components. The operational flow of the developed service is shown in Fig. 11.

5.2.1. Order management

This module can be used by the manufacturer who places transportation orders into the order pool of Yingyun. The module can also be utilized by managers who wish to verify detailed information on an order and make the necessary modifications. The “Orders” module includes two sub-modules: “Current Orders” and “Import Orders.” The “Current Orders” module provides orders overview. Users can check the general information for all imported orders and monitor their real-time status at this module. They can also check order details, remove orders and edit orders in this module. The “Import Orders” module supports new order import. The orders can be imported from different sources: database, Excel files, XML files, and DSIS.

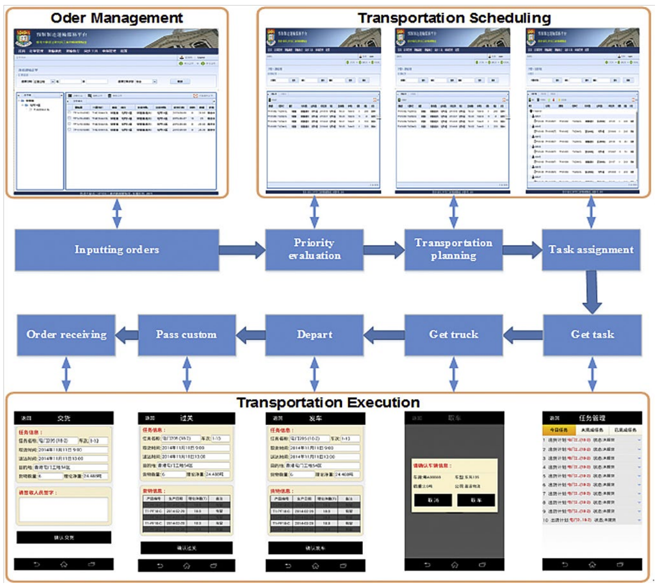


Fig. 11. Working logic of PTS

5.2.2. Transportation planning and scheduling

This module is developed for schedulers for order priority evaluation, transportation planning and transportation task assignment. Given the released orders, the scheduler evaluates the priority of transportation orders based on customers' priority, order due date and other customised parameters. This module provides two evaluation methods: "Automatic Evaluation" and "Evaluation by Due Date." Automatic evaluation sorts the orders by predesigned rules, whereas the other only considers the order due date. Manual sorting is also provided in this module. Transportation planning then begins. This module helps the scheduler decide on the transportation mode and time for each order. Two modes are provided by the module: 1) direct transportation from the WHS to Tuen Mun and 2) delivery through the buffer warehouse located in Lok Mak Chou. The transportation orders are divided automatically into detailed transportation tasks and then moves to the next stage. In the assignment stage, these transportation orders could be assigned automatically to drivers according to real-time information. The scheduler could also adjust the assignment manually by dragging and dropping of these transportation tasks.

5.2.3. Transportation execution

The transportation process is executed by the driver, who takes charge of obtaining orders, passing through customs, and delivering prefabs to the construction site. We developed two applications for the drivers. One is a web-based system that allows the driver/manager to check the transportation task status. The other is an Android mobile application that allows drivers to view the assigned task and update their real-time operations status (i.e., receiving vehicles, obtaining orders, passing through customs, and completing deliveries). The driver should enter the corresponding module and report progress in each operation (Xu et al., 2015). All real-time transportation information is also sent to a construction site and HKHA to track and trace the entire process of prefabrication construction.

PTS is adopted in pilot companies for several months, and improvements are observed from technical and business aspects. From the technical aspect, the following improvements have been made. First, PTS enables convenient information sharing. Information sharing can be achieved easily among different modules and systems through web services-enabled technologies. For this study, integrating a web-based system and a mobile app is easy. Moreover, PTS can easily exchange information with other systems and platforms. Second, PTS improves information collection efficiency. The mobile app integrates the NFC and GPS modules of the smart phone well to realise real-time transportation information collection. It reduces hardware investment for collecting these data and decreases the burden to use the system. Third, a PTS system is user-friendly. The UIs of both web-system and mobile app are designed carefully to cater to real-life working logic, which significantly improves system friendliness. This result has been verified by the end users because several minutes of training are sufficient for them to accept and use the entire system.

