RBL-PHP: Simulation of Lean Construction and Information Technologies for Prefabrication Housing Production

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Abstract

Prefabrication housing production (PHP) is widely promoted due to its potential benefits, such as reduced construction time and improved quality. However, PHP also faces many uncertainties and constraints due to the highly fragmented process of managing design, construction, and supply chain. Lean Construction principles and information technologies, e.g. Radio Frequency Identification (RFID) and Building Information Modeling (BIM), have proven to be effective to help reduce the uncertainties and remove the constraints in PHP. However, the availability of appropriate training or pedagogical approaches to transfer and share the lean knowledge and information techniques has impeded their adoption. To address the issue, this study develops a hands-on learning tool, an advanced simulation game called RBL-PHP (i.e. RFID/BIM/Lean-Prefabrication Housing Production), which simulates the process of PHP from manufacturing, logistics to the on-site assembly by integrating an RFID-enabled BIM platform with Lean Construction to training students and practitioners. Four workshops are conducted at The Hong Kong Polytechnic University, Hong Kong, China, to assess the participants' learning experience by using ex-ante and ex-post surveys. In each workshop, the performance of PHP is tested separately in a traditional round and a RFID/BIM/Lean (RBL)-enabled round on indicators including the percentage of plan complete (PPC), extra cost, and the productivity index. The results indicate that the stability and efficiency of PHP are improved in the RBL-enabled round. In addition, the simulation game can significantly improve the understanding of various knowledge concepts in PHP, such as prefabrication production structure, standardized work, smart construction objects, information sharing and communication, real-time tracking and visualization, when compared to a traditional computer-based multimedia presentation approach. It can be adopted as a useful platform to effectively train practitioners in the PHP sector on the use of lean, BIM and other innovative information technologies.

Keywords: Prefabrication housing production, Lean Construction, BIM, RFID, simulation game

Introduction

The public high-rise residential buildings in Hong Kong have benefited and will continue to benefit significantly from Prefabrication Housing Production (PHP) in the aspects of fast-track process, more sustainable and safer working environment (Tam et al., 2015). The demand of PHP will keep increasing in the future due to the fact that more than 100,000 applicants are on the waiting list for residing in public houses (Li et al., 2016a). PHP aims to achieve an industrialized construction environment where design, prefabrication, and construction activities are integrated (Babič et al., 2010). As such, the achievement of PHP is highly dependent on the integration of information. The fragmented information during manufacturing, logistics, and on-site assembly phases leads to uncertainties and constraints. Uncertainty refers to something that may occur while constraint (e.g. limited space and buffers) is something that will happen (Wang et al., 2016). If uncertainties are not resolved, and constraints are not removed, there will be project problems such as schedule delay, cost overrun, and inefficient resources allocation (Li et al., 2016b). Therefore, uncertainty reduction and constraint removal in the whole housing production process, including manufacturing, logistics, and on-site construction, are critical issues in PHP.

Lean Construction, as an increasingly popular methodology, originates from the Toyota Production System (TPS). It can help smooth the production and information flow, thus minimizing variation, the waste of material, time and human resources, and improving coordination and production quality (Salem et al., 2006). Under the principles of Lean Construction, a production planning and control tool, i.e. the Last Planner® System (LPS®), was developed by Ballard (2000) to address the limitations of traditional planning on coping with uncertainties and constraints in projects. Although the LPS reduces the workflow variability and provides a reliable working environment (Arashpour and Arashpour, 2015), it fails to enable visualized and real-time feedback of process status (Sacks et al., 2010). It is difficult to implement a robust pull planning method in real construction cases due to the difficulties in prioritizing the work activities in accordance with non-visualized signals from downstream demand (Khan and Tzortzopoulos, 2015). For example, the work teams on the construction site may find it difficult to visualize the flow of work in progress and communicate its exact status and demand with the manufacturing and logistics teams. In addition, the LPS adopts weekly work planning rather than real-time planning (Seppänen et al., 2010). The weekly feedback time may be too long for some tasks whose constraints can only be removed within a short duration of time before their execution (Sacks et al., 2010). PHP practitioners and academics in recent years are keen on exploring technological innovations to address these issues (Bosché et al., 2013; Zhong et al., 2015). For example, Building Information Modeling (BIM) can serve as a 3D platform for integrating and sharing geometric and functional information required for collaboration by various stakeholders during different stages of the project (Nath et al., 2015). Specifically, the object-oriented characteristic of BIM can be used collaboratively with prefabrication production to enhance the transparency of information in workflow and cut down the uncertainty by reducing the information asymmetry (Nawari, 2012). In addition, Radio Frequency Identification (RFID) and Global Positioning System (GPS) can be applied to analyze real-time PHP status and location information to strengthen the traceability of the BIM platform. Based on the results, the project team can identify constraints and make decisions in time (Bosché et al., 2013). Integrating RFID, BIM, and Lean Construction into a single platform can, therefore, help enable a faster reaction on addressing uncertainty and constraint (Costin et al., 2015; Fang et al., 2016).

