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Investigating supply chain management for prefabricated building projects in Hong Kong

Abstract

Prefabricated building projects (PBPs) have gained worldwide popularity over the past few decades due to their various benefits. Supply chain management (SCM) is critical to the successful delivery of PBPs because the supply chains are complex with multiple processes and stakeholders involved. Poor SCM for PBPs causes cost overruns and schedule delays. This study investigates the production, transportation, and assembly processes of a PBP in Hong Kong to quantitatively analyze and critique its SCM. Automated data collection technologies were adopted to obtain real-time information of precast components throughout the supply chain. Findings from the study show that limited considerations of resource planning, significant assembly delay, overproduction, excessive inventory, and long lead time are severe problems within the supply chain. The root causes of these problems include poor supply chain planning, poor communication between stakeholders, and poor control of working flows. This is the first study to reveal the actual situation of SCM for PBPs using empirical data from an entire supply chain. The results provide an in-depth understanding of the root causes of the problems associated with SCM for PBPs, which will be of great value in assisting stakeholders to accurately and effectively deal with them.

Keywords: prefabricated building projects; supply chain management; empirical analysis;

real-time information; precast components

Introduction

As an alternative to traditional construction, prefabrication is a popular construction method worldwide because of the various benefits it offers, such as enhanced quality performance (Tam et al. 2014), reduced cost and time (Jeong et al. 2017), and better environmental responsibility (Hong et al. 2016). These advantages have inspired the widespread development of PBPs. For example, the Hong Kong Housing Authority plan to produce up to 93,400 prefabricated public housing units by the 2019/20 financial year (HKHA 2016). Some developed countries, such as China (MOHURD 2016) and Malaysia (CIDB 2015) have issued various incentives and policies to enhance the development of PBPs.

According to Gann (1996) and Said (2015), SCM plays an important role in achieving the successful delivery of PBPs. Supply chain configuration determines the structure of a supply chain, which is an important step to achieve desired performance (Huang et al. 2005). Different industries have their own preferable supply chain configurations which have considerable impacts on the outcomes of economic, social and environment aspects (Khajavi et al. 2014; Varsei and Polyakovskiy 2017). Arashpour et al. (2017) propose an optimization model to enhance multi-supplier configurations with lower investment, contributing to optimal decision-making in advanced manufacturing of prefabricated building products. Process innovation capacities are positively correlated with supply chain configuration

(Adebanjo et al. 2018) and dynamics exist between them to influence managers' decision-making to improve the economic performance of projects (Sabri et al. 2018). On the other hand, supply chain configuration is associated with performance trade-offs. According to Brandenburg (2015), the trade-offs between ecologic factor, financial value creation and customer service level could be assessed to achieve low carbon supply chain configuration.

A supply chain can be seen as "the processes from the initial raw materials to the ultimate consumption of the finished product linking across supplier-user companies" together with "the functions within and outside a company that enable the value chain to make products and provide services to the customer" (Cox et al. 1995). SCM is the integration of business processes from end user through original suppliers that provide products, services and information that add value for customers (Cooper et al. 1997). The supply chain of a PBP involves the production, transportation and assembly processes that are linked by a client, a manufacturer, a transporter, a main-contractor, and several service/product suppliers, which create value by transforming various materials, products and components into the PBP. SCM for PBPs depends on the coordination and the relationships built among organizations involved (vertical relations), which could generate competitive advantages through lowering costs or adding value for customers (Lambert et al. 1998; Vallet-Bellmunt et al. 2011). Also, vertical integration provides the principal organization with control over strategically sensitive technology and/or capabilities whilst facilitating the achievement of efficiencies (Beach et al. 2005). However, coordinating the information, material/service/product, and capital flows in the supply chain is a complex task due to the multiple processes and stakeholders involved. Poor SCM for PBPs is usually due to deficient coordination before and during construction, inadequate project planning and design (Hwang et al. 2018), and poor concurrence of process and information (Niu et al. 2017). This results in many problems that add no value to the supply chain, including overproduction (Forsman et al. 2012), large inventory (Wu and Low 2014), and long lead time (Zhai et al. 2016).

The abovementioned drawbacks have motivated researchers to explore measures to improve SCM for PBPs. For example, various platforms have been developed to achieve real-time visibility and traceability of major supply chain processes using information technologies, such as Internet of Things (Li et al. 2016a, 2018b; Zhong et al. 2017), and radio frequency identification (RFID) technology (Altaf et al. 2018). Inventory control systems for materials have also gained wide attention as a way of reducing associated costs (Wang et al. 2018), while long lead time is mitigated by designing coordination mechanisms (Zhai et al. 2016).

However, research into SCM for PBPs has achieved only limited breakthroughs due to the following limitations: (1) only single process (e.g. production, logistics) has been investigated and analyzed rather than an entire supply chain, and (2) real supply chain data has rarely been collected for analysis due to limited accessibility to data. These restrictions have prevented studies from revealing the true picture of SCM for PBPs for the following reasons. First, the upstream and the downstream processes do not exist independently but frequently interact with each other to influence the supply chain performance (Luo et al. 2019). Therefore, the supply chain should be inspected and managed as a whole to see its actual operation through the dynamic interactions of different processes. Second, data collection and sharing are often found to be inaccurate, incomplete, and insufficient (Zhong et al. 2017) due to the inadequate use of information technologies in PBPs (Xu et al. 2018). However, valid and accurate data is a critically important element in SCM for PBPs because of its significant role in supporting stakeholders' decision-making and process improvement (Lewis and Cooke 2013). Thus, improving the quality of data is an important first step toward exploring the actual situation of SCM for PBPs.