From the business process and operation perspective, the PTS system improved the working efficiency in the case company in the following aspects. First, PTS enables traceability and visibility of the logistics information. Real-time data collection enables computerbased management style, which replaces traditional manualbased management style. It reduces the time-consuming data collection processes, such as enquiring on the status of tractors, trailers, and drivers and buffer levels at intermediate warehouses and construction sites by phone. Hence, the efficiency of business processes and operations is improved. Second, the transportation task can be generated automatically. Various non-value-added and time-consuming activities are eliminated. Take the task generation process for example. Task managers used to scheduling transportation tasks manually. Therefore, they should compare all task due dates and evaluate the priority of the transportation tasks. They then should decide whether a task should first be delivered to the intermediate warehouse and then the construction site or directly to the construction site. Nowadays, managers only need to import the order, and the evaluation process can be done automatically. Moreover, the transportation tasks are generated after evaluation. This automation freed workers for more productive and innovative jobs and improved their work efficiency. Third, the task release operation is simplified. Tedious task releasing processes is reduced. Managers usually inform drivers on their tasks by phone or pass the delivery documents to the driver. Nowadays, the transportation tasks are sent automatically to the smartphones of drivers. Drivers could see their tasks directly by logging in using their usernames, which reduces wasteful paper-based data sheets and enables the fast release of task information. Fourth, the operation errors can be largely reduced. For example, drivers should pick up the tractor and trailer before departing. These processes are usually prone to errors because of the similarity of the tractors and trailers or the carelessness of the drivers. Nowadays, drivers should read the RFID tags attached to the vehicles before driving the tractors or picking up trailers. Smartphones provide an alarm to users and refuse to process the tasks if the wrong vehicles are read. Therefore, the operation errors could be reduced. Fifth, transportation records can be generated automatically. The transportation records are created and synchronised in line with the physical transportation process in a real-time fashion, thereby enabling both managers and operators to gain access to real-time information and history records of the logistics information, which supports them to correct and improve their decision making. The manager could rationally decide on the future development of the company from either strategic or tactic perspective using collected data.

5.3. On-site assembly service

The developed on-site assembly service facilitates various assembly operations, supervisions and quality checking in the construction site. BIM is integrated into the development of the service to visualize and monitor assembly progress. Several major subservices, such as on-site assets management service, real-time supervision service, data capturing service and real-time feedback service are exploited to facilitate assembly of precast components. The operational flow of the developed service is shown in Fig. 12.

Fig. 12. Working logic of OAS

5.3.1. Staff registration

The staff registration function manages on-site workers in an effective and optimal manner. This service uses RFID technology to identify corresponding workers, foremen, and on-site managers. People of the construction company have unique identity cards with RFID tags, and this function helps them read the information embedded in the tag. The backstage platform is used to support the optimal management of these people, such as the distribution of assembly tasks, which checks the quality check of activities of different workers for further processing. Through effective manpower management provided by this function, labour is optimised significantly and precast element assembly becomes more efficient. Moreover, safety accidents on the construction site are largely reduced because this function can help position all real-time locations of the staff, and all information from the on-site assembly is captured such that risks and dangerous activities can be identified prior to happening.

5.3.2. Order management

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

5.3.3. Assembly confirmation and quality checking

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

5.3.4. Real-time progress monitoring

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

5.3.5. Progress visualisation

Real-time precast construction progress is visualised using an imported BIM Model in a web-based operating platform for monitoring produced elements, under transportation, on-site arrival and erection, which are shown in different colours to indicate the status of precast elements. Easy real-time visualisation is applied to check against domestic floor actual site construction progress and identify any delay in precast fabrication and delivery.

Therefore, all involved project stakeholders could be aware of the current situations and make associated decisions collaboratively.

5.3.5.1. Error alert. This function is developed to detect the rightness of the assembly of precast elements. Every precast component has a unique serial number that binds with a specific RFID tag and is assembled at a specific location. Coordinates of the location where the RFID tag of precast element installed read with a mobile phone based on GPS can be compared to the design coordinates based on the BIM model. The deviation in position can be shown in meters. Any deviation larger than the reasonable tolerance in GPS can be identified manually as an error in precast element installation.

