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Prefabricated construction enabled by the Internet-of-Things

Ray Y. Zhong [a,b], Yi Peng [c,d], Fan Xue [e], Ji Fang [f], Weiwu Zou [g,h], Hao Luo [f], S. Thomas Ng [h], Weisheng Lu [d], Geoffrey Q.P. Shen [e], George Q. Huang [f,*]

[a] Department of Mechanical Engineering, The University of Auckland, Auckland, New Zealand [b] Dept. of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam, Hong Kong [c] School of Urban-rural Planning and Management, Zhejiang University of Finance & Economics, Hangzhou, PR China [d] Dept. of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Pokfulam, Hong Kong [e] Dept. of Building and Real Estate, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hung Hom, Hong Kong [f] HKU-ZIRI Lab for Physical Internet, Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam, Hong Kong [g] Country Garden Holdings, Foshan, Guangdong, PR China [h] Dept. of Civil Engineering, Faculty of Engineering, The University of Hong Kong, Pokfulam, Hong Kong

Abstract:

Prefabricated construction has been used for public rental housing in Hong Kong. In order to speed up housing delivery, Hong Kong Housing Authority (HKHA) have employed advanced technologies, including Building Information Modelling (BIM) and Radio Frequency Identification (RFID), in some of their pilot prefabrication-based construction projects. However, the information obtained from BIM and RFID is not well connected and shared among relevant stakeholders. This paper introduces a multi-dimensional Internet of Things (IoT)-enabled BIM platform (MITBIMP) to achieve real-time visibility and traceability in prefabricated construction. Design considerations of a RFID Gateway Operating System, visibility and traceability tools, Data Source Interoperability Services, and decision support services are specified for developing the MITBIMP. A case study from a real-life construction project in Hong Kong is used as a pilot project to demonstrate advanced decision-making by using cutting-edge concepts and technologies within the MITBIMP to providing a basis for real-time visibility and traceability of the whole processes of prefabrication-based construction.

1. Introduction

Prefabrication refers to the practice of manufacturing the components of a structure in a factory and transporting complete or semi-complete assemblies to the construction site where the structure is to be located [35]. Building Information Modelling (BIM) plays an important role in supporting prefabrication-based construction due to its powerful management of physical and functional digital presentations. BIM currently supports the planning, design, construction, operation, and maintenance of most physical infrastructures from apartment buildings to bridges [3]. Additionally, BIM has been adopted widely for prefabrication-based construction in the U.S., U.K., Japan, South Korean, and Singapore [27,35].

Hong Kong, an international city with over 7 million population, is suffering from a lack of housing. In order to address this issue, the Hong Kong Housing Authority (HKHA) devised a ten-year public housing program [12]. BIM-based prefabrication played a great part in this program with 17% of the total concrete volume used in public housing projects being precast components between 2002 and 2005, and with precast components making up 65% of a special pilot project during that time [9,16]. However, there are several challenges when using BIM in public housing projects based on prefabricated construction. Firstly, data collection from prefabrication manufacturing to on-site construction uses paper-based manual operations. Thus, the captured data are prone to be incomplete, inaccurate, and inadequate [40]. Secondly, information sharing among different parties is confined due to the adoption of traditional methods of communication such as e-mail, phone calls, and fax. Lost information, ineffective communication, and risk-aversion are common in a construction project. Thirdly, collaboration among prefabrication manufacturers, transportation parties, and on-site assemblers heavily relies on real-time information such as the status of precast components, delivery progress, and the location of components. Such information will be fed back to BIM with a certain delay due to manual input operations so that gaps among the involved parties exist, causing poor visibility and traceability of construction progress.

Several cutting-edge technologies have been used to facilitate information collection in construction projects. One of the core technologies is the Internet of Things (IoT), with RFID (Radio Frequency Identification) being one of its key technologies used to facilitate supply chain management, safety management, facility management, and activity monitoring [4,13,17,25,31,33,38]. An elementary application of IoT is the tracking of the materials for various precast components [41]. For a secondary use of the RFID technology, information lifecycle management (ILM) for material control on construction sites has been proposed [19]. In addition to IoT, laser scanning has been proposed for collecting geometric and spatial data for BIM [2,6,7,28,32,36]. Sensors for temperature, force, and positioning have also been used to collect real-time information for better construction [1,11,29].

These studies provide useful references when integrating BIM with other critical information for facilitating construction projects. Some researchers have even incorporated these advanced technologies into BIM with real physical buildings [8]. Along with other advanced technologies, it is possible to use IoT technology in the building industry through a context-aware scenario, although this is not the case with logistics and supply chain management (LSCM). For enhancing information sharing, a link between BIM and enterprise resource planning (ERP) was introduced for visualizing construction processes among different parties [5]. This linked information visibility is based on existing data from databases in BIM and ERP. Thus, it is not a real-time traceability and visualization tool. With the development of Cloud technology, a conceptual framework of prefabricated building construction management system (PBCMS) was proposed to enable access to knowledge [20]. Despite all these efforts, some knowledge gaps still exist, which for the purposes of this study have been converted to the following research questions and corresponding solutions:

- How to create smart construction objects (SCOs) that are able to sense, behave, and execute construction logic within the echelons of prefab manufacturing, prefab transportation, and on-site assembly? This paper introduces a scheme for creating typical construction objects into SCOs using IoT and cloud technology, as well as proposing a designed and developed MITBIMP Gateway for managing the SCOs. • How to establish a system that is able to interact with BIM software and share the information among different parties so that collaborative decision making could be enhanced? This paper introduces a RFID-enabled BIM platform that uses IoT and cloud techniques for designing the architecture. The platform includes a rich set of services and tools to support collaborative decision making in construction projects.
- How to extend 3D design and modelling in BIM to a multi-dimensional application by making full use of collected real-time data so that decisions based on the solution could be more reasonable, precise, and scientific? This paper introduces a traceability and visibility service, which extends the construction business solution into a multi-dimensional level that includes other dimensions such as time (progress) and cost.

The remainder of this paper is organized as follows. Section 2 introduces the architecture of the MITBIMP and discusses design and development considerations to make the platform into a technical reality. In Section 3, a real-life public housing project from Hong Kong is used to demonstrate the necessity and usefulness of the MITBIMP. Section 4 concludes the paper by providing insights gained from implementation of the MITBIMP as well as discussing several aspects for improvement.

2. Multi-dimensional IoT-enabled BIM platform

2.1. Architecture

The proposed MITBIMP, as shown in Fig. 1, concerns production processes, stakeholders, information flow, and real-time information visibility and traceability. Whereas a conventional BIM system provides only 3D models, based on Auto-ID technology and Information technologies, the MITBIMP integrates additional dimensional information (e.g. project progress and cost) to extend the original 3-dimensional platform to a multi-dimensional one, which uses service-oriented architecture (SOA) as a key innovation to enable the platform as a service (PaaS). The MITBIMP contains three levels so as to seamlessly integrate into HKHA's current information architecture. At the bottom, IaaS (Infrastructure as a Service) level includes hardware and software layers. The hardware layer consists of the SCOs and the MITBIMP Gateway, and the software layer includes a Gateway Operating System (GOS) and management tools to manage the SCOs. The MITBIMP Data Source Management Service (MITBIMP-DSMS) level provides not only a selfservice portal for managing platform infrastructure and service provision, but also services across the MITBIMP to support Software as a Service (SaaS) and to handle the IaaS. The MITBIMP Decision Support Service (MITBIMP-DSS) level contains three major management services for various stakeholders at different stages of the construction lifecycle.

From the bottom to the top in Fig. 1, SCOs are construction objects from HKHA construction sites, where typical construction resources are equipped by RFID devices and thereby converted into “smart” objects. The MITBIMP Gateway connects, manages, and controls the SCOs through defining, configuring, and executing the construction operations. The MITBIMP-DSS is designed to suit prefabrication housing construction in Hong Kong at three key phases: prefabrication production, prefabrication logistics, and on-site assembly. In order to enhance data sharing and interoperability among BIM, HOMES (an enterprise resource planning system used by HKHA for more than 10 years) and the MITBIMP, visibility and traceability tools and Data Source Interoperability Services (DSIS) are designed to use an XML-based data sharing mechanism to enable advanced decision making.