Despite the merits of using RFID/BIM/Lean- (hereinafter referred to as RBL-) related tools in PHP, numerous implementation barriers have been identified (Mahalingam et al., 2015). It is found that one of the barriers that prevent a successful RBL implementation is the training or pedagogical approaches to transfer and share the lean principles and information technologies behind it within an organization (González et al., 2015). To facilitate the dissemination of RBL-related techniques and knowledge into the industry, it is critical to train future practitioners on the implementation of such knowledge and techniques. This study, therefore, concentrates on the development and application of an RBL-enabled simulation game for PHP (hereinafter referred to as RBL-PHP). Game-based simulations are practical hands-on learning tools for students and practitioners in the PHP field (Sacks et al., 2007). RBL-PHP, through the simulation of some facets of lean principles, prefabrication production, and RFID-enabled BIM platform in a role play game, can be used to reinforce the learning and understanding of how to integrate Lean Construction principles with information technologies to improve the productivity of PHP among students and practitioners. RBL-PHP uses an RFID-enabled BIM platform that requires proficient platform operations and collaborative working from all players to plan and control the whole process of PHP. It can provide practical learning in the simulation. Furthermore, RBL-PHP adopts Lean Construction principles such as standardized work, pull, and Just in Time (JIT) to facilitate the implementation of the RFID-enabled BIM platform when the lean principles are utilized to optimize each step of the workflow. The primary objective of this study is, therefore, to investigate RBL-PHP as an efficient training and pedagogical tool for the teaching and learning of Lean Construction principles, RFID and BIM technologies in PHP.

Background

Prefabrication Housing Production

Prefabrication Housing Production (PHP) is a process of pre-assembling materials or components of a housing facility in a manufacturing plant, and transporting the produced modules or units to the construction site where they can be installed (Li et al., 2014). Although researchers in different regions may adopt different terminologies to describe PHP, such as off-site construction, modular construction, industrialized building, precast concrete building and preassembly production (Gosling et al., 2016), PHP, as a modern method of construction, compared with the conventional cast-in-place construction, has been widely adopted over the world. Particularly, it is a widespread practice in public housing projects in Hong Kong (Jaillon and Poon, 2009). This broad implementation can be explained by its advantages, such as mitigation of limited construction space and buffers (Jaillon and Poon, 2008), reduction of on-site construction time (Tam et al., 2007), reduction of on-site waste and labor resource (Tam et al., 2015), enhancement of quality control (Jaillon and Poon, 2010), and improvement of on-site health and environment (Jaillon and Poon, 2014). Despite these significant benefits, PHP has been found to have many problems in terms of production structures and information technologies (Bock and Linner, 2015). For example, regarding the production structure, some studies classified the prefabrication production structures as non-volumetric, volumetric, and modular building (Jaillon and Poon, 2009; Li et al., 2014). However, it is not always easy to identify clear boundaries between these production structures. A few studies have therefore been initiated to classify prefabrication production using accurate production taxonomy. For example, a hierarchical modular structure from high-level to low-level including units, modules, components, and materials is proposed by Bock and Linner (2015). In addition, although prefabrication and information technology are two separate concepts that are not dependent on each other, the integration of these two concepts is believed to have great benefits such as data consistency and better standards and interoperability (Li and Becerik-Gerber, 2011).

Lean Construction

Many uncertainties and constraints, such as overproduction, defective products, waiting time and moving from buffers to assembly, have been identified in the traditional PHP process, including manufacturing, logistics and site assembly (Senaratne and Ekanayake, 2011). Lean Construction for PHP refers to the utilization of lean production principles into the whole construction project delivery system to achieve lean manufacturing, lean supply chain and lean site assembly (Salem et al., 2006). It aims to improve construction processes with minimum constraints or waste and maximum value by meeting customer demands (Sacks and Goldin, 2007). To achieve the objective, the construction processes are categorized into two groups: conversion activities and flow activities (Mao and Zhang, 2008). While conversion activities add value to the material or information which are transformed into the final product, flow activities do not add any value. Instead, flow activities bring constraints and uncertainties such as inspection, moving and waiting (Wu, 2014). The Lean Construction tools, such as Just in time (JIT) and standardized work, are proven to be useful to eliminate flow activities and identify constraints or uncertainties that lead to abnormal situations (Yu et al., 2011). JIT refers to a production system where materials are utilized immediately when they are delivered to avoid overproduction (Wu and Low, 2011). JIT construction adopts a pull-driven method that aims to minimize the buffers and inventories (Wu and Low, 2010). Accordingly, the upstream outcomes should only be available when required by downstream activities (Sacks et al., 2010). Standardized work is executed through a work package that consists of work sequence, workforce requirements and clarified work scope for which a worker is responsible. For each task, a standardized worksheet provides step-by-step instructions to ensure workers follow the best practice. For each step, the work element sheet provides detailed specifications on safety and quality (Hassan and Kajiwara, 2013). Improving the efficiency of conversion activities, through the use of new information technologies to enhance the transparency, automation, and traceability of construction process is also critical to achieving Lean Construction (Senaratne and Ekanayake, 2011).

RFID-enabled BIM Platform (RBIMP)