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

6. Evaluation of the effectiveness of the RBIMP platformthrough simulation

6.1. Development of a hybrid dynamic model for evaluating theeffective of the platform

The hybrid dynamic model is a model that developed with hybrid system dynamic and discrete event simulation method, with an aim to evaluate and simulate impacts of schedule risks in PHC by considering interrelationships underlying various activities and variables from dynamic perspective. The main purpose of the model is to provide a practical tool for explaining and validating the benefits and weaknesses of RFID-enabled platform proposed to deal with identified major schedule risks prior to applying the platform for the management of PHC. Once functions of the platform are proposed by the researchers and managers for hedging potential schedule risks, the potential effect of the functions of the platform on the schedule performance can be evaluated and simulated through the model and the findings based on the model can be relayed to others through hands-on training to analyze the benefits and weaknesses of the devised function of the platform. Take function “mitigating installation error of precast elements” for example, through the model, the potential effect of the function can be simulated to check whether it will result in enhancement on the schedule performance of PHC.

To develop the hybrid dynamic model, the purpose and boundaries of the model are first defined, and the overview description of the model's structure is provided. Then, system dynamics model is developed through the causal loop and stock flow diagram with the help of

Vensim software. Please be kindly noted that given limited length, the detailed development processes of the causal loop and stock flow diagram can be referred to the published article by the authors. System dynamics model and its associated attributes are encapsulated into a discrete event module and consequently forming the final hybrid dynamic model with Anylogic software, as shown in Fig.13. Prior to further evaluation of the mitigation impact of the RFID-enabled platform on the schedule risks, testing the verification and validation of the hybrid dynamic model, which contains model structure test and model behavior test, is crucial to build confidence into the model. Model structure test includes direct structure test and indirect structure test are conducted to verify whether this research build the model right, while model behavior test is conducted to validate whether this research build the right model. Model structure test includes direct structure test and indirect structure test (Barlas, 1996; Barlas and Kanar, 2000). Direct structure test, including dimensional consistency test, boundary adequacy test, parameter confirmation test, and structure confirmation test, checks model rationality by comparing the structure of developed model with real system structure from a qualitative point of view to help calibrate the model to fit real world situations (Barlas, 1996). The indirect test takes the advantages of both direct structure test and quantitative test, aiming to validate the model structure indirectly by conducting various behavior tests on model behavior patterns. Indirect test includes extreme-condition test, behavior sensitivity test, and integral error test (Barlas, 1996). The hybrid dynamic model meets the requirement of all the tests.

6.2. Evaluation of the effectiveness of the developed platform

Built on the theoretical assumption that the impact of schedule risks on the schedule performance of PHC can be mitigated through reducing the attributes of schedule risks variables after implementing RFID-enabled platform for the management of PHC. Schedule performance is simulated to evaluate the effectiveness of RFID-enabled platform through

