MODELLING RISKS IN THE SUPPLY CHAINS OF PREFABRICATED BUILDING PROJECTS IN HONG KONG

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Certificate of Originality

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Abstract

Prefabrication is an effective strategy to improve the working conditions and eventually the quality control during construction. The various benefits of prefabrication include cost and time savings, decreased labor demand, enhanced environmental performance, and improved quality management. These attractive superiorities have led to the extensive use of prefabrication worldwide. Prefabrication has been applied in the Hong Kong construction industry since the mid-1980s for the purpose of addressing the serious housing shortage. The Housing Authority's encouragement and investment have largely stimulated the technology development, with increasing use of prefabrication being observed from the percentage of precast volume and the types of precast elements. Effective supply chain management (SCM) is the key in the successful delivery of projects using prefabricated components. However, the supply chains of prefabricated building projects (PBP) are considered to be complex because of the multiple complexities in the organization, task and information aspects. Various problems exist in the supply chain of PBP and result in a series of supply chain risks (SCR) which need to be deeply understood for the development of mitigation strategies.

This study aims to examine the impacts of the dynamically interacting SCR on the performance of PBP in Hong Kong. The specific objectives include (1) To investigate the real situation of SCM for PBP, identify the embedded problems and analyze their root causes; (2) To identify stakeholder-associated SCR and analyze their interactions in the context of PBP in Hong Kong; and (3) To develop a dynamic model for assessing the impacts of the SCR on the performance of PBP. First, this research investigates the

production, transportation, and assembly processes of a prefabricated building project in Hong Kong using advanced data collection technologies and document analysis. Real-time data of precast facades throughout the supply chain is obtained, which provides valuable implications about the real situation of SCM for PBP and the problems involved. Interviews with stakeholders from the case project are conducted to analyze the root causes of the problems. Then, literature review and interviews with experts are adopted to identify stakeholder-associated SCR in PBP. Social network analysis (SNA) and case study are subsequently carried out to analyze the interactions between the SCR in the context of PBP in Hong Kong. Critical SCR and links in the risk network are identified and prioritized. Finally, a dynamic model using the system dynamics (SD) is developed to assess the impacts of the SCR on the performance of PBP. Multiple performance of PBP are considered in the model, including inventory, schedule, and quality.

This research contributes to the body of knowledge by providing an in-depth understanding of current SCM for PBP in a realistic way, with the real situation of multiple processes of a prefabrication supply chain being fully revealed. This research also fills a current knowledge gap by developing a dynamic social network to understand stakeholder-associated SCR in the context of PBP in Hong Kong and overcoming the limitations of traditional static risk analysis. In addition, this is the first study to comprehensively assess the impacts of SCR on the multiple performance of PBP, providing valuable implications about SCR management research in enhancing the performance PBP.

Publications

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2. Luo, L., Mao, C., Shen, L.Y. and Li, Z.D., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system: A case study from China. Engineering, Construction and Architectural Management, 22(6), pp.622-643.

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Chapter 1 Introduction

Prefabrication is in many ways technologically superior to traditional cast-in-situ construction. Its benefits include cost and time savings (Mao et al. 2016), decreased labor demand (Nadim and Goulding 2010), enhanced environmental performance (Hong et al. 2016), and improved quality management (Tam et al. 2014). These attractive superiorities have led to the extensive use of prefabrication in many developed countries and regions. In Sweden, for example, approximately 74% of detached single houses used the factory-based construction method between 1990 and 2002 (Segerstedt and Olofsson 2010). In the United States, the manufactured housing industry constituted around 20% of the property market and ranked as the second largest housing units supplier in 2003 (Jeong et al. 2006). In Hong Kong, precast components comprised around 17% of the total concrete volume utilized in public housing projects in 2002 (Chiang et al. 2006); this percentage increased to 65% in a pilot project in 2005 (HKHA 2005). Meanwhile, some developing countries are making efforts to foster prefabrication development. In China, for example, the use of prefabrication is incorporated into its 13th Five-Year Plan (MOHURD 2016), which provides a powerful engine for the development of prefabrication technologies. In Malaysia, the government proposed the “IBS Roadmap 2003-2010” and “IBS Roadmap 2011-2015” programs to promote the adoption of industrialized building systems (CIDB 2003, 2010).