Tackling the aforementioned limitations will contribute significantly to a fuller understanding of SCM for PBPs. This study therefore aims to investigate the real-time status of SCM for PBPs in Hong Kong, identify the problems embedded in SCM, and analyze the root causes of the problems. By doing this, this study provides valuable implications about the true picture of SCM for PBPs and is of value in assisting the stakeholders involved to understand the problems and their root causes at different stages of the supply chain, thereby allowing those problems to be tackled more efficiently and effectively. By referring to this study, future research could investigate the real-time status of SCM in the domain of management in engineering and explore the root causes of the problems embedded to improve the supply chain performance of other engineering projects.

Research background

The construction industry is a typical project-oriented industry with substantial complexities and uncertainties (Kerzner 2017). Project management is the application of knowledge, skills, tools, and techniques necessary to meet the project requirements, which is accomplished through five groups of processes, including initiating, planning, executing, monitoring and controlling, and closing (Project Management Institute 2012). The uniqueness of projects and the separated processes implemented by different stakeholders with various specialties (Eriksson 2015) make project management a difficult task. Conventional project management has been criticized to place great emphasis on the satisfaction of time, budget and scope constraints, while continuous improvement, customer-centric thinking, and reflective learning are rarely considered (Böhle et al. 2016). Also, the traditional ways of management and tools (e.g. critical path method) are insufficient in dealing with the unique challenges in projects, resulting in considerable wastes, such as overproduction, lead time, transportation, inappropriate processing, and inventories (Ansah et al. 2016). Under this circumstance, the construction industry considerably lags behind other sectors in terms of efficiency and performance.

Originating from the manufacturing industry, the concept of SCM was applied in the construction industry as a strategy to increase the internal efficiency of organizations, reduce wastes, and add value for projects (Ansah et al. 2016; Meng 2019; Saad et al. 2002). In project management literature, SCM applies to temporary multi-organizations to enhance their collaboration in large, complex, and multi-faceted projects (Thomé et al. 2016). According to Hatmoko and Scott (2010), problems in SCM may create high disruption to construction projects with the largest impact being from delays in material flow. To streamline the complex flows, a temporary construciton supply chain significantly relies on real-time information sharing and communication between stakeholders to enhance the integration of the upstream and the downstream (Isatto et al. 2015; Shi et al. 2016). Supply chain integration is highly associated with the establishment of close and long-term relationships between stakeholders (Costa et al. 2019; Meng et al. 2011). Effective SCM contributes significantly to achieving improved performance of projects (Koolwijk et al. 2018; Xue et al. 2010), such as reduced lead time, shortened project durations, increased operational efficiency (Min and Bjornsson 2008), and improved labor performance (Moon et al. 2015).

This study focuses on investigating the production, transportation and assembly processes and their dynamic interactions in a PBP instead of exploring how to satisfy the project objective within the restricted resources. Therefore, this is a study associated with SCM for a PBP rather than a project management research.

Construction SCM

Increasing number of studies have explored to apply SCM theory in construction projects in recent years (Badi and Murtagh 2019; Balasubramanian and Shukla 2018; Li et al. 2019; Wang et al. 2017). However, significant obstacles exist and impede the implementation of SCM, which are mainly due to the attributes of construction projects, including limited integration between different disciplines (London and Pablo 2017), adversarial supply chain relationships (Kim and Nguyen 2018a), complex interface conflicts (Ju et al. 2017), and various uncertainties and constraints in the fragmented processes (Li et al. 2018c).

Improving collaboration and integration in construction projects has been considered to be important in dealing the insufficient communication among the interrelated agents and enhancing supply chain performance (Koolwijk et al. 2018). Higher supply chain integration is likely to increase the adoption of systemic innovation within the collaborative project delivery of complex projects (Hall et al. 2018). Supply chain partnering is found to be highly interdependent with information technologies (Papadonikolaki et al. 2016). Xu et al. (2018) therefore integrated a variety of technologies, such as building information modeling (BIM), RFID and Internet of Things to create a seamless cooperation environment for stakeholders to achieve lean prefabrication. Similarly, Li et al. (2018b) designed an Internet of Things-enabled BIM platform to enhance the effectiveness of collaboration in PBPs of Hong Kong. To enhance supply chain performance, Zekavat et al. (2015) adopted information and communication technology in holonic construction management to identify the most important problem areas to support the process control, while Moon et al. (2017) developed a process-centric dynamic quality control model based on RFID to pursue continuous improvement in concrete SCM.

The relationships between stakeholders have an important influence on collaboration, therefore evaluating and promoting the relationships have attracted wide attention in the SCM area. For example, Kim and Nguyen (2018a) developed a framework to reveal the situation of stakeholder relationships and identify areas for improvement, while Kim and Nguyen (2018b) provided a model to assess the positive impact of supply chain relationship on the performance of construction projects. Stamatiou et al. (2018) developed a process-based model to improve claims management which is found to have an adverse impact on stakeholder relationships and thereby affect the whole supply chain processes. Liu et al. (2018), on the other hand, proposed a criteria system to assess the maturity level of supplier management and designed a maturity grid to pursue continuous improvement of supplier relationships.