There are three sets of service-oriented facilities that are based on cutting-edge IoT technologies for building up the infrastructure to create an intelligent construction environment. The first set includes smart objects, the MITBIMP Gateway and GOS. Visibility and traceability tools and data source interoperability service are deployed in PaaS as the second set, and a prefabrication production management service, a cross-border logistics management service, and an on-site assembly management service are provided in SaaS as the third set of services.

2.2. SCO, MITBIMP and Gateway Operating System (GOS)

SCOs are typical construction resources such as tools, machines, and materials, which are converted into smart objects through binding them to different RFID devices. The purpose of SCOs is to create an intelligent construction environment within typical prefabrication production sites such as factories, warehouses, logistics and supply chains, and construction sites. SCOs are building blocks for such intelligent environments, within which they are able to sense and interact with each other. Typical construction resources are converted into SCOs through various tagging schemes. Firstly, critical prefabrication components such as volumetric kitchens, toilets, and precast facades, are tagged individually, which means that an item-level tagging scheme is adopted because they easily influence the progress in prefabrication-based construction. For non-critical materials such as dry walls and building blocks, tray-level or batch-based tagging scheme are adopted. That means tags are attached to the trays that carry multiple minor prefabrication components. Workers such as machine operators, vehicle drivers, logistics operators, and on-site assembly workers, are tagged with RFIDenabled staff cards. Such construction resources attached with tags are passive SCOs.

The deployment of RFID readers follows a systematic approach. In a typical prefabrication production factory, machines and buffers are equipped with RFID readers because they are value-

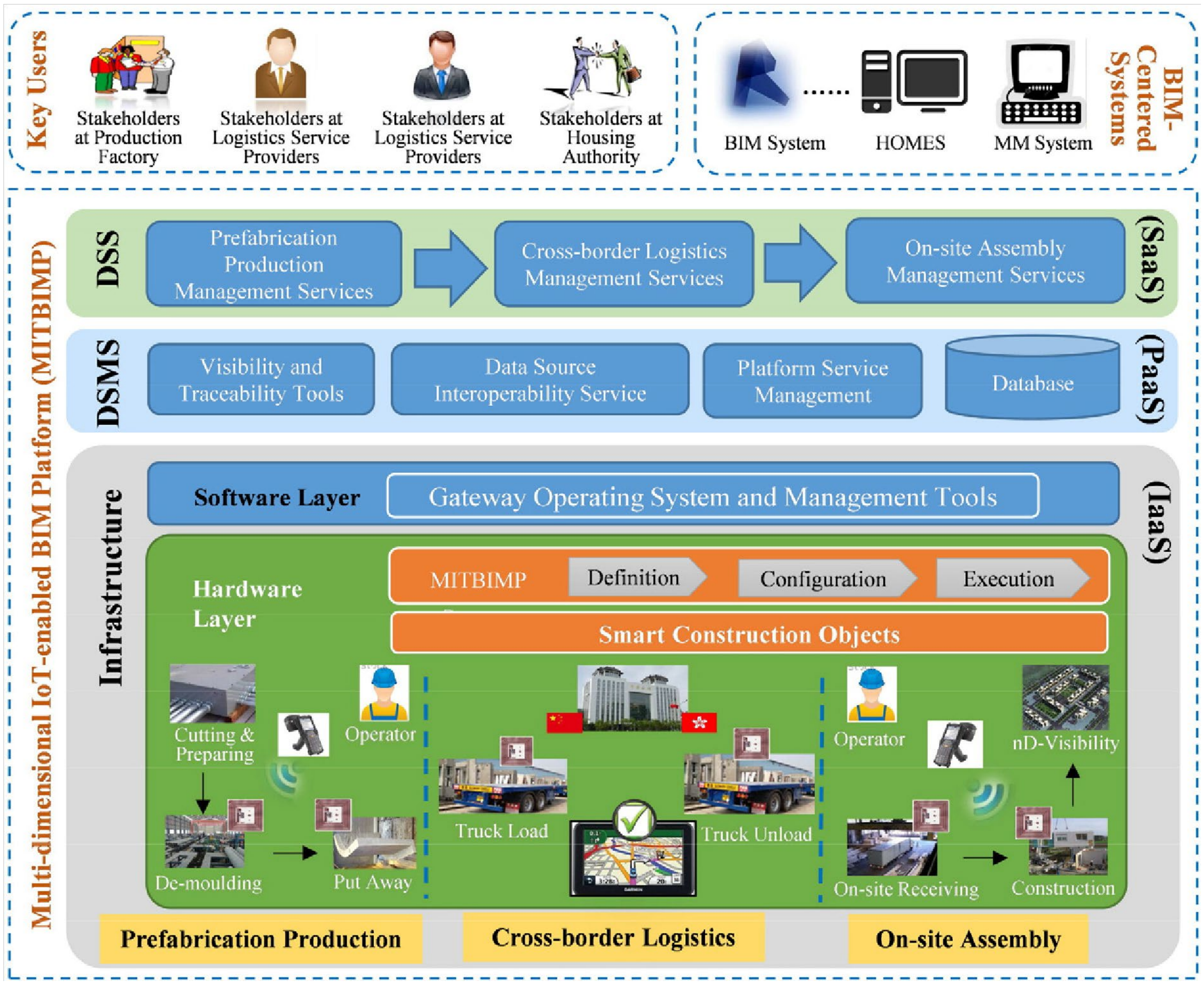


Fig. 1. Overview of multi-dimensional IoT-enabled BIM platform (MITBIMP).

adding points, whose working status must be real-time monitored. Buffers are material tracking points where movements of various items can be traced and the inventory of prefabrication components can be controlled. As they are frequently on the move, logistics operators and inspectors are equipped with PDAs. Once bound by RFID readers, they have become active SCOs that can sense and detect passive SCOs. Both active and passive SCOs are able to sense and interact with each other to create an intelligent construction environment.

The MITBIMP Gateway is an IoT-enabled industrial computer, which performs several key functions in the project to establish an easy-to-deploy and simple-to-use information infrastructure. Firstly, it connects with and hosts a set of SCOs through wired or wireless communication standards. This not only allows workers/operators to access information such as prefabrication production status, but also defines, configures, and executes corresponding prefabrication-based construction through various services. Secondly, it communicates and interacts with upperlevel decision-making systems, such as the MITBIMP-DSS, through providing useful and real-time information in a standardized format; it acts as a bridge between the frontline SCOs and the MITBIMP-DSS. Thus, decisions and their executions could be seamlessly synchronized in prefabrication-based housing production. Thirdly, it processes, caches, and exchanges real-time data and events locally and temporally. To this end, complex event processing (CEP) technology is used to integrate the construction information into a standardized scheme, which could be understood, shared and used by different EISs (Enterprise Information Systems) throughout the construction industry. Finally, it provides a rich set of facilities for service definition, configuration and execution.

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

Design and modelling in 3D have already been realized by commercial software such as ArchiCAD (GRAPHISOFT®), the Dassault Systems (3DEXPERIENCE Company®), and AutoCAD (Autodesk Inc.®). However, the other two dimensions of time and cost are not easy to achieve. The MITBIMP visibility and traceability tools proposed in this research will extend the construction businesses solution from 3D to 5D as shown in Fig. 2.

In the context of prefabrication-based construction, it is increasingly critical for construction companies to be knowledgeable about a product's real-time status, the processes it has gone through, and its history of movements across transactions. Traceability, defined as the “ability to show where a part has been since it was manufactured or last certified”, has become a key concern for HKHA. Prefabricated components pass through numerous different states during their lifecycle: they can change location, custodian, condition (i.e. new/used, serviceable/unserviceable, and scrap), function and form; they can also be installed, repaired, maintained, stored and shipped, and can be exposed to various conditions (i.e. temperature, humidity, and vibration).