Last Planner® System (LPS®) is a production management system that applies pull and look-ahead planning to remove constraints and make downstream activities ready (Ballard, 2000). Weekly work planning is adopted to reduce uncertainty and find relevant causes for variances. LPS also uses the percentage of the plan completed (PPC) to measure and monitor the process (Ballard, 2000; Kim et al., 2014). However, LPS is difficult to visualize the flow of work process (Sacks et al., 2009). Building Information Modelling (BIM) can be utilized to simulate and visualize the construction process with 3D geometric models and ample information to facilitate communication among stakeholders (Sacks et al., 2009). In addition, LPS is the weekly work planning that may lead to a long response time to address daily constraints. Sacks et al. (2010) developed the KanBIM concept which can manage day-to-day status feedback and support human decision making or negotiation among stakeholders. As PHP contains multiple phases from manufacturing, logistics to site assembly, the direct use of LPS and BIM in PHP has an apparent gap related to the interoperability and real-time traceability of information. Dave et al. (2016) therefore developed a communication framework by adopting IoT (Internet of Things) to strengthen the use of Lean Construction management and tracking technologies such as RFID and GPS, which are critical components of IoT, to track the status of workers, materials, and equipment in the whole process. A conventional RFID system contains an antenna, a transceiver (RFID reader) and a transponder (Radio Frequency tag). The antenna sets up an electromagnetic area where the tag detects the activation signal and responds by transmitting the stored data from its memory through radio frequency waves (Wang et al., 2016). RFID can be applied to monitor unit status during manufacturing and site assembly stages while GPS can be adopted to locate the units during logistics phase and calculate the remaining time to site. One RIFD-enabled BIM platform has been developed for PHP by researchers in Hong Kong (Zhong et al., 2015; Li et al., 2016b). The platform's architecture has three dimensions: infrastructure as a service (IaaS), platform as a service (PaaS) and software as a service (SaaS), which is shown in Figure 1. The IaaS level contains hardware and software layers. The hardware layer consists of the smart construction objects (SCOs) (Niu et al., 2015) and the RBIMP Gateway, while the software layer involves a Gateway Operating System (GOS) to manage the SCOs. SCOs with functional data and data collection devices are enabled by the RFID system and other innovative technologies. The GOS is developed to aggregate and pre-process the massive real-time data such as Industry Foundation Classes (IFC) data converted from BIM software (e.g. Revit), GPS data, RFID data (e.g. schedule, cost, production attributions) and point cloud data. In addition, the PaaS level is related to the data source management services (DSMS) which facilitate the heterogeneous information and application systems by applying XML-based BIM model and connecting the backend RFID system with BIM model. This enhances the initial BIM platform to a multi-dimensional one. The SaaS level consists of three management services (manufacturing, logistics, and on-site assembly) to enhance the information sharing and communication for stakeholders' decision-making at different stages.

Figure 1 The architecture of the RBIMP

Although the RBIMP is expected to lift productivity, after the implementation of RBIMP in the project "Tuen Mun Public Housing" of Hong Kong, the lack of training has been identified as the key factor to impede the adoption of RBIMP in the industry. Current teaching/training methods are also ineffective in disseminating the knowledge, which consequently hinders the best use of RBIMP (Zhong et al., 2017).

Simulation Game in Construction Management

Simulation game, as an experience-based learning approach, has increasingly gained popularity in the construction management field for school education and industrial training (González et al., 2015; Sacks et al., 2007; Wang et al., 2016). The core merit of a simulation game is that it integrates characteristics of simulation (about a real-life situation, event or activity) and games (players, rules, competition, co-operation) to transfer the knowledge of technologies and theories among practitioners and students (Rusca et al., 2012). Lego™ based simulation games have been commonly adopted in construction management which delineate the lean principles and information technologies. Sacks et al. (2007) developed an LEAPCON simulation game to investigate pull flow, reduced batch size and multi-skilling by comparing it with the traditional construction process. The results show that the lean technologies can significantly improve areas such as customized design, cash flow and waiting time. González et al. (2015) presented a simulation game LEBSCO as a learning tool to transfer the knowledge of lean production principles into construction. The simulation game is also helpful to improve the understanding of lean principles among students. A simulation game in LNG (Liquefied Natural Gas) industry was also used to evaluate a constraint management framework which involves lean principles and information technologies such as BIM, RFID, GPS and other sensing technologies (Wang et al., 2016). However, it should be noted that these games have some limitations: (1) The Lego™ materials utilized in previous studies are too simple to represent real-life situations, such as the process of PHP in this study; (2) The concepts and tools of Lean Construction principles and information technologies, particularly the advanced techniques and concepts behind the real PHP practices, were not sufficiently taught in previous games (González et al., 2015). (3) The integration of information technologies into the BIM platform has been discussed more as a conceptual framework in previous studies (Wang et al., 2016).

RBL-PHP Simulation

This simulation game uses two different approaches to teach PHP control and planning techniques. The first approach is based on the traditional learning method of computer-based multimedia presentation. The second approach adopts the RBL-PHP method.

Study Groups

The experimental group consists of one hundred and thirty-six participants, which are chosen from a group of postgraduate students and undergraduate students in the Department of Building and Real Estate at The Hong Kong Polytechnic University, Hong Kong, China. The participants are categorized into two experimental groups. One is computer-based presentation (CP) group, and the other is the RBL-PHP group. Each group consists of sixty-eight participants. The participants of RBL-PHP are divided into four workshops, and each workshop comprises seventeen participants (thirteen undergraduate students and four postgraduate students) whom all have a background in construction management. Particularly, ten of the sixteen postgraduate students have more than three years of working experience in the construction industry. Such arrangement can help collect significant comments, suggestions, and insights from the perspectives of both academic scholars and industry practitioners. The aim of the experiment is to investigate the RBL-PHP systematically before using it to teach students and train practitioners. Some adverse effects in the experiment, including Hawthorne effect (McCarney et al., 2007) and practice effect (Goldberg et al., 2010) have also been considered. The former illustrates the phenomena that individuals adjust or improve their behavior in response to their awareness of being observed, while the latter represents the phenomena that people adapt or improve an aspect of their behavior when they are tested more than once. To address these adverse effects, the participants' groups and roles are not informed before the setup, and they are not informed whether each group will adopt similar approaches or will have the same purpose.