Increasing interest in supply chain optimization is also observed in recent research. This is because optimizing material management could improve the productivity of construction supply chains (Moon et al. 2018). Liu and Lu (2018) therefore proposed a resource-constrained scheduling optimization model to mitigate the complexity of material SCM in the construction industry. Jaśkowski et al. (2018) put forward a decision model to facilitate the planning of resource scheduling for the purpose of minimizing the total inventory management expense of the irregularly consumed materials or components. On the other hand, van den Berg et al. (2017) designed a board game for students to experience supply chain optimization, which could promote the understanding of construction SCM knowledge.

SCM for PBPs

Prefabrication is a manufacturing process, generally conducted at a specialized facility, in which various materials are joined to form a component part of the final installation (Tatum et al. 1987). According to Koskela (2003), SCM for PBPs is more difficult than that of conventional construction due to its dual production environments (factory and site), more design work and prefabrication lead time, a longer error correction cycle, and stricter requirements for dimensional accuracy. Also, the multi-disciplinary stakeholders from different firms usually consider their own goals and values individually with little concern for supply chain performance (Ju et al. 2017). This is particularly true if a company works by projects and the fragmentation is likely to induce a series of problems in the production, logistics, and assembly processes.

Production planning is an important managerial activity for component manufacturing considering its significant impacts on the delivery task, lead time competitiveness, and the effective use of molds and machines (Benjaoran and Dawood 2006). Precast production usually uses the make-to-order way in which components are manufactured based on the assembly progress. Therefore, delivering the precast components as required by the assembly schedule has high priority in production planning. Effective planning plays an important role in balancing the production line and enhancing the productivity for benefit maximization (Altaf et al. 2018). However, precast production has difficulties both inside and outside the factories. Specifically, over-early or over-late manufacturing is likely to cause storage problems, late delivery, and time-consuming component location inside the factory via the traditional way. Immediately finding the right component for the right floor and right part of the construction is therefore quite hard outside the factory (Yin et al. 2009). These problems have motivated extensive discussions about production planning optimization (Liu and Lu 2018).

Inventory management is critically important in guaranteeing the smoothness of the construction processes (Lu et al. 2011). Excessive inventory is the most serious non-value-adding activity that may interrupt production activities and generate great wastes of energy and raw materials (Wu et al. 2014). According to Tserng et al. (2006), excessive inventory could be mitigated by improving information communication between stakeholders to reduce demand uncertainty or conducting effective production planning to reduce the gap between supply and demand.

Although the logistics of component delivery have a considerable impact on project cost, time and construction progress (Chiang et al. 2006), it seems to garner only limited consideration when it comes to how it affects the performance of PBPs (Hwang et al. 2018; Sahin et al. 2018). Since transporting large volumes of engineered materials requires close communication between practitioners (Gosling et al. 2016), Niu et al. (2017) proposed a smart construction objects-enabled system to assist decision-making by improving the concurrence of process and information at the logistics stage.

The assembly process is in the downstream of the supply chain that determines the demand for precast components. Numerous schedule risks with mutual interactions exist in the assembly process (Li et al. 2018a). Therefore, the contractor should closely and openly interact with the client to diminish variations at the assembly stage (Doran and Giannakis 2011). Integrated use of information technologies, such as RFID and BIM, could effectively mitigate risks and enhance the schedule performance of PBPs (Li et al. 2017c).

PBPs in Hong Kong

PBPs have been implemented in Hong Kong for decades in order to mitigate the serious housing shortage. Since the mid-1980s, the Housing Authority has mandatorily utilized precast units in all public housing projects. A dimensional coordination and standardization approach with large-panel steel formwork and various precast elements have been utilized in PBPs (Tam et al. 2014). The most commonly used precast components include precast façade (51%), precast staircase (22%), semi-precast slab (9%), and semi-precast balcony (7%) (Jaillon and Poon 2009). This study traced precast façades to investigate the status of the supply chain of a PBP; precast façade is a term specifically referring to a type of precast components forming the external walls of PBPs, which has been widely used by the Housing Authority (HKHA 2016) and in related studies in Hong Kong (Hong et al. 2016; Tam et al. 2014).

The Housing Authority has become the largest PBP client in Hong Kong and has adopted the design-bid-build contract mode, in which the client employs a designer and a main contractor for design work and supply chain coordination respectively. The main contractor recruits the manufacturer, transporter, and assembly sub-contractor directly and therefore plays an important role in connecting the upstream production, logistics, and the downstream demand. All these stakeholders will report project progress to the Housing Authority once a week.

The supply chains of PBPs are complex and have encountered various problems. Due to the high labor cost and compact area in Hong Kong, most precast factories are in Guangdong Province in Mainland China, generating a cross-border supply chain that may have multiple variations. The low adoption of information technologies (Xu et al. 2018) impede real-time data sharing across complex supply chains (Zhong et al. 2017), which considerably affect stakeholders' decision-making (Niu et al. 2017). Significant hindrances also negatively influence the implementation of PBPs in Hong Kong, such as lack of storage space on site and long lead time (Zhang et al. 2018), resulting in considerable schedule delay of projects (Li et al. 2016b, 2017a; b). The mitigation of these problems depends on better stakeholder coordination.

Research methodology

To address the research questions, a combination of case study, document analysis, and interviews were adopted. Advanced information technologies were used to collect a vast amount of empirical data within the supply chain of a real-life project. This was followed by document analysis that was intended to substitute for the data not collected by the information technologies due to technical problems. In doing so, a complete dataset of the project was developed to show the real-time status of the supply chain. Statistical analysis of the dataset was conducted to reveal the actual situation of the SCM for the project and identify the embedded problems. Experienced stakeholders of the case project were then interviewed to analyze the root causes of the problems. **Fig. 1** shows the research design of the paper.