It can be foreseen that the wider utilization of prefabrication can significantly contribute to the building industry, and there is still much room for increasing the application of precast structures in construction. In promoting prefabrication development, previous research in the United Kingdom (Housing Forum 2011), the United States (Said 2015), Hong Kong (Chiang et al. 2008), and Japan (Gann 1996) considers supply chain management (SCM) to be the key in the successful delivery of projects using prefabricated components. As Chiang et al. (2006) point out, it is the control over the supply chain, rather than the prefabrication technology itself, that is the sustainable competitive advantage of a construction company. However, SCM for PBP is a complex task. There are many stakeholders within the entire supply chain system, which include clients, designers, manufacturers, contractors, and various suppliers who partake in different processes of the chain. Prefabrication should be integrated from the outset of the design stage, which requires frequent interactions between participants to ensure close coordination in maintaining labor, materials, and equipment (Čuš-Babič et al. 2014) and consequently adds considerable difficulties to the supply chain. Koskela (2003) explains the complexity of SCM for PBP from four perspectives: (1) longer chain caused by at least two construction environments, namely factory and site; (2) larger amount of design work and earlier design for cast-in-situ construction because of prefabrication lead time; (3) longer error correction period; and (4) higher requirements for dimensional accuracy.

Due to the abovementioned complexity, prefabrication supply chains are fragmented, which leads to many problems throughout the whole supply chain, such as schedule delay in Hong Kong (Li et al., 2016), late deliveries, inappropriately supplied components and component damages in Singapore (Pheng and Chuan 2001a), and redesign and extra cost in Malaysia (Kamar and Hamid 2011). Therefore, significant improvement in SCM for PBP is needed to tackle these problems and enhance the overall performance of prefabricated buildings.

1.1 Research background

1.1.1 PBP in Hong Kong

Hong Kong is a high-density city with a very large population and a serious housing shortage. The increasing housing demand requires that residential buildings should be supplied at a fast pace without sacrificing quality. Prefabrication makes it possible to achieve this goal by reducing construction time by 20% with improved quality control. Since the mid-1980s, the Housing Authority has applied prefabrication in public housing programs, along with standard modular design. The Housing Authority's encouragement and investment have largely stimulated the technology development, with increasing use of prefabrication being observed from the percentage of precast volume and the types of precast elements. A comprehensive database comprising up to 179 residential buildings in Hong Kong shows that the percentages of buildings using precast façade, precast staircase, semi-precast slab, and semi-precast balcony are 51%, 22%, 9%, and 7% respectively (Jaillon and Poon 2009). In 2002, precast elements comprised around 17% of the concrete volume in public housing projects (Chiang et al. 2006). This proportion was tripled to 65% in a pilot project in 2005 by extending the use of precast concrete to prefabricated bathrooms, kitchens, and structural walls (HKHA 2005). Nowadays, almost half of local residents are accommodated in public housing projects. PBP will continue to proliferate in Hong Kong's building sector given the Housing Authority's ambitious goal of producing up to 93,400 public housing units from 2015/16 to 2019/20 (HKHA 2016).

The design-bid-build (DBB) contract mode is used for PBP in Hong Kong. The Housing Authority is the client of public housing projects who directly recruits a consultant for design work and a main contractor for management of the project supply chain. The main contractor employs a manufacturer, a transporter, and an assembly sub-contractor and reports the project status to the client on a weekly basis. In case of any urgent orders, the transporter usually arranges a temporary storage area near the site as a buffer to keep components in inventory for a short period.

The supply chains of PBP in Hong Kong are considered to be complex for the following reasons. First, the project team is composed of multi-disciplinary practitioners from different organizations whose decision-making is based on their individual goals and value systems with limited considerations of supply chain performance, resulting in organizational complexity (Ju et al. 2017). Second, most precast factories are in the Pearl River Delta area of Mainland China from where the components are transported by trucks through customs to Hong Kong, resulting in substantial uncertainty and task complexity during the transportation process. As the cost, time and construction progress largely depend on the logistics of the component delivery (Chiang et al. 2006), any variations in cross-border transportation may significantly affect project performance. Third, the fragmentation and discontinuity involved separate the supply chain into individual parts with poor coordination and information-sharing between stakeholders, making it difficult for practitioners to obtain real-time information (Li et al. 2016). This situation is exacerbated by cross-border transportation and limited use of information technologies (Xu et al. 2018), thereby generating considerable information complexity. These complexities make it difficult to coordinate multiple information, material/service/product, and fund flows, thus requiring close interaction and frequent information-sharing among the stakeholders to guarantee a smooth supply chain.