RBL-PHP General Outline

RBL-PHP is a simulation game that intends to enhance the learning and understanding of RFID/BIM/Lean-enabled prefabrication housing production among students and practitioners. To achieve the aim, RBL-PHP integrates aspects of RFID-enabled BIM platform and Lean Construction principles. Through simulating a real world PHP environment by building Lego^{TM} houses, it educates and trains players about lean principles and information technologies in a fast paced and interactive way.

The simulation game consists of two rounds. The first round is related to the use of traditional planning and control (without RBL tools), and the second round is related to the implementation of RBL-based planning and control. These two rounds are then comparatively analyzed to demonstrate the benefits and differences of the RBL-based approach. The project goal of the each round is to construct four buildings with the shortest duration, the highest accuracy and the maximum percentage of plan complete (PPC). The general outline is shown in Figure 2. As can be seen in Figure 2, there are three phases simulated in this game, including (1) Manufacturing. Each building is assembled from five units, and each unit is composed of two modules, and each module consists of several components such as floor slab, façade, window, door, wall panel, tie beam, and staircase. Units refer to high-level building blocks which are completed with many three-dimensional building sections. Modules represent elements which are on a hierarchical level above components. Materials represent elements on a hierarchical level below components. The unit should be entirely assembled before it is delivered to the site; (2) Logistics. The major tasks of logistics company include receiving transportation order, establishing transportation schedule (e.g. select drivers and trucks) and controlling transportation process. The drivers should deliver the units in time and prevent the quality loss; (3) Site assembly. The building assembly takes place on the construction site, which consists of several activities including delivery check, site preparation, unit hoisting and unit installation. The owner should also conduct final check before project delivery. Each round runs for 45 minutes and each minute in the simulation game is considered as one month in real life. Upon completion of each round, the cost and time, and PPC are calculated.

Figure 2. The general outline of RBL-PHP

RBL-PHP has twelve specific roles that are determined based on real PHP projects. The specific role of each participant is listed in Table 1. This simulation game can be played with at least 12 people, but not exceeding 21. These numbers of players are decided by several rounds of testing. The minimum number of players is also determined by a number of rules, including 1) The critical roles should always be occupied by at least one player; 2) More players should be assigned to the roles that have higher workload (e.g., there are at least three players as manufacturing workers, who are responsible for component, module, and unit assembly); 3) Some player can have multiple roles (e.g. the project manager can be both the owner and timer of the project). The maximum number of players is established by considering the workload of each role, as well as the space constraints of the simulation game.

Table 1 Personnel Requirement in RBL-PHP

RBL-PHP Concepts

Many concepts behind the RFID-enabled BIM platform and Lean Construction principles are taught during both the simulation and the curriculum. The experiment highlights the primary aspects of BIM/RFID technologies and Lean Construction principles, keeping them uncomplicated and workable. These concepts are clarified by comparing the traditional CP method and the RBL-PHP method. The concepts to teach in the simulation are selected based on the architecture of RBIMP (see Figure 1). The key technical components of RBIMP should be taught, including BIM and smart construction object. In addition, the contributions of these technical components to information sharing and communication, real-time tracking and visualization should be provided. The Lean Construction principles which include the pull method, standardized work, work package and constraint analysis that can facilitate the use of RBIMP in PHP should also be explained to all participants. The concepts are interpreted and listed below:

- Prefabrication Housing Production (PHP): Components/ modules/ units are manufactured before they are delivered to construction sites for on-site installation. This concept may enable the participants to understand the conceptual difference between materials, components, modules, and units after introducing the lean principles. It should be noted that it is not allowed to release the workflow of PHP or any other standardized work steps in the traditional round to mitigate the practice effect.
- Constraint Management: It is a critical concept in the planning and control of PHP, which ensures that work plans assigned to construction practitioners are successfully (Blackmon et al., 2011). Constraints may include risks identified in the future such as incomplete drawings and specifications, shortage of workforce and materials, lack of temporary structures, limited work space, uncompleted preceding works, inclement weather, lack of work permits and safety issues, which can be divided into four types including technological, resource, spatial and information (Wang et al., 2016). The players may experience many constraints in the traditional round, and some constraints may be removed in the RBL-based round by using RBL-related technologies.
- Standardized Work: It is a fundamental tool in lean principles to creating a repeatable and predictable process. This simulation game adopts standardized work chart (SWC) and work element sheet (WES) to break down the working process to form three work packages, including manufacture work package (MWP), logistics work package (LWP) and assembly work package (AWP). These work packages can help the workers improve the quality and productivity in the RBL-based round of simulation.
- Just-in-Time (JIT): It is a concept in inventory management where prefabricated products are produced and transported to meet the site demand in the right time, at the right location and with the right amount. This concept can be implemented by adopting a pull system. In the traditional round, the manufacturing workers are pushed to produce regardless of the demand from the site. In the RBL-round, the construction site can order the exact units by using the RFID-enabled BIM platform.
- High transparency in information communication: This concept involves the use of BIM as a collaborative platform to visualize the overall construction process and enhance information sharing among the plant manager, logistics manager, site manager, project manager, and owner. The RFID-

enabled BIM platform is adopted in the RBL-round to enhance the transparency of information communication.