<Insert Fig. 1 here>

Case study

Case study is a necessary and sufficient method to address certain important research questions in social sciences, which holds up well in comparison with other research methodologies in this area (Flyvbjerg 2006). This method has been widely adopted in research on PBPs, such as Gibb's (2001) investigation of the application of standardization and preassembly. Case studies are often used to present general principles and hard empirical data supplemented with a case study is valuable for showing concrete examples of abstract concepts and processes (Fellows and Liu 2015). The generalizability of case studies could be improved by the selection strategies of illustrative cases, which are usually required to be representative of general conditions (Flyvbjerg 2006). According to Fellows and Liu (2015), the purpose of case study is to secure theoretical generalization rather than statistical generalization, therefore, only a small number of cases are usually recruited for an in-depth analysis.

In order to guarantee theoretical generalization of the case study, a public housing project was selected, which is considered to be representative of PBPs in Hong Kong for the following reasons. First, the project was developed by the Housing Authority, which is the largest PBP client in Hong Kong providing public housing for over 50% of its residents and having project teams with similar management skills as other PBPs. Second, all the public housing projects utilize a modular design and have similar height, floor plan, structure type, assembly cycle, and volume and types of precast components, indicating the generalization of the case study project.

The case study was conducted across the project implementation time to provide an in-depth analysis of the SCM. This was done by continuously collecting real-time data of precast components from the initial production stage to the final assembly phase using effective information technologies. Millions of data entries or points were finally collected to form a dataset of the project, which illustrates the SCM principles within the case study project.

The case study project recruited for this study provides valuable insights regarding the actual situation of SCM for PBPs. The case study project ran from June 2015 to September 2017, with the aim of constructing five buildings of 34-38 stories to accommodate 14,000 people. **Fig. 2** illustrates relevant photos of the project.

<Insert Fig. 2 here>

Data collection

Automated data collection technologies were adopted to trace the status of the supply chain. An integrated system combining RFID, global positioning system (GPS) and BIM technologies, as the means of an experiment to test the performance of such systems for future possible large-scale adoption, was provided by the client to collect real-time data of precast components across the supply chain. RFID is composed of a reader and a tag and uses radio waves of various frequencies to identify objects. A tag stores information within a microchip buried inside the object and transmits the signal via an antenna. Passive RFID relies on a nearby reader to provide energy for data extraction, while active RFID has a power source inside to support wireless communication. RFID has been extensively used for SCM in various industries, such as retailing, food and restaurant, health care and logistics (Zhu et al. 2012). The construction industry also utilizes RFID to track and locate materials and components (Ergen et al. 2007) to obtain real-time information of supply chains (Li et al. 2018b; Zhong et al. 2013), which is useful for quality, inventory, and transportation management (Yin et al. 2009). RFID could be connected with BIM to trace and visualize the status of construction supply chains (Qi et al. 2018).

This study tracked the status of the precast components using data collected by RFID, which was then automatically uploaded via GPS to the BIM system for visualization. Because of cost considerations, the client only applied the integrated system to one building of the case project while the other four buildings still used traditional document-based method to record the supply chain processes. Therefore, only that building with the system was recruited for real-time data collection. In addition, only façades had RFID embedded for further cost reduction and were traced for analysis. However, real-time information of façades only is able to represent the status of the project supply chain. Passive RFID was embedded into each façade and scanned by workers using readers at the production, delivery (from the factory), arrival (at the site), and erection time to accurately record the status of the façades.

The investigated building has a total of 37 floors; Floor 1-34 each has 46 façades and the

3 top floors each has 37 façades, generating a total of 1675 façades. Precast facades could be divided into five types according to their designs, and the ones with similar size and appearance are considered as one category. **Fig. 3** shows the design drawings of the facades.

<Insert Fig. 3 here>

Document analysis

Document analysis is traditionally used in the construction industry to retrieve historical project information. In cases where an RFID failed to record data, the manufacturer's production records and the main contractor's master program were used as supplementary information, which played an important role in completing the dataset of the project.

Interviews

Interviews with stakeholders from the case project were conducted to analyze the root causes of the problems in the supply chain. Four experts working for the project were invited to participate in face-to-face interviews, including the client, the manufacturer, the main contractor, and the assembly sub-contractor. Since they attended the case study project from the beginning, they knew the project situation very well and therefore were able to provide deep insights into the problems in the supply chain and their root causes. The background information of the stakeholders is shown in **Table 1**. Requiring the experts to carry out the analysis objectively was important to ensure the reliability of the interview results.

Objectivity could be achieved by in-depth and detailed descriptions of issues, from which the fairness and consistency of their meanings could be judged (Charmaz 1995). The interviewed stakeholders were invited to answer three questions with which to analyze the problems and their sources embedded in the SCM: (1) Do the described problems really occur in the SCM for the PBP? (2) How do the problems occur in the supply chain? and (3) What are the root causes of the problems? They were asked to provide as many details as possible. By doing this, how and why the problems occur in the project was discussed in detail, ensuring that all possible occurrence and their sources were considered. Each interview lasted at least three hours during which time the stakeholders were able to provide an in-depth and detailed analysis of the research questions. In view of the high consistency of their descriptions, the interview results are taken as being objective.

Research findings

The real-time data of precast components accurately reflects how the supply chain is operated and managed. This section presents a statistical analysis of the dataset to show the actual situation of the SCM for the case study project, including the operation of the production, logistics, and on-site assembly stages, and the inventory and lead-time management of the supply chain. The actual situation reveals a series of problems in the SCM of the project, including limited considerations of resource planning, significant assembly delay, overproduction, excessive inventory, and long lead time, which are analyzed in the following sections.