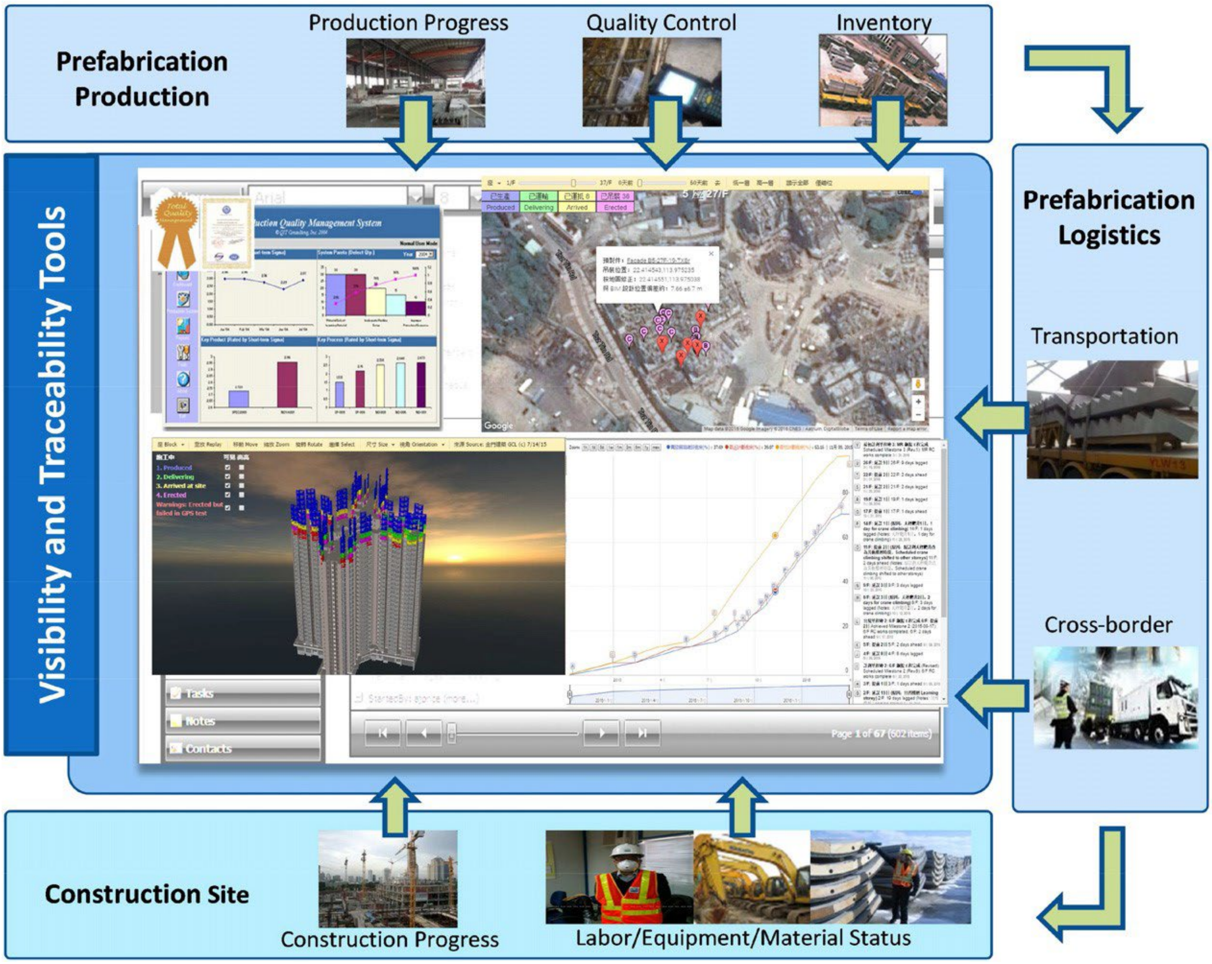


Fig. 2. MITBIMP traceability tools.

Tracking is the ability to determine the current state of a part at any traceability data, which constitute the history of a part (previous locatime, while tracing is the ability to determine the past 'states' and the or- tions and custodians, processing, maintenance and usage history). An igin (raw materials, subparts) of the parts. Tracing is based on effective and efficient information tracking and tracing system enables

Fig. 3. MITBIMP visibility tools.

HKHA and construction companies to rapidly intervene in targeted situations to reduce operational cost and increase productivity.

The MITBIMP traceability tool uses RFID technology to identify various objects in a fully automated manner via radio waves. RFID tags are embedded in the prefabricated components and go through the whole lifecycle of manufacturing, transportation, assembly and maintenance. The MITBIMP Gateway will be set up as a data collector on the prefabrication shop floor, transportation vehicles, cross-border checkpoint, and construction site. All RFID events are captured and stored on MITBIMP tracing servers, which can be shared among other participants.

The MITBIMP visibility tool in Fig. 3, also known as the prefabrication-based construction project control center, provides systematic support for monitoring and controlling. By integrating, visualizing and exploring project data from different perspectives and at various levels of detail, a MITBIMP visibility tool fosters new insights and reveals the complete picture of what is going on in a prefabrication-based construction project.

In case of problems or unexpected deviations, the MITBIMP visibility tool also allows drilling down to present historical project data to examine and identify root causes. The basis of the MITBIMP visibility tool is a measurement infrastructure that periodically extracts data from different operational data sources in a project, such as production plans, transportation process, assembly task management, time recording, quality control, as well as the results from daily builds, tests and statistical analyses. Each of these data sources serves a specific purpose and provides a unique view of the project. For a holistic view, the relevant aspects of these individual views have to be integrated. Therefore, the data is loaded into the MITBIMP visibility tool, linked along various dimensions, and aggregated to concise metrics and indicators. Such data could be presented in the form of project scorecards, customized reports and interactive dashboards.

2.3. MITBIMP Data Source Interoperability Services (MITBIMP-DSIS)

The MITBIMP-DSIS works as an information-sharing adapter so that all heterogeneous data sources could be seamlessly integrated. Fig. 4 demonstrates the key principles of the MITBIMP-DSIS, which uses an Application Information Service (AIS) that serves as a middleware for providing an information query service for different data sources so as to address current challenges in information sharing.

The AIS applies software agent technology that is capable of accomplishing tasks in an autonomous way without human intervention. The agent-based services are managed by AIS Universal Description, Discovery and Integration registry (AIS-UDDI), which facilitates collaboration among agents and enhances register, publish, find, bind and invoke processes. There are several key services in the MITBIMPDSIS: SOA-based Data Access Service, Agent-based Application Information Service, and AIS UDDI Service.

The purpose of SOA-based Data Access Service is to standardize the data access from different heterogonous sources. First, the data requestor sends a data request token to the service. The token is a Structured Query Language (SQL) statement that indicates: 1) the Data Information Model (DIM) to retrieve, 2) the target data sources to query, and 3) the criteria to filter specified records in “SELECT”, “FROM”, and “WHERE” statements respectively. Second, AIS Agent receives and parses the token. Third, based on the “SELET” syntax, the AIS Agent retrieves corresponding DIM in a library. DIM is a schema of data model, such as WIP (Work-In-Process) information and may consist of different information sets from several data sources.

The purpose of the Agent-based AIS is for data requestors to access heterogeneous data sources. Agent technology is adopted to design and develop the platform. It is important to address a few issues in order to design a practical agent model. Firstly, the entitled APIs and drivers of various data sources, including RFID devices, need to be managed and referenced in a uniform manner. Secondly, a unified query mechanism is needed to translate requests to suitable query languages that are required for the data sources. Finally, raw data retrieved from data sources need to be integrated and compiled to a specific format.