- Real-time traceability and check: This concept involves the use of tracking technologies (e.g. RFID and GPS) and sensing technologies (e.g. photogrammetry) to track the real-time status of prefabricated components, which can be employed for making managerial decisions, such as calculating the remaining time to site, assessing the quality of production and improving the lead time of responding to changes.
- Smart Construction Objects (SCOs): Developing SCOs is a necessary component of IoE (Internet of Everything) (Evans, 2012). PHP resources such as workers, materials, components, modules, units, equipment and tools can be smart by enhancing them with tracking, sensing, processing, storage, and communication capability so that SCOs have inbuilt autonomy and awareness.

RBL-PHP Simulation Process

In the traditional round of the game (See Figure 3), the owner places an order and delivers design drawings to the project manager. All design drawings in this game are represented by the pictures of units (see Figure 4). The project manager receives the order, checks the design drawings and coordinates collaboration between manufacturing, logistics and on-site assembly.

The plant manager discloses the design to manufacturing workers and plans the production process based on his individual perspective without considering the actual demand in the downstream process. Manufacturing workers are required to produce as many as possible in compliance with the design drawings. Final products will be inspected by the plant manager and delivered by a logistics company. The logistics manager allocates drivers to transport the products to the construction site. On-site assembly activities are push based (i.e. passive), and it is difficult to plan the schedule and resources.

Figure 3 Processes in the traditional round

Figure 4 Design Drawings of Four Buildings in Traditional Round of Game Playing

In the RBL-based round, the following modifications are made and highlighted in Figure 5, while other conditions remain the same as in the traditional round:

Figure 5 Processes in the RBL-PHP round

- Prefabrication Production Structure: The second round adopts a hierarchical modular structure from high-level to low-level including units, modules, components and materials (Bock & Linner, 2015). An example of the system is shown in Figure 6. This hierarchical modular structure can facilitate the object-oriented activities by the establishment of the standardized work in the manufacturing phase.

Figure 6 Prefabrication Production Structure

- Constraints Identification: Workshops are organized before the beginning of the second round to summarize the constraints occurred in the first round. In addition, a few pre-identified constraints (e.g. constructability) are also discussed. Team discussions are then organized to address these constraints using techniques such as the standardized work.
- Standardized Work: In the second round, the standardized work chart (SWC) associated with material/component/module/unit forms the work package to guide the workers. Take the wall assembly process in the manufacturing phase as an example (See Figure 7). There are eight steps in the wall assembly process. The work element sheet (WES) number is labeled with the each step to guide the process. Each work step is measured from five different aspects (Mariz et al., 2012) including design (the degree of conformity between completed production and BIM model), quality, waste, knack and rework. The schedule, cost, and percentage of plan complete (PPC) are also recorded in the SWC.

Figure 7 Standardized Work Chart

- RFID-enabled BIM Platform: In the second round, the RBIMP is utilized to eliminate stocks and buffers as much as possible. In addition, units are delivered from upstream to downstream workstations at the precise time and with accurate quantity. To achieve the above objectives, the units/trucks' traceability, information sharing, and communication are enhanced as smart construction objects in this platform.

For example, the detailed process of RBIMP is shown in Figure 8. The RBIMP adopts RFID technology to identify different objects in an entirely automated manner. RFID tags are embedded in the prefabricated units. The RBIMP gateway will be set up as a data collector in the manufacturing plant, logistics trucks, and construction site. All RFID events are captured and stored on the tracking servers in the RBIMP, which can be shared among all the participants. The units/modules are represented in various colors based on the phases in the BIM platform, which can be blue (manufacturing), green (delivery), yellow (arriving at the site) to the actual color (assembly). The units are checked and documented by photogrammetry technology (e.g. by using Autodesk 123D Catch Software to reconstruct the 3D model of the unit from the numerous photos) to compare the as-built model and as-designed model when leaving the plant and arriving at the site.The truck is identified and confirmed by using drivers' phone to scan the truck's NFC (Near Field Communication) tags.

Figure 8 RBIMP Workflow

It should be noted that RBL-PHP retains some main characteristics of LPS, such as the collaborative control and commitment-based planning. However, most planning functions in the RBL-PHP have been improved. The look-ahead planning with constraints analysis in the RBIMP adopts 4D and 5D simulation, which means that the workflow can be simulated exhaustively to identify the scenario with optimal time and cost performance. In addition, the pull planning method is enhanced by allowing the process to be traceable and visualized. This can help all participants make adjustments so as to meet the requirement of upstream and downstream activities. More importantly, the real-time planning method based on real-time tracking and positioning method accelerates the decision-making process among key stakeholders. PPC can also be visualized in the RBL-PHP to identify the reasons that lead to the variance of the workflow.

RBL-PHP Design and Evaluation

As discussed earlier, 68 participants are allocated to four workshops in RBL-PHP, and another 68 participants are taught through a computer-based presentation. Each workshop involves 17 participants for a two-round role-play game. The required duration of each workshop remains 140 minutes based on several rounds of trials. The game instructions are provided before each round, and the ethics forms are required to be filled in before the game. The design of the workshop is shown in Figure 9.

Figure 9 Workshop Process

The metrics related to the performance of the two rounds are measured, using:

1. PPC: PPC is applied to measure the actual completion at the end of each time interval. The time interval is fixed at 9 min in this study. The PPC for each completed activity is recorded in the SWC. From the project manager's point of view, the number of assembled units on-site is used to calculate PPC. In this study, there are four buildings to construct, and each building is assembled from five units, indicating a total number of 20 units. The formula to calculate PPC is:

$$PPC = Q_a/Q_t.$$

   Where Q_a refers to the number of assembled units and Q_t refers to the total number of units (20).