Supply chain operation

The operation of the production, logistics, and on-site assembly stages constitute a major part of the supply chain. Each process displayed considerable fluctuations, indicating significant variations in the supply chain.

Production stage and embedded problems

According to the manufacturer, the production time of all types of facades is almost the same (1 day). Therefore, production analysis in this section does not consider the production time of different facades and instead is based on measurement of facades by number. The production of precast components is restricted by the factory's resource constraints. It is therefore important to conduct reasonable planning to meet the on-site assembly demand for components, satisfy the internal resource constraints, and optimize the overall manufacturing costs (Zhai et al. 2006). The case study project showed unbalanced resource deployment across the production phase, indicating limited considerations of resource planning.

As can be seen in **Fig. 4**, daily manufacturing records of façades show a highly fluctuating production schedule throughout the project. Although façades were generally fabricated by floor sequence, there were considerable production disorders amongst the floors. For example, after beginning to work for Floor 7, the production line was found to go back to manufacture several façades of previous floors (e.g. Floor 5), which suggests that the factory conducted fabrication individually rather than by complete batch. This situation frequently happens during the manufacturing stage and may reflect the substantial impact of disregarding supply to other buildings, indicating that the manufacturer failed to well coordinate the production schedule of the whole project Also, the distribution of the total amount of daily produced façades was greatly disorganized without any patterns, implying an unbalanced deployment of resources (e.g. molds, labor, and equipment) across the production phase. According to Zhong et al. (2013), dynamic fluctuations during manufacturing is due to a mismatch between planning and scheduling as a result of frequent disturbances, such as uncertain downstream demand, engineering changes, and emergent orders.

The scatter plot shown in **Fig. 4** below demonstrates that a minimum of one façade and a maximum of 14 façades were manufactured daily with five façades being produced on average every working day, which was far from reaching the realistic production capability of the factory. As the project documents illustrate, 36 façade molds were prepared for this project, implying that the factory was able to produce 36 façades daily. Most molds and equipment therefore stood idle during the manufacturing phase, causing significant waste and revealing poor planning of resources.

<Insert Fig. 4 here>

By contrast, the number of monthly manufactured façades had an upward trend with relatively lower fluctuations as shown in **Fig. 5**. This implies that the manufacturer was likely to produce more precast components in the later stages of the supply. Minimum and maximum amounts of façades produced monthly were 22 and 187 respectively, which reveals a great gap between manufacturing efforts devoted to different episodes of supply.

<Insert Fig. 5 here>

The production duration of façades for each floor is shown in **Fig. 6**, which displays a downward trend of fabrication time for each floor, indicating that the manufacturing speed accelerated with the project schedule. Specifically, the longest time (65 days) and shortest time (10 days) was spent on fabrication for Floor 5 and Floor 30 respectively. On average, 30 days were used to complete the production of façades for each floor. Furthermore, several days' interruption frequently took place during the manufacturing phase, resulting in significant time buffers. This is because the manufacturer was working for multiple projects at the same time and failed to balance the production resources for different projects.

<Insert Fig. 6 here>

Logistics stage and embedded problems

The logistics process consisted of two sub-processes: cross-border transportation from the factory to the staging area (Logistics A) and local transportation from the staging area to the construction site (Logistics B). Logistics arrangements were subject to the schedule of on-site assembly in order to ensure the arrival of precast components in time. The logistics time of each floor’s facades and the number of facades conveyed each time remained relatively stable during the transportation phase, indicating the well control of the transportation task in the case project.

The logistics durations of each floor’s façades are shown in **Fig. 7**, which demonstrates that time used for the logistics decreased with the project's progress. The transportation of façades for the initial floors took more time than the subsequent floors, indicating that schedule of the project was relatively slow at the beginning of the supply. Logistics of the first floor’s façades spent the longest time on both of the two sub-processes; logistics A and B lasted 43 days and 19 days respectively. The shortest time used for these two processes was only one day, implying that the transporter did have the capability to provide fast delivery. The average time spent in completing the transportation of each floor’s façades in the two sub-processes was 7.1 days and 6.9 days respectively. Considering that the cross-border and the local transportation processes could be finished within one day, the actual logistics rhythm of the transporter is relatively slow due to the unstable downstream demand for components. This situation added the batches of component arrival which may have negative impacts on site layout management with delay of on-site assembly.

<Insert Fig. 7 here>

The number of façades shipped each time by cross-border transportation (Logistics A) is illustrated in **Fig. 8**. According to the manufacturer, heavy trucks were used for the transportation with each truck capable of conveying 7 or 8 façades at a time. The entire logistics task was separated into 116 batches with each batch shipping 7 to 46 façades and most frequently shipping 15 or 23 façades, the latter of which constitute almost half a floor.

<Insert Fig. 8 here>

On-site assembly stage and embedded problems

The assembly of precast components for typical floors in Hong Kong's prefabricated public housing projects is six-day cycle (Chan and Chan 2002; Li et al. 2018a). The Housing Authority conducts this cyclic erection of floors in order to optimize cost, time, and resource benefits. However, significant assembly delays were observed at the assembly stage of the case study project, resulting in various problems in the supply chain.