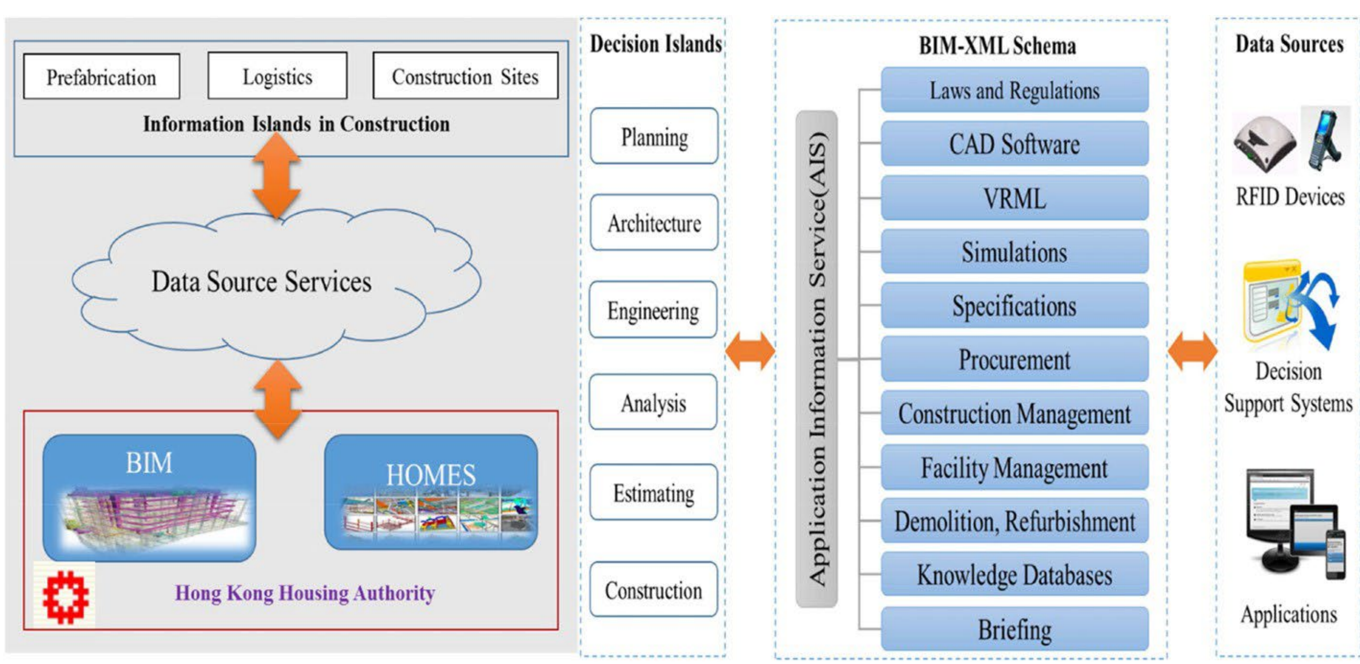

Prefabrication
Logistics
Construction Sites
Information Islands in Construction
Data Source Services
BIM
HOMES
Hong Kong Housing Authority
Decision Islands
Planning
Architecture
Engineering
Analysis
Estimating
Construction
BIM-XML Schema
Application Information Service(AIS)
Laws and Regulations
CAD Software
VRML
Simulations
Specifications
Procurement
Construction Management
Facility Management
Demolition, Refurbishment
Knowledge Databases
Briefing
Data Sources
RFID Devices
Decision
Support Systems
Applications

Fig. 4. Data source interoperability service in MITBIMP.

The purpose of AIS UDDI Service is to descript, discover and integrate the MITBIMP-DSIS and BIM/HOMES. It acts as a facilitator that provides a yellow page directory service to agents; it is an XML-based registry, which is developed for agent services and executes different actions based on the type of AIS agent and request. Rule-based methods are adopted to accelerate decision making by agents. The fundamental element of a rule is a function that has a name, a set of arguments, and a return value, and the function itself can be an argument for another function. All rules are described in a standard structure and stored in an XML file, which can be further updated. An agent can apply the corresponding rule by choosing and loading it from the XML file.

2.4. MITBIMP Decision Support Services

The MITBIMP Decision Support Service (MITBIMP-DSS) works as SaaS for suiting the three echelons in prefabrication housing construction in Hong Kong. Three sets of service-oriented decision support (software) systems are particularly developed as Plugins to HKHA's BIM/ HOMES from prefabrication production, prefabrication logistics, and construction assembly sites.

2.4.1. Prefabrication production service

Prefabrication production service is responsible for working out optimal plans and schedules using advanced models or algorithms such as GA (Genetic Algorithm), ACO (Ant Colony Algorithm), and PSO (Particle Swarm Optimization). The key users are HKHA and its collaborative prefabrication producers. There are several major sub-services, which assist in various end-users to facilitate the prefabrication production operations.

2.4.1.1. Production planning service. The purpose of the production planning service is to select and translate a set of to-be-prefabricated components from BIM software into a required format (e.g. drawings and quantities) for prefabrication firms, and to generate standardized production orders. Several key tasks are involved. Order information, including identifier, time, component specification, volume, and materials, are extracted from BIM. The condition of these orders is obtained for evaluating the readiness and urgency of these orders that are then shortlisted and released to prefabrication firms according to their priorities.

2.4.1.2. Production scheduling service. The purpose of the production scheduling service is for schedulers/supervisors in prefabrication firms to decide who is to do what with which module. It uses

Hybrid Flow Shop or Job-Shop scheduling models. Key users are module operators and supervisors. The following steps are sequenced to facilitate decision making:

- Break down and list the tasks assigned from the production planning service
- Re-prioritize the tasks
- Assign specific tasks to specific operators
- Monitor the progress of individual tasks
- Keep track of statuses of modules and operators
- Insert identifiers, codes or RFID labels

2.4.1.3. Internal logistics service. The purpose of the internal logistics service is to arrange materials and/or facilities for the prefabrication production. It uses graphic-based algorithms to work out optimal solutions. Key users are logistics operators and supervisors who monitor the material delivery and consumption reflected from the RFID-enabled real-time data. Based on the data, supervisors can clearly monitor the inventory and make decision on whether certain material needs to be topped up and how much should be purchased. Logistics operators can take/put back suitable materials or modules for the chosen task. They carry portable PDAs to check, query, and deliver materials efficiently and effectively.

2.4.1.4. Production execution service. The purpose of the production execution service is for facilitating and executing production processes. Key users are operators and planners/schedulers who are able to keep and update a task pool, which provides further details for the production plans and schedules released from planning and scheduling services. For example, some operators may take sick leave and/or some facilities may require repair or maintenance in a specific shift. Site planners/schedulers may then re-prioritize tasks dynamically with the assistance of real-time traceability and visibility facilities for operators, facilities, and materials.

Using the prefab production service, HKHA/planners/schedulers and operators follow standardized operations, which are shown in Fig. 5. For HKHA/planners/schedulers, they are able to use the tools and facilities to fulfil their daily operations, such as prefabrication tasks management, material requirement, and statistical data. Such decisions are real-time reflected in prefabrication production sites over wireless and wired networks by RFID facilities. Additionally, RFID facilities collect real-time production data, thus, HKHA/planners/schedulers can trace and track materials, workers and equipment. Furthermore, statistical data are more precise and timely through prefabrication production execution and control.

Operators carry various RFID devices to accomplish their daily operations and get jobs through tapping their RFID staff cards on readers. Logistics operators use mobile devices (such as Symbol Workabout Pro 4® ZIH Corp.) to deliver the materials according to the job assignment. After getting the materials and job instructions, operators carry out the prefabrication production. Processed components are then moved to the next stage until all the processing stages are undertaken. Finally, the finished prefabrication components are inspected and shipped. Throughout all the processes, RFID facilities play critical roles in collecting various types of information about prefabrication production, thereby allowing plans and schedules to be strictly followed.

2.4.2. Prefabrication logistics service

The prefabrication logistics service is responsible for managing and controlling prefabrication logistics from production sites to the final destination. It uses ACO algorithms for figuring out the best solutions. This service helps HKHA to real-time track the progress of prefabricated components moving between the PRD (Pearl River Delta) and Hong Kong. There are several major sub-services that assist various endusers to facilitate prefabrication logistics management.