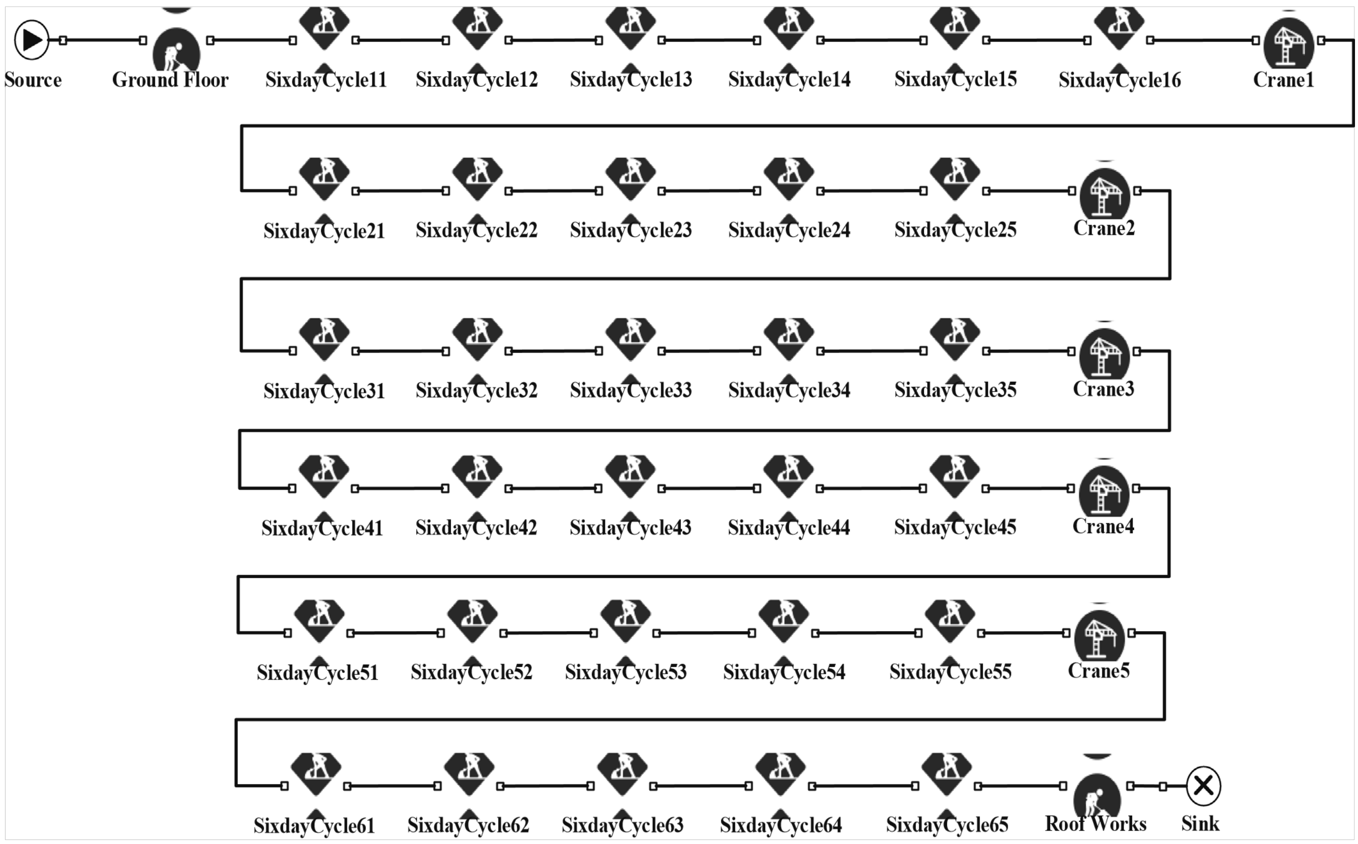


Fig. 13. The hybrid dynamic model for precast structure works.

comparing the schedule indicator before and after the application of the platform. Please be noted that risk is measured by two criteria in this research, including impact and likelihood. So, if risk is decreased by 20% after the use of RFID-enabled platform, it means that the impact and likelihood of the risk are simultaneously decreased by 20%. Take a risk of which the impact on schedule performance complies with triangle distribution with probability of occurrence of 0.8 for example, the risk decrease by 20% means that the three values adopted for triangle distribution shrinks by 20% and the probability of occurrence is cut by 20% to 0.4.

As shown in Table 2, planned schedule and actual schedule of precast structure works are chosen as bench mark indicators. The planned schedule is the original schedule plan indicated by the master program of the PHC project, while the actual schedule is the real schedule situation of completed PHC precast structure works. The model simulated variable values after implementing RFIDenabled platform for the management of PHC are compared to its historical data of planned schedule and actual schedule of precast structure works to evaluate the improvement. As indicated in the Table 6.7, the actual schedule of precast structure works of the studied PHC project is 626 days, which reaches a delay of 117 days compared to planned schedule, while the simulated schedule by the hybrid model after applying the RFID-enabled platform is 630.7 days, with an overall improvement of 15.23%. The simulation results demonstrate the satisfactory effectiveness of RFID-enabled platform. Per the simulation results, the suggested risk mitigation solutions provided by the RFID-enabled platform are useful to alleviate the adverse influence of risks on the schedule performance of PHC project. In evaluating the effectiveness of the RFIDenabled platform from a more practical perspective, continuous monitoring and assessment by the hybrid dynamic model is deemed necessary and the performance of the RFID solutions should be reviewed and monitored periodically in the future research.