The actual assembly duration of typical floors (Floor 2-34) is shown in **Fig. 9** with significant schedule delays across the assembly stage despite long-term efforts devoted to good on-site construction practice. The second floor took up to 16 days to complete because of the lengthy learning and preparation process in the early stage of the on-site construction, while the assembly of the subsequent floors was relatively faster with the erection duration of typical floors averaging out at nine days. A sharp increase in the assembly time occurred at Floor 22 and Floor 27 because of a lack of labor and component damages respectively, resulting from inferior resource planning and poor site layout management. Only Floor 5 and Floor 6 realized the goal of completing the assembly within the cycle time, while other floors lagged behind the expected schedule resulting in a delay of 102 days and considerable cost overruns. This situation reveals poor control of the assembly process.

<Insert Fig. 9 here>

Inventory and lead time management

The planned and actual concreting schedule of the investigated building is shown in **Fig. 10**, indicating significant assembly delays of most floors. The overall progress of the supply chain is illustrated in **Fig. 11**. There can be seen little consistency between upstream production and downstream demand, resulting in overproduction, excessive inventory, and long lead time. Overproduction is the root cause of excessive inventory, long lead time, and unnecessary movement (Ohno 1988). Excessive inventory is also considered to be a significant waste since it occupies space and induces storage costs with the potential risk of component damages (Pheng and Chuan 2001), while long lead time is associated with schedule delay and extra costs. This section describes the inventory and lead time situation of the case study project to show overproduction, excessive inventory, and long lead time in the SCM.

<Insert Fig. 10 here>

<Insert Fig. 11 here>

Inventory management and embedded problems

Excessive inventory existed in the factory, the buffer, and the site, indicating considerable time and money invested in advance before generating any value for the supply chain. This section provides the amount of inventory and stock time of façades throughout the supply chain of the case study project.

The inventory amount in different supply chain stages of the investigated building is shown at the top of **Fig. 12**. It can be seen that the façades kept in stock in the factory almost always number in the hundreds, which is substantially higher than the inventory amount in the buffer and the site. This implies that the manufacturer preferred to store large quantities of components before they were really needed. Initially, the amount of factory inventory demonstrates an upward trend, increasing to 300 façades in the 227th day of the project. A fluctuation then follows with the maximum inventory reaching 332 façades, which amounts to the number of façades for up to seven floors. The maximum inventory in the buffer and the site is 69 and 115 façades respectively. The average amount of façade inventory in the factory, the buffer and the site every working day is 212, 14, and 17 respectively. Considering that inventory situation may be influenced by the factory's response to the demand from the other four buildings of the project, the bottom of **Fig. 12** shows the amount of façade inventory of the whole project based on the production record of the manufacturer, which reveals similar trend with that of the selected case building across the supply chain. The maximum and the average amount of façades in stock for the whole project is as high as 1249 and 720 respectively, indicating excessive inventory in the factory. Holding such a great number of components is likely to cause a series of problems, such as poor layout management and damage to components. Given the limited area of the site in Hong Kong, the inventory should have been reduced.

A large inventory can be ascribed to overproduction in the factory. According to the manufacturer, the safety inventory that should have been stored was two floors of façades (92 façades). Safety inventory means the extra stock kept on hand as a cushion to mitigate risk of stockouts caused by uncertainties of surroundings or nature (Lin et al. 2011), which plays an important role in responding to reasonable demand variability (Minner 2003). In the actual situation, safety inventory could be influenced by various factors such as the production demand probabilistic distribution, the initial and updated production schedules and plans of the factory and the overall level of contractor satisfaction (Jung et al. 2004), indicating considerable difficulties in the control of inventory management. This study observed that the quantity of façades in stock far exceeded the safety inventory with up to 321 working days of excessive inventory, which reveals severe overproduction by the manufacturer. This situation is mainly caused by the over-early production principle adopted by the factory which did not only work for this project and meanwhile had many other businesses to deal with. Also, benefiting from overproduction while not taking the risk of excessive inventory, the main contractor initially over-forecast the demand for façades before they were actually needed (Tsay 2008), and the manufacturer therefore had to produce the façades as early as possible to complete the order.

<Insert Fig. 12 here>

The average stock time of different floor façades in the factory, the buffer, as well as the site is shown in **Fig. 13**. The stock time in the factory is significantly higher than that in both the buffer and the site almost throughout the supply chain. Specifically, the initial stock time in the factory is at a very high level (up to 114 days) but then decreases rapidly in line with the project schedule, which suggests improved coordination between the manufacturer and the main contractor. On the other hand, stock time on the site is relatively short for the first 17 floors and then takes an upward swing reaching a peak of 31 days for the 31st floor, indicating reduced efficiency of the assembly work. Because of the close proximity of buffer and site, stock time in the buffer remains relatively stable. The average stock time in the factory, the buffer, and the site is 44, 4, and 14 days respectively.

Excessive inventory and long stock time is the norm in the construction industry since the manufacturer or the contractor would like to supply or acquire the components/materials before needed (Tserng et al. 2006). The manufacturer in the case study project adopted an over-early production principle by beginning to plan production four months in advance, which is the main cause of such high inventory in the factory. The main contractor also preferred to store large quantities of components on the construction site. This situation resulted in a lot of waste and extra costs in the supply chain.

<Insert Fig. 13 here>

Lead time management and embedded problems

In SCM theory, lead time generally refers to the time from the moment the client places an order to the moment it is ready for delivery. Given the multiple orders and complex coordination process in the cross-border supply chain, this study defines lead time as the time from the moment the manufacturer begins production to the moment the precast components arrive at the construction site. **Fig. 14** illustrates the lead time of façades for different floors, showing that the waiting time of components remains at quite a high level across the supply chain, averaging out at as much as 48 days. Also, a downward trend of lead time with project progress can be seen, implying better supply chain performance in the later stages. Vrijhoef and Koskela (2000) pointed out that a considerable lead time in the beginning, particularly because of inventory and delays, is caused by uncoordinated planning and inter-organizational problems.