2. Extra Cost: The extra cost can be caused by the overly produced units that are transported to the construction site, the defective units that need rework, and the manufactured-in-process (MIP) units which cause delay. The cost of each unit is listed in Figure.10. The cost of the each component includes the cost of material, labor, equipment, and transportation. Extra cost is calculated to measure the economic performance of RBL-PHP.

Figure 10 Cost Data of Units

3. Productivity Index: The productivity index is a measurement of the ability to manufacture, transport and assemble. Three separate indices are used (Sacks et al., 2007), including:

   (1) Productivity Index of manufacturing (P_m). The formula used to calculate P_m is:

$$P_m = (Q_p - Q_{d1})/(T_{f1} - T_{s1})$$

   Where: P_m refers to the Productivity Index of manufacturing; Q_p refers to the number of produced units in the plant; Q_{d1} refers to the number of defective units in the plant; T_{s1} refers to the start time of production of the first unit; and T_{f1} refers to the finish time of the production of the last unit; D_1 refers to the duration from T_{s1} to T_{f1} and $D_1 = T_{f1} - T_{s1}$.

(2) Similarly, the Productivity Index of logistics (P_l) is calculated by:

$$P_l = (Q_t - Q_{d2})/(T_{f2} - T_{s2})$$

Where: P_l refers to the Productivity Index of logistics; Q_t refers to the number of transported units; Q_{d2} refers to the number of defective units in the logistics stage; T_{s2} refers to the start time of transportation of the first unit; and T_{f1} refers to the finish time of the transportation of the last unit; D_2 refers to the duration from T_{s2} to T_{f2} and $D_2 = T_{f2} - T_{s2}$.

(3) The Productivity Index of on-site assembly is calculated by:

$$P_a = (Q_a - Q_{d3})/(T_{f3} - T_{s3})$$

Where: P_a refers to the Productivity Index of on-site assembly; Q_{d3} refers to the number of defective units in the on-site assembly stage; T_{s3} refers to the start time of assembly of the first unit; T_{f3} refers to the finish time of the assembly of the last unit; D_3 refers to the duration from T_{s3} to T_{f3} and $D_3 = T_{f3} - T_{s3}$.

In addition, to evaluate the participants' confidence in understanding RBL-related knowledge, a two-step evaluation process is adopted. Separate questionnaire surveys are conducted at the beginning and the end of the simulation game and the computer-based presentation. The questionnaire contains ten questions to assess the confidence in understanding ten concepts, including prefabrication production structure, constraint management, standardized work, work package, JIT, pull/push, BIM, smart construction objects, information sharing and communication, real-time tracking and visualization. Participates are required to provide a rating about each question from 0 (not confident) to 10 (greatly confident). In order to validate whether there is a significant improvement between ex-ante and ex-post survey in the proposed RBL-PHP approach, meanwhile to verify whether the RBL-PHP approach has higher improvement than the traditional CP teaching method, the differences in responses between the two surveys in RBL-PHP and the differences in responses between two approaches (The data set of each approach is the differences in responses between two surveys) could be analyzed by a paired samples t-test and an independent samples t-test, respectively, if the data is normally distributed. The paired samples t-test is adopted to compare the means of ex-ante and ex-post survey on the same group of participants (RBL-PHP group), and the independent samples t-test is used to compare the means of two independent groups (RBL-PHP and CP group). The non-parametric test will be adopted if the data is not normally distributed. The normality is checked by Shapiro-Wilk test at a 0.05 significance level. Additionally, the radar chart is adopted to evaluate the variations of each question.

Results and Discussions

Performance of RBL-PHP

The results are shown in Tables 2, 3 and 4 respectively. Table 2 illustrates the actual duration and the PPC values of the two rounds in each workshop. In the first round, an average duration of 45 mins is recorded. In addition, an average of 43.5 mins is recorded in the second round, which suggests that only 3.33% reduction in project duration if achieved through RBL-PHP. It is observed that although the Lean Construction principles such as standardized work, work package and pull method can help reduce the duration significantly, information technologies, including BIM/RFID, increase the difficulty in playing the game. A close examination of the duration suggests that the differences between the two rounds are significant at the end of the first 9 minutes and the last 9 minutes. At the end of the first 9 minutes, the average PPC of the RBL-based round is 10%, compared to an average of 6.25% in the first round. This demonstrates the effectiveness of lean principles in a manufacturing environment as the main activities in the first 9 mins happen in the manufacturing plant. The difference at the end of the last 9 minutes is attributed to the delay in manufacturing in the first round of workshop A and C. The average PPC is increased by 8.11% in the RBL-based round in the last 9 mins.

Table 2 The Percentage of Plan Complete in the Simulation Game

Table 3 shows the results of the simulation game on extra cost. As can be seen from Table 3, the extra cost of the traditional round is significantly higher than the RBL-based round. An average extra cost of $7747.5 is recorded in the traditional round when a much lower value of $1540 is recorded in the RBL-based round. An 80.12% reduction in the extra cost has been achieved, mainly due to the removal of constraints in the RBL-based round. In the traditional round, as the push system is adopted, three units are overproduced in the four workshops. By integrating the pull method and JIT into the RBL-based round, overproduction has been eliminated effectively. The defective units are measured by a comparison between as-designed and as-built units. If there is a difference, the extra cost will occur. The defective units inspected in the plant will lead to rework immediately without generating extra cost, while the defective units identified after the logistics will lead to extra cost. In the RBL-based round, visual and intuitional as-designed BIM models, and photogrammetry technologies help the project team identify defective units and reduce the number of defective units from twelve to four in total. The other source of extra cost is the manufacturing-in-progress (MIP) (similar to the work-in-progress concept) units which are caused by the constraints in the manufacturing phase. The standardized work, work package, and the hierarchical modular structure simplify the manufacturing workflow and smooth the manufacturing tasks or activities. In the RBL-based round, the manufacturing progress is improved, and the extra cost of MIP is removed.