2.4.2.1. Transportation planning & scheduling service. The purpose of the transportation planning and scheduling service is to make optimal decisions related to the delivery of precast components. Once the precast components are finished, the prefabrication production service will trigger the logistics tasks, which are synchronized with the BIM system. Transportation optimization models for prefabrication logistics are designed and developed as web services, and specific rules are used for making transportation plans and schedules for construction logistics control. This service consequently provides tools for end-users to create rules as individual services and publish them on a repository for use by transportation planners and schedulers in different practical situations.

2.4.2.2. Real-time transportation monitoring service. The purpose of the real-time transportation monitoring service is to track the current status and location of prefabricated components throughout the logistics and supply chain. This service uses RFID and GPS technologies to track transportation vehicles in real time and then graphically present their status, progress, and current location in 3D using a Kanban system.

2.4.2.3. Fleet management service. The purpose of fleet management service is to manage vehicles transporting prefabrication components in order to share resources among different parties, such as prefabrication production companies and HKHA's transportation partners; the main users being logistics operators. This service uses RFID technology to create a smart transportation environment for enhancing real-time information sharing throughout the process of prefabrication handling, loading, and transportation. The real-time information is utilized for coordinating decisions and operations of different parties involved in fleet planning, scheduling, execution, and control.

By using the prefabrication logistics service, logistics execution and control are improved. Fig. 6 shows the coordination of decision-making parties such as HKHA, transportation partners, and

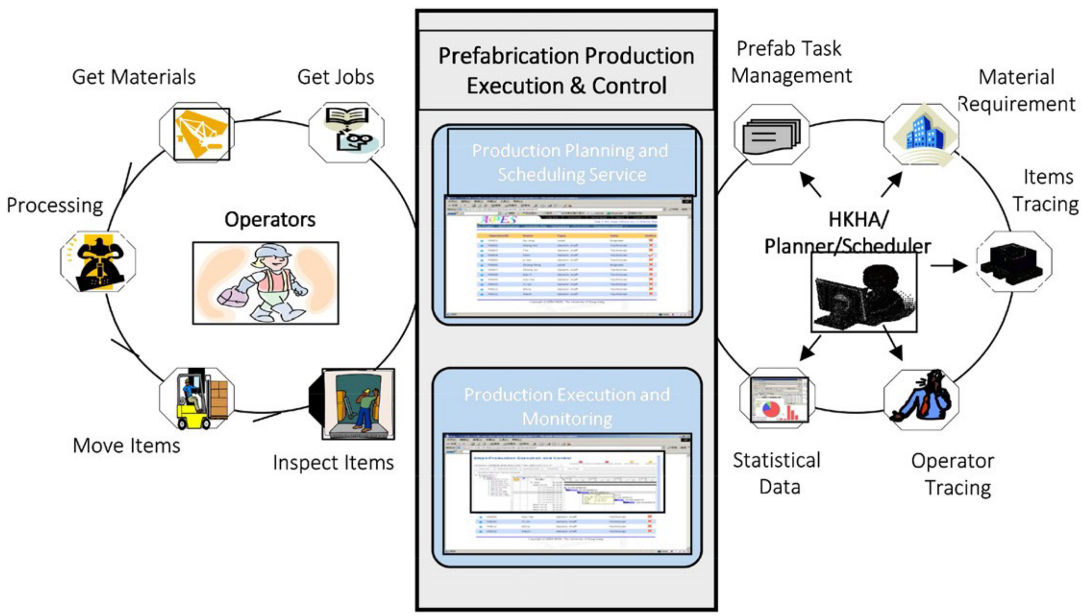


Fig. 5. Prefabrication production execution and control.

operators/drivers. HKHA and transportation partners are able to make decisions regarding logistics tasks, fleet management, and loading schemes. The decisions will be timely obtained by the operators/drivers, since all the logistics information is captured with RFID technology, which allows precise and complete statistical analysis.

Operators/drivers tap their RFID staff cards to get logistics jobs, logistics operators load the prefabricated components according to the logistics tasks, and drivers then tap their staff cards on a vehicle and deliver the components. By twining the logistics decision-making and execution to a level that is real-time, the transportation of prefabricated components becomes smoother.

2.4.3. On-site assembly service

The on-site assembly service is responsible for assisting various operations and supervisions at the prefabrication assembly sites. There are four major sub-services: on-site asset management service, realtime supervision service, data capturing service, and real-time feedback service.

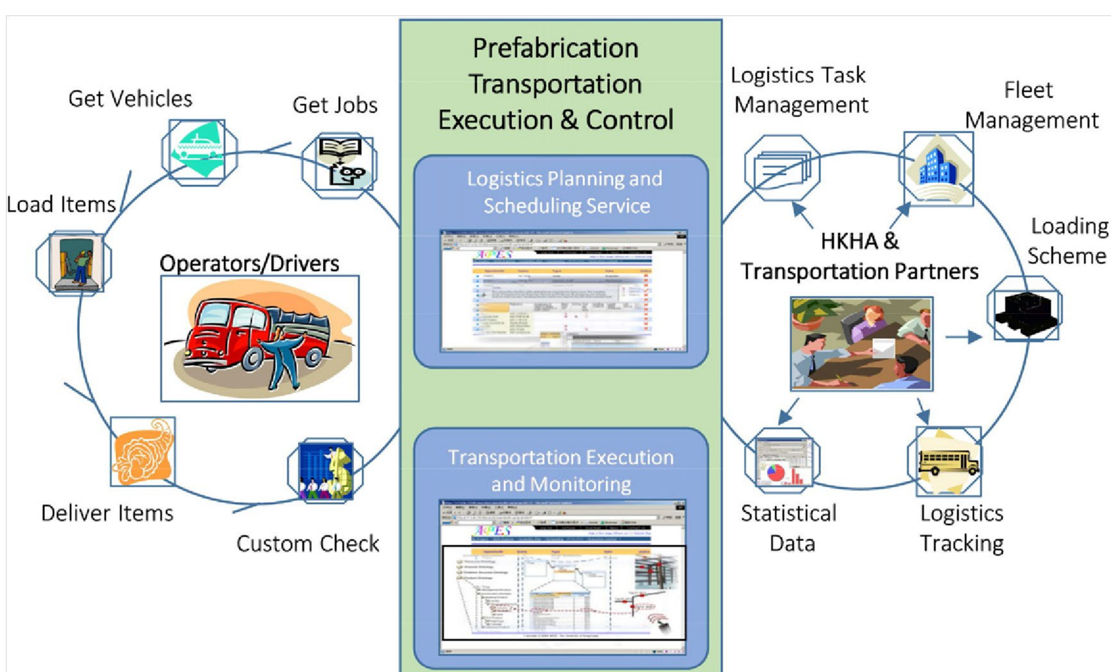

Prefabrication Transportation Execution & Control
Logistics Planning and Scheduling Service
Transportation Execution and Monitoring
Get Vehicles
Get Jobs
Load Items
Operators/Drivers
Deliver Items
Custom Check
Logistics Task Management
Fleet Management
Loading Scheme
HKHA & Transportation Partners
Statistical Data
Logistics Tracking

Fig. 6. Prefabrication logistics execution and control.

2.4.3.1. On-site asset management service. The purpose of the onsite assets management service is to optimally manage a construction project's resources, including workers, tools, and machinery. RFID technology is used to identify the resources and then the MITBIMP is used to support optimal site management through the distribution of materials and workers, storage of materials on site, and the positioning of crane towers. Through this optimal site management, labor usage could be optimized and assembly time could be shortened. With RFID asset information included in the service, safety control becomes much easier because all the information from on-site assembly is captured thereby allowing safety issues and risks to be observed in advance. The service also provides tools for controlling the issues and risks so that on-site construction safety will be largely improved.