Table 2

Schedule performance before and after implementing the platform based on simulation.

No.	Task	Planned schedule (days)	Actual schedule (days)	After using the platform (days)	Improvement

1	Ground Floor and Transfer Structure	246	264	253.0	4.17%
2	Six-day Cycle11	6	7	6.0	14.29%
3	Six-day Cycle12	6	9	6.0	32.89%
4	Six-day Cycle13	6	8	6.1	23.88%
5	Six-day Cycle14	6	6	6.0	0.00%
6	Six-day Cycle15	6	7	6.0	14.29%
7	Six-day Cycle16	6	8	6.1	24.00%
8	Crane Lift 1	1	1	1.0	0.00%
9	Six-day Cycle21	6	12	6.2	48.67%
10	Six-day Cycle22	6	9	6.1	32.44%
11	Six-day Cycle23	6	6	6.0	0.00%
12	Six-day Cycle24	6	9	6.1	32.78%
13	Six-day Cycle25	6	9	6.1	32.44%
14	Crane Lift 2	1	1	1.0	0.00%
15	Six-day Cycle31	6	7	6.2	10.86%
16	Six-day Cycle32	6	6	6.0	0.00%
17	Six-day Cycle33	6	7	6.0	14.29%
18	Six-day Cycle34	6	7	6.0	14.29%
19	Six-day Cycle35	6	6	6.0	0.00%
20	Crane Lift 3	1	1	1.0	0.00%
21	Six-day Cycle41	6	6	6.0	0.00%

22	Six-day Cycle42	6	6	6.0	0.00%
23	Six-day Cycle43	6	9	6.3	30.56%
24	Six-day Cycle44	6	9	6.0	33.11%
25	Six-day Cycle45	6	6	6.0	0.00%
26	Crane Lift 4	1	1	1.0	0.00%
27	Six-day Cycle51	6	6	6.0	0.00%
28	Six-day Cycle52	6	8	6.2	22.50%
29	Six-day Cycle53	6	7	6.4	9.14%
30	Six-day Cycle54	6	12	6.1	49.08%
31	Six-day Cycle55	6	6	6.0	0.00%
32	Crane Lift 5	1	1	1.0	0.00%
33	Six-day Cycle61	6	6	6.0	0.00%
34	Six-day Cycle62	6	12	6.0	49.75%
35	Six-day Cycle63	6	9	6.1	32.67%
36	Six-day Cycle64	6	12	6.3	47.42%
37	Six-day Cycle65	6	6	6.0	0.00%
38	Roof Works	72	114	84.5	25.88%
40	Overall	509	626.0	530.7	15.23%

7. Conclusion

By appreciating the latest innovations and technologies in the construction industry, this research develops an RFID-enabled realtime BIM platform that integrates various involved stakeholders, offshore prefabrication processes, information flow, and state-ofthe-art construction technologies to mitigate the influence of schedule risks on the schedule performance of PHC project. The RBIMP focuses on stakeholder integration to encourage BIM-based communication and coordination; in addition, this platform utilizes BIM to connect SCOs. A series of services from prefabrication production to prefabrication transportation and on-site assembly are provided in the platform to create an intelligent construction environment and raise project delivery efficiency. The trackability, traceability and visualisation of project resources, such as labour, materials and equipment are realised by RFID-enabled SCOs and BIM gateways. With this platform, real-time information transfer efficiency among BIM system and on-site works are improved, in that the monitoring, control and management of on-site construction work can be improved. Finally, the absence of interoperability between different stakeholders and heterogeneous EISs of project participants are significantly alleviated by the platform, such that communication efficiency among contractors and other stakeholders are improved considerably, thereby resulting in improved time and cost control, less rework and disputes, and high productivity.

The limitations of the developed platform in this research should be outlined for further development and broader application. Most workers involved in the three major processes of prefabricated house construction are not well-educated and are unaware of the power of advanced IT technology. Hence, the effect of implementing the platform is discounted. Technical training courses should be arranged to demonstrate the main functions of the platform and assist responsible workers to become familiar with specific operations. The UI of web systems and smartphone apps should also be refined to make the UI user-friendly and suitable with the operation habits of site workers. Fault-tolerant techniques should also be introduced into the platform to eliminate errors caused by faulty operations and inputs.