The factory adopted an over-early production principle and therefore had enough time to plan the production and control the lead time. However, since lead time starts from the moment the factory begins manufacturing, the over-early production commencement results in the occurrence of long lead time. This phenomenon suggests that the manufacturer lacked a reasonable resources deployment concept to balance time, cost, and resource merits, resulting in significant waste throughout the supply chain. Also, poor coordination between upstream production and downstream demand for components is responsible for the significant lead time (Arashpour et al. 2016). Such long waiting time is common in the prefabrication sector globally, such as in Mainland China (Luo et al. 2015), Malaysia (Nawi et al. 2011), and the UK (Blismas et al. 2005) and is considered to be a barrier affecting the development of PBPs.

<Insert Fig. 14 here>

Discussions

Above data analysis has revealed the actual situation of the SCM and a series of problems embedded in different stages of the case study project, including limited considerations of resource planning, significant assembly delay, overproduction, excessive inventory, and long lead time. In order to explore how and why these problems occur, four experts from the case study project were interviewed to solicit their opinions. First, the analysis results of the real-time data were reported to the experts with emphasis on the identification of the problems embedded in the SCM. With great familiarity with the project, the experts highly recognized the existence of the problems. Second, they were invited to provide detailed descriptions about the occurrence of the problems one by one in detail. Third, based on the analysis in the second step, the root causes of the problems were discussed with the experts in detail. The following sub-sections present the results of the interviews to display how the problems occur under the effects of their root causes which include poor supply chain planning, poor communication between stakeholders, and poor control of working flows. The considerable negative impacts of these three factors on the supply chain performance of PBPs were echoed in previous studies on Singapore (Hwang et al. 2018), Australia (Sahin et al. 2018), and Malaysia (Pozin et al. 2016).

Poor supply chain planning

The profile of the supply chain for the case study project reflects poor planning prior to project implementation. The manufacturing and on-site construction phases are major parts of the supply chain and detailed planning of the activities plays an key role in improving productivitiy and efficiency of the projects (Arashpour et al. 2015; Li et al. 2018b; Wang and Hu 2017). However, as pointed out by the interviewed stakeholders, on-site construction often does not go according to plan and so disturbs original resource arrangements. This is because the supply chain of a PBP is much more vulnerable and complicated than that of a traditional project (Wang et al. 2019), and therefore has more variations which need to be minimized (Arashpour et al. 2019). The mismatches between the plan and the actual implementation had a considerable impact on the supply chain, including uncertain demand for precast components, overproduction and long lead time in the factory, disrupted transportation schemes, and schedule and cost problems. These issues are common worldwide and Wu and Low (2012), Nahmens and Mullens (2011) and Xu et al. (2018) therefore proposed lean prefabrication as a strategy to reduce the huge wastes and the resultant losses. On the other hand, the production profile shows that the factory followed the traditional rule of earliest due date regardless of resource considerations, which is criticized to be a trial and error approach to production planning because it does not guarantee a good result (Zhai et al. 2006).

The main contractor was the major planner of the project responsible for developing the master program, which is the most important document for milestone arrangements during the production, transportation, and assembly stages of the project. However, the master program of the case study project was revised up to seven times, which greatly disrupted the plan across the supply chain. Although the enterprise resource planning (ERP) system used by the main contractor played an important role in integrating the internal and external information flows, it mainly focused on the managerial level of decision-making while the shop-floor schedule was only weakly connected to the system. This situation has been validated by Zhong et al. (2017) in PBPs of Hong Kong. According to the assembly sub-contractor, the shop-floor supervisors adopted a paper-based schedule that was often disrupted by engineering changes. There was therefore a gap between the planning and the actual schedule, resulting in a considerable waste of resources and time throughout the supply chain.

Poor communication between stakeholders

Severe inconsistency between production, transportation and on-site assembly indicates poor communication between stakeholders, which is revealed as one of the root causes of excessive inventory and long lead time. As the coordinator of the supply chain, the main contractor plays a critically important role in integrating the project team. This is in line with construciton management practice in which the contractor is always the focus of SCM (Fernie and Thorpe 2007). Its interactions with the manufacturer and the transporter are greatly influential to the smooth implementation of the project, while the contractor-client relationship is highly correlated with on-site productivity (Pheng and Chuan 2001) and variation reductions in the assembly phase (Doran and Giannakis 2011). Unfortunately, the main contractor from the case study failed to integrate the upstream production, transportation, and the downstream assembly processes, thereby bringing about a fragmented supply chain.

The overproduction, excessive inventory and long lead time could be ascribed to the main contractor's poor communication with other stakeholders. When interviewed, the manufacturer complained that they did not receive the latest on-site information quickly since the main contractor often informed the factory of their demand very late without prior communication. The factory therefore had to use the earliest due date principle in case any sudden orders arrived, which generated huge overproduction and excessive inventory with long waiting time. Also, because the main contractor was deficient in communicating with the transporter about the latest delivery schedule of precast components, the transporter often conveyed components to the buffer several days in advance, causing excessive inventory and long lead time in the buffer. This phenomenon shows the inefficient and inaccurate information sharing between stakeholders in PBPs as evidenced by Xu et al. (2018) and Zhong et al. (2017).