2.4.3.2. Real-time supervision service. The purpose of the real-time supervision service is to monitor the status of various workers, machines, and materials on a construction site. The main users are HKHA and on-site supervisors who are responsible for controlling the construction objects and reporting to various stakeholders about the progress, current challenges, and barriers. This service provides a Gantt chart or a nD virtual reality presentation, which uses the RFID assembly data to reflect realtime construction progresses in terms of prefabrication assembly status, material consumption, and worker assignments. This way, all the involved project stakeholders could know the current situation and make associated decisions collaboratively.

2.4.3.3. Data capturing service. The purpose of the data capturing service is to collect useful RFID data from a large number of dataset so that meaningful and useful information could be extracted. The main users are on-site foremen who use the real-time and meaningful information to coordinate different parties to fulfil the project. This service provides a set of tools to capture, format, and display the relevant information to support their decision making, especially when machines breakdown and fragmentations occur. By using this service, on-site operations will be much smoother due to enhanced coordination and precise decision making from various parties.

2.4.3.4. Real-time feedback service. The purpose of the real-time feedback service is to report the current on-site assembly situation to different involved parties and other interested associations. Its main users are project liaison personnel responsible for negotiating and coordinating with various parties, such as environmental bodies and governmental departments. For closely related parties like the HKHA, prefabrication manufacturers, logistics partners, and designers, key information such as progress, current status, and on-site situations is real-time fed back so that they could make decisions on JIT logistics in line with the current assembly requirements. For other interested associations like HKCA, CIC, statistical reports will be generated according to the data captured from frontline construction sites. Using this service, on-site assembly execution and control could be supervised in real time. Fig. 7 demonstrates the execution and control of on-site assembly through typical end-users. HKHA and on-site managers are able to manage the assembly tasks and make material requirement plans. With real-time feedback from assembly sites, prefabrication components, workers, and tools are traced and tracked in real time. The real-time data is also used for forming reports and statistical analysis.

Operators/workers on construction sites use RFID facilities to assist with their daily operations. They can tap their staff cards to get jobs, and corresponding prefabrication components will be moved to pre-defined locations for them to carry out the task. Logistics operators move various components based on the assembly task, after which the assembly is inspected and all the information captured.

3. Case study

A real-life case study from a prefabrication-based construction project in Hong Kong is used to demonstrate the necessity and usefulness of the developed MITBIMP. Difficulties in implementing such a system in the case project are also discussed.

3.1. Case background

The project is an on-going public housing project located in Tuen Mun District, New Territories, Hong Kong. The project involves building five 34–38 storey residential buildings, providing about 5000 public units with the expectation of holding about 14,000 people. Social facilities, such as a kindergarten, a day care center for the elderly, a commercial center and shops, and several community centers/halls are also planned as part of the project. The main stakeholders of the project involved in the construction phase include the HKHA as the designer and client, a local construction company as the main contractor, an offshore production factory located in Huizhou, Guangdong Province, China, and several third-party cross-border logistics companies.

The process of the prefabrication-based construction of the selected case can be found in Fig. 8, which includes three main phases: prefabrication production, cross-border logistics and on-site assembly. As the project client, HKHA coordinates and monitors the project quality, cost

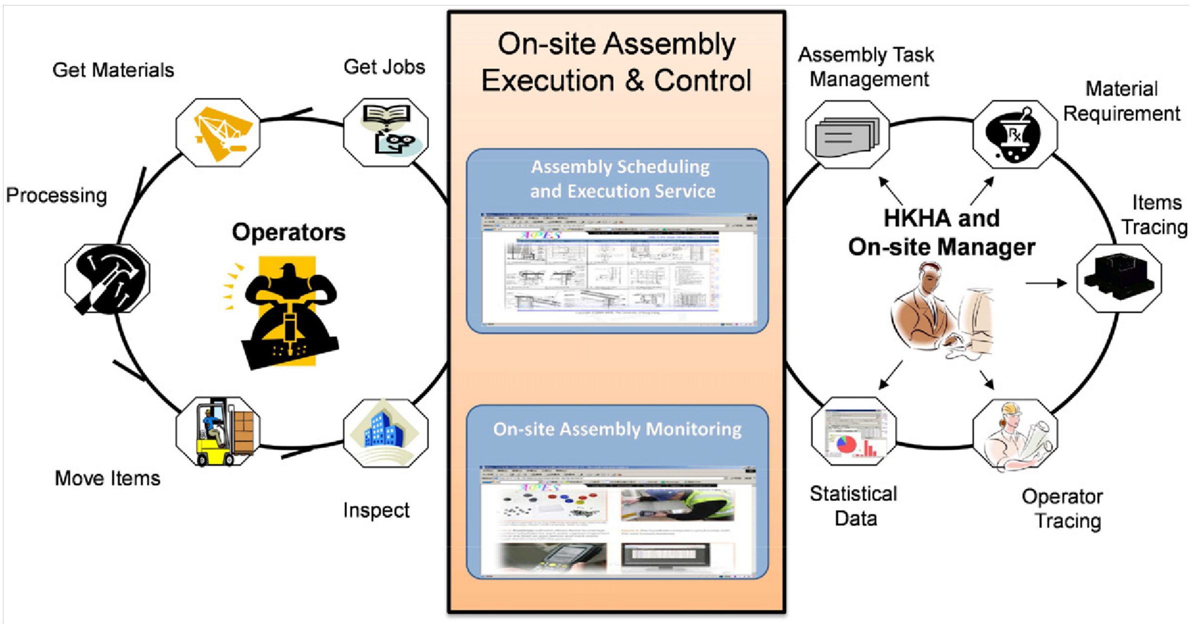


Fig. 7. On-site assembly execution and control.

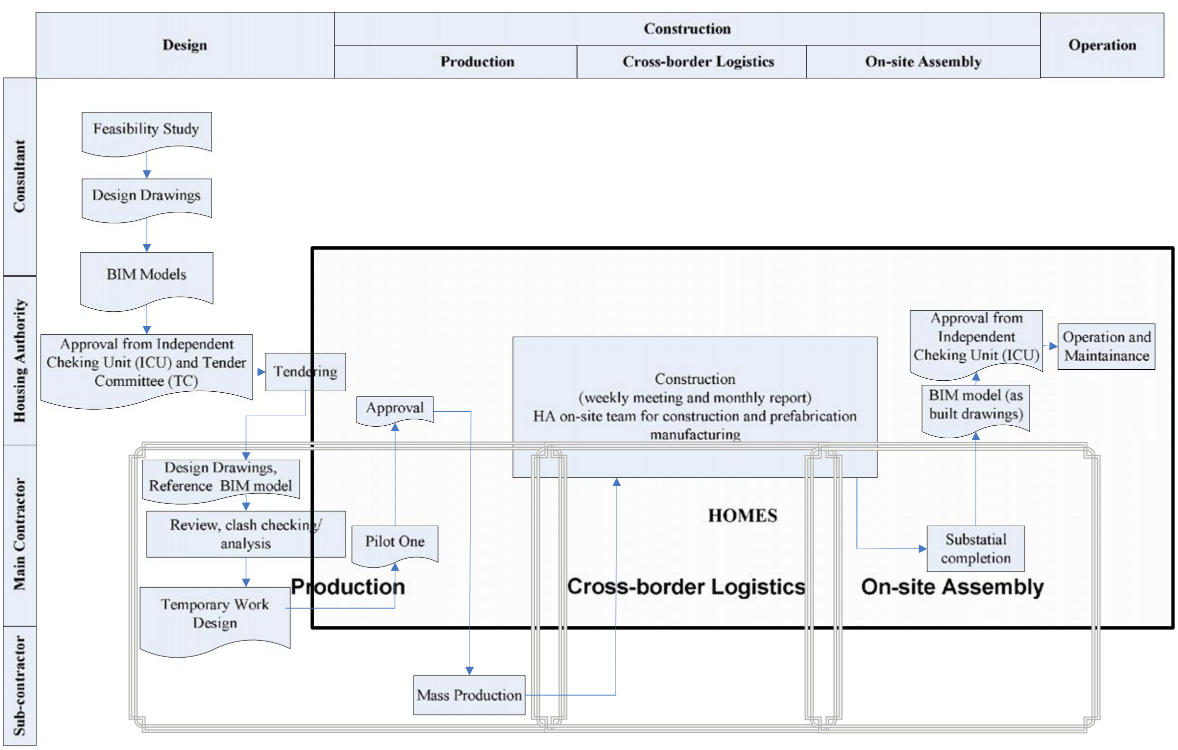


Fig. 8. Process of the prefabrication construction of the selected case.

and progress, from the project inception stage up until the substantial completion of the project. The main contractor implements the BIM models to prefabricated work designs and makes a pilot mock-up before mass production and construction. After approval of the mock-up samples, subcontractors can start mass production. Logistics companies and the main contractor can then deliver and assemble prefabricated components after approval from HKHA.