Acknowledgments

The research team, which includes the Department of Industrial and Manufacturing Systems Engineering, the Department of Civil Engineering, and the Department of Real Estate and Construction of the University of Hong Kong and the Department of Building and Real Estate of the Hong Kong Polytechnic University, thanks the HKSAR ITC/LSCM R&D Centre for partially funding this research through the Innovation and Technology Support Program (Project Reference: ITP/045/13LP). The research team is also grateful to the Hong Kong Housing Authority and its contractors for their support and participation in this research via real project applications.

References

Habitat Int. 57, 74e87.

Li, C.Z., Hong, J., Xue, F., Shen, G.Q., Xu, X., Mok, M.K., 2016b. Schedule risks in prefabricated house construction in Hong Kong: a social network analysis. Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics.

J. Clean.

Prod. 134 (Part B), 482e494. Sys. Dyn. Rev. (Wiley) 12 (3), 183e210.

Li, Zhengdao, Clyde, Qiping Shen, Geoffrey, Xu, Xiaoxiao, Xue, Fan, Sommer, Lucila, Barlas, Y., Kanar, K., 2000. Structure-oriented Behavior Tests in Model Validation.

Luo, Lizi, 2017. Schedule risk modeling in prefabrication housing production. 18th International Conference of the System Dynamics Society. Bergen, Norway.

J. Clean. Prod. 153, 692e706.

Census and Statistics Department, 2015. The Hong Kong Annual Digest of Statistics

Niu, Y., Lu, W., Chen, K., Huang, G.G., Anumba, C., 2016. Smart construction objects. 2015. Census and Statistics Department. Hong Kong Special Administrative

J. Comput.

Civ. Eng. 30 (4), 04015070. Region.

Pang, L.Y., Zhong, R.Y., Fang, J., Huang, G.Q., 2015. Data-source interoperability

Hong, J., et al., 2015. Life-cycle energy analysis of prefabricated building composervice for heterogeneous information integration in ubiquitous enterprises. nents: An inputeoutput-based hybrid model. J. Clean. Prod.

Adv. Eng. Inf. 29 (3), 549e561.

Hong, J., Shen, G.Q., Mao, C., Li, Z., Li, K., 2016. Life-cycle energy analysis of pre-

Wang, J., Li, Z., Tam, V.W., 2015. Identifying best design strategies for construction fabricated building components: an inputeoutput-based hybrid model. J. Clean. waste minimization. J. Clean. Prod. 92, 237e247. Prod. 112, 2198e2207.

Xu, G., Huang, G.Q., Fang, J., 2015. Cloud asset for urban flood control. Adv. Eng. Inf.

Hong Kong Housing Authority, 2016. Forecast Public Housing Production. http://

29 (3), 355e365.

www.housingauthority.gov.hk/en/about-us/publications-and-statistics/

Zhang, X., Shen, L., Wu, Y., 2011. Green strategy for gaining competitive advantage in forecast-public-housing-production/index.html. housing development: a China study. J. Clean. Prod. 19 (2), 157e167.

Li, Z., Shen, G.Q., Alshawi, M., 2014a. Measuring the impact of prefabrication on

Zhang, X., Skitmore, M., De Jong, M., Huisingh, D., Gray, M., 2015. Regenerative construction waste reduction: an empirical study in China. Resour. conserv. sustainability for the built environment e from vision to reality: an introducRecycl. 91, 27e39. tory chapter. J. Clean. Prod. 109, 1e10.

Li, Z., Shen, G.Q., Xue, X., 2014b. Critical review of the research on the management

Zhong, R.Y., Peng, Y., Fang, J., Xu, G., Xue, F., Zou, W., Huang, G.Q., 2015. Towards of prefabricated construction. Habitat Int. 43, 240e249. physical internet-enabled prefabricated housing construction in Hong Kong.

Li, C.Z., Hong, J., Xue, F., Shen, G.Q., Xu, X., Luo, L., 2016a. SWOT analysis and Internet

IFAC

PapersOnLine 48 (3), 1079e1086. of Things-enabled platform for prefabricated house construction in Hong Kong.