Table 4 presents the productivity index of the two rounds. The average values of the productivity index in the traditional round are lower than those in the RBL-based round. The productivity is greatly improved in all the three phases, including manufacturing (P_m; 0.34-0.51; 50.0% increase), logistics (P_l; 0.53-0.65; 22.6% increase) and on-site assembly ($P_{a;}$ 0.39-0.51; 30.8% increase). It appears that a significant increase in productivity can be obtained by applying the RBL-PHP platform in the manufacturing stage. This is achieved by effectively reducing the number of defective units (Q_{d1}; 4.5-0.5) and the production time (D_1; 43.75-30.75). Efficient information sharing and communication in the RBL-based round may have contributed to the increase in productivity.

The results may be affected by a few errors and bias. For example, the defective units should be repaired or reworked by manufacturing workers in the manufacturing plant. However, in the trial rounds, some site workers are found to repair the units unintentionally in the simulation game. This can be partially due to the human nature (e.g. attitudes or motivations) in a competition or a game. As such, all participants are informed about the procedure of the game at the beginning of the game and the procedure must be strictly followed. In addition, participants with prior knowledge of RFID/BIM/Lean Construction may find the RBL-based round easier to operate. To mitigate such effect, sufficient instructions are given to all participants before each round

Table 3 The Extra Cost in the Simulation Game

Table 4 The Productivity Index in the Simulation Game

Participants' learning effects

The ten questions are grouped into three aspects, including the concept of prefabrication (prefabrication production structure), Lean Construction (constraint management, standardized work, work package, JIT, pull/push), and information technologies (BIM, smart construction objects, information sharing and communication, real-time tracking and visualization). The radar chart (Figure 11) illustrates the average values of confidence in understanding the ten concepts in a scale from 0 (not confident) to 10 (greatly confident). The radar chart is widely adopted to monitor the improvement of multivariate data in practice (Salem et al., 2006) and education (González et al., 2015). The results indicate that all the participants in both RBL-PHP group and CP group have insufficient knowledge of RBL-related concepts before the game and the presentation, and the average values of 3.65 and 3.59 are recorded respectively. The post-game survey indicates an average value of 6.22, an increase of 70.41% on the confidence in understanding RBL-related knowledge. While the post-presentation survey indicates an average value of 5.45, an increase of 51.81% on confidence in understanding RBL-related knowledge. The mean value of confidence in understanding each concept has significantly increased can also prove that there is no compelling negative effect on learning when multiple concepts are involved, and the underlying reason can be that these concepts are all well connected with each other and there is underlying synergy when teaching them together. In the RBL-PHP group, significant improvements are identified in prefabrication production structure (from 3.68 to 7.01), standardized work (from 3.66 to 7.19), smart construction objects (from 3.54 to 6.82), information sharing and communication (from 3.72 to 6.97), real-time tracking and visualization (from 3.51 to 6.81). On the other hand, the constraint management concept is only discussed and taught in the instruction stage of the RBL-based round, without adopting any tools or methods to enhance the user experience in constraint identification, monitoring, and removal. This may lead to a minor improvement in this concept (from 2.25 to 4.00). However, there is a significant improvement in constraints management (from 2.62 to 5.66) in CP group, which indicates that the curriculum is more helpful on teaching the theoretical concepts. The BIM technology has been widely discussed in the industry, leading to a marginal improvement in understanding the concept after the presentation (from 4.84 to 5.97) and the simulation game (from 5.51 to 6.91).

Figure 11(a) Average values of confidence in understanding the concepts in the RBL-PHP group

Figure 11(b) Average values of confidence in understanding the concepts in the CP Group

To explore the statistical significance of the above findings, the normality of results is tested by Shapiro-Wilk test, which is shown in Figure 12 (a) (b) (c) (d) and Table 5. The null hypothesis is that the result is normally distributed. The *p*-values (0.076, 0.172, 0.919 and 0.162) in Table 5 are higher than the chosen significance level 0.05, indicating that null hypothesis cannot be rejected. Meanwhile, the Q–Q plots and histograms (see Fig.12) also verify the above conclusion.

Figure 12 (a) Histogram and Q-Q plot of ex-ante survey in the RBL-PHP group

Figure 12 (b) Histogram and Q-Q Plot of ex-post survey in the RBL-PHP group

Figure 12 (c) Histogram and Q-Q plot of differences between ex-ante and ex-post survey in the CP group

Figure 12 (d) Histogram and Q-Q plot of differences between ex-ante and ex-post survey in RBL-PHP Group

Table 5 Shapiro-Wilk Test of Normality

The paired samples t-test is then applied on a sample of 68 participants to determine whether there is a statistically significant mean difference between the value of confidence in understanding when participants conduct the simulation game in RBL-based round compared to a traditional round . The null hypothesis is that the true mean of the value of confidence in understanding of post-ante survey is significantly greater than the ex-ante survey. Table 6 shows the test results at a confidence interval of 90% and a 0.05 level of significance. The one-tailed *p*-value (0.000) is much lower than the chosen significance level 0.05. This implies that the confidence in understanding RBL-related knowledge after the simulation game is significantly improved. An independent samples t-test is run on a sample of 136 participants to determine if there are differences in the differences of confidence in understanding between two surveys based on two teaching approach (RBL-PHP group and CP group). Both groups consisted of 68 randomly assigned participants. The null hypothesis is that the true mean of differences RBL-PHP is significantly greater than the mean of differences in CP. Table 7 shows the test results at a confidence interval of 90% and a 0.05 level of significance. The one-tailed *p*-value (0.000) is much lower than 0.05. This implies that the improvement of confidence in understanding RBL-related knowledge via the simulation game is significantly higher than the traditional computer-based multimedia presentation.