3.2. Problems identified in the case

Field studies and interviews of relevant stakeholders were conducted between June and September 2014 to identify the major problems in the selected case. It was found that the main stakeholders have several fragmented applications with RFID or BIM. For example, BIM models were substantially employed into the design phase together with HKHA, but not widely adopted in the on-site construction phase. RFID was mainly incorporated as an ERP-like system in the construction phase to trace the status of construction components. However, the contractor preferred a traditional paper-based working mechanism. These problems are found to be common problems in Hong Kong's construction industry.

Information fragmentation also presents difficulties when trying to improve efficiency in the three critical stages. From the case study interviews, problems associated with manufacture of the prefabricated components were identified as follows:

- It was unclear how to pass the design information to the manufacturers without any ambiguity.
- It was extremely difficult, if not completely impossible, for both the client and suppliers/manufactures to handle the ordering information automatically.
- Embedding design information into the prefabrication components for further use was also a challenge. The traditional approach caused difficulties in retrieving the data efficiently for other uses, such as production and inventory management, and transportation. As a result, components might be mistakenly delivered to other construction sites causing a serious delay to the project.
- Decision-making in prefabrication manufacturing was based on untimed and inaccurate data, and rule of thumb. Communication was carried out by traditional means, such as phone and fax.

- Problems encountered by the logistics companies were identified as follows:

- Prefabrication production and logistics companies did not share their information. Extra time spent on negotiating, discussing, and making decisions affected logistics efficiency significantly.
- Traditional communication methods (e.g. telephone, fax and paperbased formats) were used for exchanging information among the prefabrication manufacturer, main contractor and the 3 party logistics (3PL) company. This approach caused issues such as lagged information, which impacted overall construction planning and progress.

Problems encountered by the on-site assembly were identified as follows:

- Construction sites are getting increasingly smaller so higher efficiency in site management planning, such as JIT delivery of prefabricated components, could help substantially. To achieve this goal, availability of real-time information on products is essential.
- Verification of the components was inefficient, mainly due to the wide use of paper or painted labels. The accuracy of the verification process was not guaranteed since the paper-based documents, or even handwritten and modified labels were usually ambiguous.
- There was a lack of real-time information about prefabricated and onsite work completed by the contractor for monitoring the cash flow. Currently, a quantity surveyor (QS) is assigned to check the bill of quantities (BQs) manually to confirm the works completed by the contractor, and to make recommendations on payment to the contract manager.

The identified challenges provided specific requirements that the developed MITBIMP should satisfy: 1) provide a common platform for information sharing between the stakeholders; 2) have the visibility and traceability for tracking the components throughout prefabrication production, transportation, and assembly; and 3) embody decisionmaking support for critical stakeholders, including cost estimation, duration scheduling, and three-dimensional information of the buildings. In order to provide such functions, the system is designed based on the requirements to automatically collect information, be compatible with existing systems, and provide cloud services.

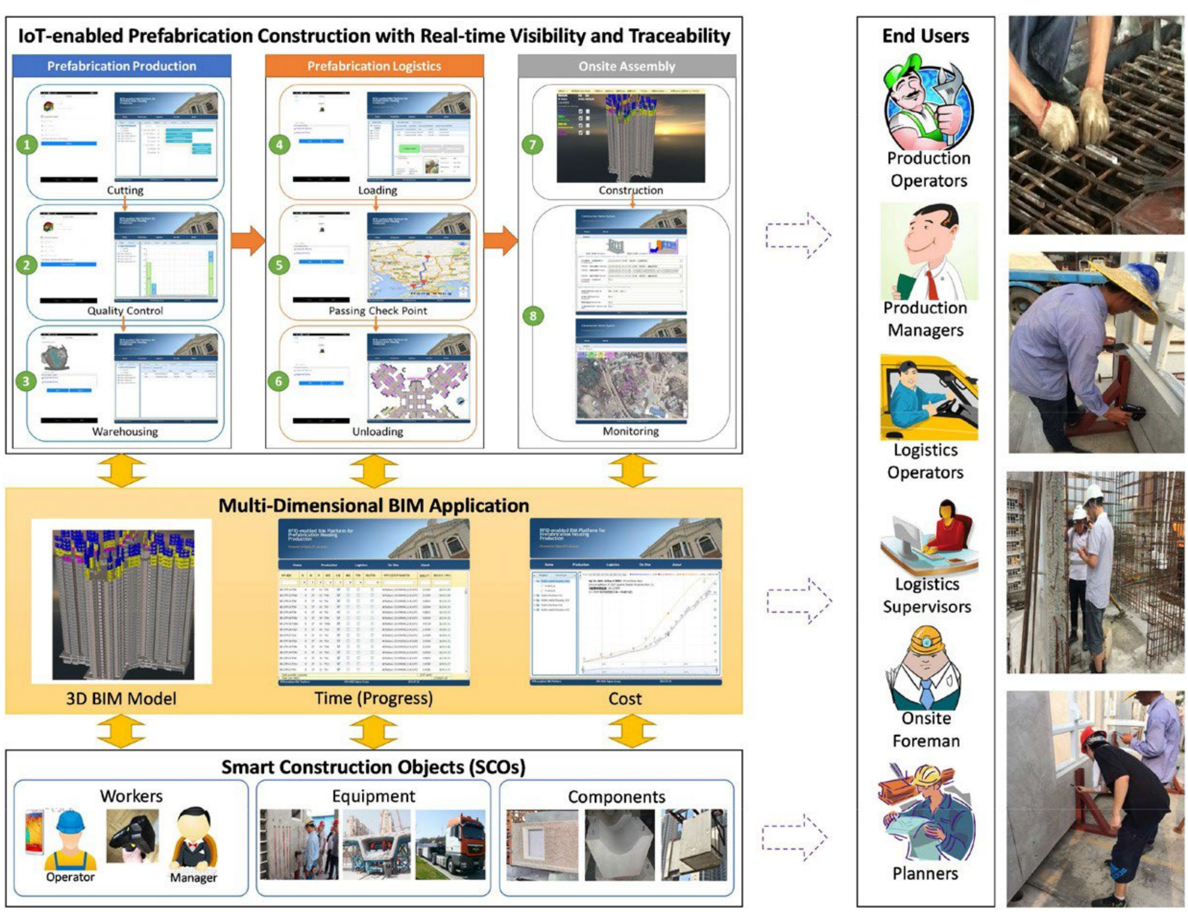
3.3. Implementation of MITBIMP

UHF (Ultra High Frequency) RFID technology was embedded into the prefabrication components with plastic protective shells to collect critical real-time information in the prefabrication manufactory, including generating a materials list for production, demoulding, quality control, and availability for logistics. Hand-held RFID readers collected RFID and GPS data. For example, RFID and GPS data of the logistics truck were collected by the driver to obtain critical real-time information in the logistics process, including load prefabrication components on trucks, leaving the prefabrication manufactory, transportation route, custom clearance, handover on the construction site, and confirmation of the prefabrication components. RFID was used to guide and monitor the assembly process, the critical information of which includes lifting and confirmation of the assembly.

All the collected real-time information from RFID and GPS are connected with BIM in the developed MITBIMP. Traceability and visibility of the physical building information, progress, and cost are available for the client and contractor to monitor throughout the whole construction process. Fig. 9 illustrates how the MITBIMP operates in the three stages.