1.1.2 Construction SCM

In recent years there has been a considerable amount of research devoted to the development of SCM theory in the construction industry (e.g. Arantes et al. 2015; Behera et al. 2015; Kamar and Hamid 2011). The application of SCM is found to be difficult due to the following characteristics of construction projects: temporary multiple organizations (Cheng et al. 2010a), adversarial short-term relationships (Abdullah and Nasir 2017), and obstacles in handling networks of multiple stakeholders, materials and components supply, and various services (Aloini et al. 2012).

To address the problems in construction supply chains, studies have found that collaboration and integration based on real-time information sharing, and commitment management among stakeholders (Isatto et al. 2015), are critical elements to improve supply chain performance (Koolwijk et al. 2018; Xue et al. 2010) by reducing lead time, shortening project durations, and increasing operational efficiency (Min and Bjornsson

2008). These benefits have motivated scholars to further explore and enhance collaboration between stakeholders. For example, Xue et al. (2018) analyzed collaborative management in prefabrication to find its positive effects on cost performance; Das et al. (2015) developed an ontology-based web service framework to support heterogeneous data transfer for better supply chain collaboration; and London and Pablo (2017) adopted an actor-network approach to expanding conceptualization of collaboration in PBP to facilitate theory development.

Since collaboration is characterized by close relationships between stakeholders, investigating and improving supply chain relationships in construction has become an important topic. For example, Jeong et al. (2013) proposed a framework to optimize the manufacturer-supplier relationship in PBP; Kim and Nguyen (2018) provided a structural model to identify supply chain relationship traits and assess their impacts on project performance; and both Meng et al. (2011) and Kim and Nguyen (2017) measured stakeholder relationships and discovered major areas for relationship improvement by developing a maturity model and an analytical hierarchy process framework respectively. While acknowledging the above research in enhancing collaboration between stakeholders, poor coordination and poor information sharing are still found to be the norm in the construction industry because of its one-off characteristics.

Optimizing supply chain performance also gains increasing attention in existing studies. Since material flows have been found to remain the focus of current construction SCM practice (Ying et al. 2015), recent research has placed considerable emphasis on material supply optimization. For instance, Liu and Lu (2018) initiated a scheduling optimization model for prefabrication projects to optimally balance material delivery dates and downstream demand by minimizing the direct labor cost related to late delivery and the inventory cost caused by early supply; Jaśkowski et al. (2018) proposed a planning decision model to minimize the total inventory management cost by optimizing the supply of materials/components that are consumed irregularly; Moon et al. (2018) developed a radio frequency identification (RFID)-enabled tracking system to optimize material management at the supplier stage of a mega project in order to improve field productivity; Arashpour et al. (2017a) optimized supply decision-making of prefabricated products taking supplier selection and multi-supplier configurations into account. On the other hand, Ju et al. (2017) proposed a value optimization strategy to reduce interface conflicts and eliminate potential risks of delay and cost overruns by reallocating interface responsibilities between associated contractors, while van den Berg et al. (2017) developed a game approach, which enables students to experimentally experience the way supply chain optimization actually works. Before optimizing material flows, it is important to streamline the information flows which play an important role in assisting with stakeholders' decision-making and thereby directly influence other flows, including material/service/product and fund flows. Future research therefore could pay more attention to optimize information flows.

In addition, the literature reveals significant principles and approaches to improving construction supply chain performance, such as the use of lean concept (Barriga et al. 2005; Yu et al. 2011), partnering principles (Kumaraswamy and Matthews 2000), building information modelling (BIM) technology (Papadonikolaki et al. 2016), and e-marketplace (Alarcón et al. 2009). Some studies have also explored environmental considerations in the development of sustainable supply chains (Balasubramanian 2014; Balasubramanian and Shukla 2018; Dadhich et al. 2014; Facanha and Horvath 2005), while other studies have focused on organizational behavior (Jagtap and Kamble 2015; Mostafa and Chileshe 2018), claims management (Stamatiou et al. 2018), occupational risk management (Barreto and Pires 2015) and supplier evaluation (Seth et al. 2018) in construction supply chains. For the specific area of PBP, SCM research includes planning and controlling the design of prefabricated building systems (Wesz et al. 2018), value stream mapping (Jarkko et al. 2013), and market equilibrium modelling for self-manufacturing or outsourcing decisions (Han et al. 2017).