Table 6 Paired Samples T Test

Table 7 Independent Samples T Test

Aside from the above statistical analysis, qualitative observations are also conducted, based on which some implications can be identified. This game can bring psychological impact on the real PHP process. The participants have hands-on experience on how information flow is smoothed by information technologies and how value can be added by the Lean Construction principles, as stated by one participant: "*The game* *reduces the psychological distance of PHP with Lean Construction principles and information technologies, and it makes the ten concepts more tangible*." (Manufacturing worker, Workshop B). In addition, the game stimulates the participants to embrace the knowledge of Lean Construction and information technologies. One participant noted, "*I kept a high attention level during the game. After the second round introduction, I tried to recall the constraints in the first round and developed a strategy to make the pull methods work more smoothly with the RFID-enabled BIM platform.*" (Site Manager, Workshop A). More importantly, the game gives the participants comparative experiences and inform them what may happen when Lean Construction principles and information technologies are not adopted, as noted by one participant:"*The second round facilitates sharing information among different stakeholders. It helps get novices to the same knowledge level. The visualization is really important, and you can learn how to make decisions in the second round.*" (Plant Manager, Workshop C). The game also provides a collaborative platform for the team to share information and knowledge. As stated by one project manager:"*In the traditional round, the information was communicated and delivered from top to bottom in the team. Namely, project manager disclosed the project and design intentions to plant/logistics/site managers, and then plant/logistics/site managers broke down responsibilities and assigned tasks to front-line workers. It increased the communication cost to allow managers and front-line workers to discuss potential improvements together in this kind of liner organization. In the RBL-based round, RBIMP helped represent and visualize the geometric and functional information to provide both decision-making supports for managers and specific workflow for front-line workers.*" (Project Manager, Workshop D). It seems that the RBL-PHP is useful to improve the learning experience on RBL-related concepts. However, the detailed improvements including the impact individual behaviors on the usefulness of the platform and the degree of improvements require more in-depth research.

Conclusions and future work

The primary contributions of the proposed RBL-PHP simulation game to the body of knowledge are twofold. It enriches the learning tools of construction management, particularly the PHP field, by integrating Lean Construction principles into RBIMP to simulate the process of PHP and adopting the Lego^{TM} materials as the prefabricated components. Traditionally, students or practitioners learn the knowledge through a series of curricula or workshops by using chalkboards, handouts, and computer presentations, which often leads to negative feedback in learning effectiveness, especially when complex concepts are involved. In this study, the hands-on experience in a role-play simulation game can effectively and successfully transfer the knowledge to the students and practitioners in a vivid and thought-provoking environment. In addition, this study expands the core concepts of PHP to include hierarchical production structure, Lean Construction principles (e.g. standardized work, JIT, and the pull system) and information technologies (e.g. BIM, RFID, GPS, and photogrammetry). The pedagogical approach to disseminating the core concepts of modern PHP can reduce uncertainties, remove constraints, enhance information sharing and communication, and realize real-time tracking in the process of manufacturing, logistics, and on-site assembly.

The most significant finding of this study is that RBL-PHP can help train and teach the participants about RBL-related knowledge in a meaningful and effective learning process when compared with the traditional learning method, which is related to a computer-based multimedia presentation. Participants (with and without industry experience) provide very positive feedback in applying the RBL-PHP as a robust and efficient learning tool to integrate the information technologies and Lean Construction principles into PHP. An average increase of 70.41% in understanding RBL-related knowledge after playing RBL-PHP is reported. Significant improvements are identified in understanding prefabrication production structure, standardized work, smart construction objects, information sharing and communication, real-time tracking and visualization. The study also finds that RBL-PHP can increase PPC by 8.11%, reduce extra cost by 80.12%, and significantly improve productivity, especially in the manufacturing stage which records a productivity improvement of 50%. One interesting finding is that there are strong connections between the concepts of BIM, Lean Construction and prefabrication because teaching multiple concepts in the simulation does not have a negative effect on learning. A future study on investigating the theoretical and conceptual connections among these concepts is recommended.

There are several limitations of the current study. The level of modularization in real PHP projects is not as high as in the simulation game. Only the façade, staircase, ground floor water tank, panel wall, slab, and volumetric bathroom are prefabricated in real PHP projects in Hong Kong. In order to reduce the difficulties in tracking a large number of components in the RBIMP, the well-assembled unit is considered as one piece to transport to the construction site. Secondly, the logistics process is simplified in the simulation game due to its spatial constraints. Thirdly, the optimization approaches of resources management regarding people, materials, and equipment are not utilized in this simulation game. In addition, this study does not evaluate the performance of each RBL-PHP component. A comparative study between the LPS and RBL-PHP may be useful to identify the contribution of each RBL-PHP component to the productivity improvement.

Acknowledgement

This research was undertaken with the benefit of a grant from Ministry of Science and Technology of the People's Republic of China, The Thirteenth Five-Year National Key Research Projects (Project No. 2016YFC0702005-04).

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