The MITBIMP platform successfully addressed the problems identified in the interviews. The paper-based records were subsequently freed for many processes and only reserved for verification in key processes. The usage of BIM technique was henceforth extended to the construction phase. If the histories of building components and the project progress were kept for future operations and the maintenance phase, the BIM of built works could also be utilized. However, the MITBIMP did not change the core current business processes. Instead, some real-time data gathering was integrated to the processes in convenient ways. For example, an inspector in the production factory can scan the component object for a confirmation of quality checking. The dissemination of real-time data and the status of the virtual models are can also be used in multiple ways. Apps and SMS notification are used to guide the relevant workers.

Changes have been made to the prefabrication manufactory in several aspects. Firstly, the data required by the factory and those exchanged with other stakeholders has become more accurate and reliable. Secondly, the ability of responding to design and job plan changes are much stronger. The management of the factory has become more efficient due to real-time information sharing. Lastly, construction resources are optimized as a result of decision making based on realtime data from the production sites.



IoT-enabled Prefabrication Construction with Real-time Visibility and Traceability
Prefabrication Production
Prefabrication Logistics
Onsite Assembly
Cutting
Quality Control
Warehousing
Loading
Passing Check Point
Unloading
Construction
Monitoring
Multi-Dimensional BIM Application
3D BIM Model
Time (Progress)
Cost
Smart Construction Objects (SCOs)
Workers
Operator
Manager
Equipment
Components
End Users
Production Operators
Production Managers
Logistics Operators
Logistics Supervisors
Onsite Foreman
Planners

Fig. 9. Demonstration of the developed MITBIMP in the selected case.

Cross-border logistics has also been improved. The logistics providers adopt better services to the factory by making full use of the data from production, logistics companies have a dynamic tracking and control function for visualizing delivery of prefabrication components, and cross-border logistics and supply chain management has become more efficient.

The main contractors benefit from knowing the real-time information of prefabrication components. The data collection on site has become effective, reliable and more value-added. Therefore, the whole on-site main contractor team is more resilient when facing design changes, order changes, or changes due to repairing defective components.

The client, HKHA, benefits from obtaining real-time information. The visibility and traceability tools enable HKHA to monitor the status of components in real-time. The multi-dimensional information of cost and progress provided by the MITBIMP helps the client to manage the progress and arrange payment accordingly. Historical information of the stakeholder's performance stored in the MITBIMP is used for facilitating contractor and sub-contractor selection.

3.4. Discussion on implementation of difficulties and responses

Besides qualitative improvements, quantitative improvements are also significant. From the pilot run of the MITBIMP in the case study, Table 1 presents a statistical analysis of the improvements. These data come from the Tuen Mun project. Several KPIs are presented by comparing before and after implementation of the MITBIMP. The first pilot run of the MITBIMP was 1 October 2015. The statistical analysis is carried out as shown in Table 1 from the comparison of before the first pilot run (1 March 2015 to 30 September 2015) and after the first pilot run (2 October 2015 to 30 April 2016).

From Table 1 it can be seen that for each construction stage, information transferring has been greatly improved by using the RFID data collection approach. The paper work at the production and logistics stages is reduced by 48.3% and 40% respectively. Along with the reduction, production efficiency has also been improved. For each stage, take the façade for example, the production lifecycle and waiting time for delivery are enhanced by 40% and 25% respectively, as well as the assembly time has improved by 6.67%. As full use of collected information has been made via visibility tools, time costs on locating and order picking at both production and logistics stages are improved by 31.25% and 40% respectively. This implies a great saving on the cost of labor associated with finding different components on construction sites.

During implementation of the MITBIMP, several difficulties from real world practices were encountered. A few crucial difficulties with proper responses are highlighted as follows.

Firstly, some places, such as cross-sea bridges or long tunnels, may not have a wired network or WiFi/3G/4G signals during the process of logistics and on-site assembly. One solution is that the equipment/terminals have the ability of tracking records of time, location, and status in an offline mode. Servers on the Internet have the ability to receive and record a batch of tracking data. Once the network is available, all the data can be resumed to the corresponding history.

Secondly, even though placing them under aluminum windows or inside concrete components protects RFID tags, they may not be detected due to damage. One solution is that backup tags can be prepared in

Table 1

Phase	KPI	Before	After	Improvement
Production	Paper work	200–300 A4 papers/day	110–145 A4 papers/day	48.3% averagely
	WIP inventory	110 sets in average	98 sets in average	10.9%
	Production lifecycle	10 days in average (façade)	6 days in average (façade)	40%
	Time cost on locating	7–8 min in average	5.5 min in average	31.25%
Logistics	Paper work	5 papers/car	3 papers/car	40%
	Waiting time for delivery	2 h	1.5 h	25%
	On time rate of delivery	92.5%	99.8%	7.3%
	Order picking time	2 h/car	1.2 h/car	40%
On-site assembly	Assembly time	6 day per cycle	5.6 day per cycle	6.67%

KPIs comparisons (before and after).

several key check points so that once the RFID tag cannot be identified, then the component can be quickly associated through other labels such as a bar code or printed serial number. The original tag is then marked as “expired” and a new tag can be attached as a replacement that inherits all historic data.

Thirdly, defective components, which are often found in the first few stories, can be the toughest obstacles in the whole project. A defective component usually needs to be repaired on site, or to be replaced by another one, or to be sent back to the factory in the worst case. To handle these exceptions, the record of a component covers extra reparation, exchange history, and rollback. The related functions are also necessary for the end users.

4. Conclusions

This paper presents a multi-dimensional BIM platform with IoT-enabled real-time visibility and traceability for the prefabricated construction industry. Problems in the prefabrication-based construction industry in Hong Kong have been identified. An innovative multi-dimensional BIM platform has been established. A case study from a public rental housing project in Tuen Mun, Hong Kong, has been used to demonstrate the necessity and usefulness of this platform.

Several contributions are significant from this study. First, smart construction objects (SCOs) enabled by IoT technologies are created to build upon a smart construction environment along with prefabrication-based construction in Hong Kong. SCOs and IoT-enabled smart Gateway works collaboratively to ease operations within the three echelons of prefabrication: manufacturing, logistics, and on-site assembly. Second, using cutting-edge technologies, a multi-dimensional BIM platform is established for leveraging the real-time captured data from SCOs to make advanced decisions. This platform is able to provide various services, tools and mechanisms to different stakeholders to help fulfil daily operations and improve efficiency by enhanced information sharing and advanced models. Third, this platform captures real-time data to form a closed-loop visibility and traceability mode in which different end-users can monitor a project's status, progress, and accumulative cost in a real-time fashion. Thus, different parties can focus on different aspects during the life cycle of a prefabrication-based construction project, and they can work cooperatively through real-time visibility tools to solve problems or deal with unexpected deviations. Finally, this research extends the traditional 3D BIM application in prefabricationbased construction into nD by using IoT-enabled real-time visibility and traceability tools. Key concerns such as time and cost are seamlessly integrated into BIM so that multi-dimensional applications could be achieved.

In order to make continuous improvements to the MITBIMP, it is recommended that future research be carried out from several aspects. First of all, industrial standards, such as Construction Standard CS2:2012 and ISA 95, could be integrated into the platform so that the operation, behaviour, and data formats can be standardized to make further efficiency enhancements. Secondly, after deploying the SCOs and smart Gateway in various construction sites, including manufacturing factories, logistics companies, and assembly locations, a huge amount of construction data could be captured and collected. Such data carry rich implicit information and knowledge, which requires advanced technologies such as Big Data to explore [42]. Thirdly, the concepts and core technologies from this research could be extended into other industries such as pharmaceutical and chemical, both of which could benefit from the safety and efficiency offered by real-time visibility and traceability. Finally, in addition to future technical improvements, the real-time system could be developed to facilitate different kinds of real-life projects in different regions, which will help with verifying the system's generalizability.

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