Such poor communication combined with frequent variations engenders mistrusts between stakeholders, which is another source of overproduction in the factory. The on-site construction is a complex process that often does not go according to plan, thereby requiring timely information exchanges between stakeholders to coordinate the working packages, labor, and resources in the supply chain. However, the manufacturer complained that the changes in the master program and the design were often not updated to them in time, resulting in disrupted production rhythm, poor layout management of components, and increasing operation costs. As a result, the manufacturer did not believe that the project could be implemented as planned, and therefore produced large amounts of components in advance and kept them in stock to address those problems caused by the poor information transfer by the main contractor. According to Wu et al. (2017), trust mechanism should be built among stakeholders on the basis of equal cooperation, which could effectively add value for the project.

The poor interactions between the stakeholders may be due to their ineffective communication methods. The project stakeholders share the latest progress information and variations with each other mainly by email, WhatsApp, and hard copies of project documents. These forms of traditional communication result in weak coordination between the upstream production and the downstream demand for precast components. According to Zhong et al. (2013), this weakness should be tackled by means of advanced information technologies to monitor inventory and overproduction on a real-time basis, thereby considerably improving the supply chain performance of PBPs.

Poor control of working flows

The supply chain is composed of multiple processes and stakeholders that are hard to control due to the complex working packages and heavy resource deployment. Such complexity generates diverse variations in the supply chain and reveals the stakeholders' inability to effectively control the working flows. Since upstream and downstream do not exist individually but have close mutual impacts on each other, the variations taking place in either phase may influence the operation of the entire chain.

The interviewed stakeholders reached a consensus that delayed assembly schedules have a considerable propagation impact on supply chain operations. The delay often occurs in PBPs of Hong Kong and results in a series of supply chain risks (Luo et al. 2019). The main contractor attributes excessive installation time to low productivity and multiple errors that break the construction rhythm. First, identifying the right component from the inventory on the construction site takes quite a long time because components often have similar sizes and shapes and are placed together in a compact area of the site; misplacement of components is also found to occur occasionally during the assembly stage. Such poor layout management makes it difficult to quickly recognize the components belonging to the right floor and the right part of the building. This is particularly the case if the components identification marks are unclear or incorrect (Wu and Low 2014).The large amounts of inventory make it time-consuming to find the correct component. According to the main contractor, construction workers may not find a component to be the improper one until getting ready to install it or after installing it in an inappropriate place. Consequently, the component has to be taken back to the storage and more time will be taken to identify the proper one. The delay of one floor has propagation impacts on the subsequent floors, thereby negatively affecting the schedule of the whole project. Also, component damages which have been found to take place in PBPs of Singapore (Pheng and Chuan 2001) and Malaysia (Azwanie et al. 2016), often arise from the frequent movement of inventory, resulting in extra hours and repair costs. Furthermore, inspecting component quality consumes much time due to slow procedures and the low productivity of workers. In addition, those common problems frequently occur in PBPs, such as tower crane breakdown, safety accidents (Fard et al. 2017), and design change (Jaillon and Poon 2010, 2014) are also observed on the construction site of the project, which are significant causes of schedule delay and cost overruns. Such deficient control of multiple flows results in high variety of downstream demand for precast components and consequently causes a mismatch between the production and assembly schedule. Greater efforts are therefore required to inspect, manage and coordinate complex on-site work.

The factory also had insufficient control of the various working flows, which considerably affected component quality and delivery schedule. Although the components were produced in a controlled off-site environment, they may still have some defects and therefore did not meet the quality requirement. Some components may have been damaged as a result of a large inventory and unnecessary movements due to poor layout management in the factory. The defects and damages caused by the poor control of working flows bring about the re-production of components, which demands extra time and money of the manufacturer and delayed delivery of components. It was also observed that the case study project mistakenly took delivery of components from the factory as confirmed in Pheng and Chuan’s (2001) work, which significantly affected installation implementation. Although all the components had a serial number marked on the surface to show their identity information, workers often made mistakes by marking wrong serial numbers or making the label ambiguous, which impeded component identification during installation.

In addition, due to the complex cross-border supply chain, damage occurred to components during transportation, which caused a delay to the schedule. However, it was problems resulting from poor control of the working flows in the upstream production and the downstream assembly phases that affected the supply chain operation the most.

Conclusion

As an alternative to traditional construction, prefabrication has gained worldwide attention because of its technological benefits. Many countries and regions therefore have established large-scale PBPs. The SCM for such PBPs plays an important role in enhancing successful delivery. However, the multiple processes and stakeholders involved make SCM for PBPs a complex task. Before any measures could be developed to address the problems in the supply chains of PBPs, it is important to fully understand the actual situation of SCM for PBPs.

The supply chains of PBPs in Hong Kong are relatively more complex because of the cross-border transportation process. This study investigated the real-time status of a supply chain for a PBP in Hong Kong by tracing precast components across the production, logistics, and on-site assembly processes. Automated collection technologies were adopted to obtain real-time data of precast façades across the supply chain. The findings show that limited considerations of resource planning, significant assembly delay, overproduction, excessive inventory, and long lead time were serious problems which produced considerable non-value-adding waste in the supply chain and led to cost overruns and schedule delays. The root causes of the problems include poor supply chain planning, poor communication between stakeholders, and poor control of working flows.

This is the first study to reveal the actual situation of SCM for PBPs using empirical data from an entire supply chain. The paper provides an in-depth understanding of the problems and their root causes associated with SCM for PBPs, which will help stakeholders to manage supply chains for PBPs more efficiently and effectively.

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