1.1.3 SCM for PBP

A construction supply chain is a network of many organizations and relationships connected by information flows, materials, services or product flows, and fund flows between stakeholders (Xue et al. 2007). According to Koskela (2003), SCM for PBP is more difficult than that of traditional construction due to the multiple production environments (factory and site), more design work and prefabrication lead time, a longer error correction cycle, and stricter requirements for dimensional accuracy. The supply chain should be integrated at the beginning of the design phase, requiring strong coordination among stakeholders to arrange labor, materials and equipment resources

(Čuš-Babič et al. 2014). Such coordination requires frequent communication and collaboration between stakeholders to convey proper and up-to-date information (Abedi et al. 2014). The multi-disciplinary stakeholders, however, are from different organizations whose decision-making is based on their individual goals and value systems with limited considerations of supply chain performance, resulting in organizational complexity (Ju et al. 2017). This 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; Wang et al. 2018), while other studies have focused on planning and controlling the design of prefabricated building systems (Wesz et al. 2018), value stream mapping (Jarkko et al. 2013), and market equilibrium modeling for self-manufacturing or outsourcing decisions (Han et al. 2017).

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. Therefore, facilitating stakeholder communication is an important issue worthy of further study.

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 PBP (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. However, this is not enough to enhance the logistics process because of the frequent variations in the downstream demand for precast components. Also, the site space for component storage is often limited in Hong Kong. Therefore, real-time monitoring of the assembly schedule and site layout situation needs to be further improved.

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 radio frequency identification (RFID) and building information modeling (BIM) is developed to effectively mitigate risks and enhance the schedule performance of projects (Li et al. 2017b).

1.1.4 SCR in PBP

SCR refer to risks that can modify or prevent part of the movement and efficient flow of information, materials and products between the actors of a supply chain within an organization, or among actors in a supply chain (Lavastre et al. 2012). Due to supply chain fragmentation, many uncertainties and complexities originate from the interfaces of different stakeholders (Behera et al. 2015). As a consequence, SCR arise and have a direct impact on project performance (Demirkesen and Ozorhon 2017).

Studies have provided insights into SCR in PBP in both developed and developing countries. In Australia for example, the poor process uptake, such as procurement, logistics, and site operations, are identified as the barriers that affect the supply chain value of PBP (Sahin et al. 2018). In Sweden, long lead time and scarcity of suppliers are critical supply chain issues hindering industrialized construction (Larsson et al.

2013). In Singapore where prefabrication supply chains are relatively more comparable to that in Hong Kong because of their similar PBP development background, SCR include lack of coordination prior to and during construction, inadequate project planning and design efforts, limited transportation and logistics considerations (Hwang et al. 2018), large inventory, inappropriate staffing arrangements, and unclear identification marks (Wu and Low 2014). In developing countries where PBP are still in their infancy, supply chains are relatively more fragmented than those in developed countries. In China for example, prefabrication supply chains suffer from a lack of experienced professionals (Mao et al. 2015), supporting technologies, and large-scale production systems (Zhang et al. 2014), all of which result in significant economic risk, market risk, on-site management risk, and technical risk (Luo et al. 2015). In Malaysia, the lack of communication between multidisciplinary stakeholders (Pozin et al. 2016) and inefficient transportation, logistic and material delivery processes (Azwanie et al. 2016) result in fragmentation and disconnection of prefabrication supply chains. Since these studies have been conducted worldwide, it would appear that SCR in PBP is a global issue.

PBP in Hong Kong have been investigated to identify SCR that significantly affect time, information and schedule performance. For example, Zhai et al. (2016) pointed out that lead-time hedging issues are often created by contractors informing manufacturers of their component requirements an earlier due date than necessary, while Niu et al. (2017) found that the low concurrence of process and information negatively influences decision-making across the supply chain. In addition, data collection and transfer across complex supply chains are often revealed to be inaccurate, incomplete, and insufficient (Zhong et al. 2017) as a consequence of insufficient use of information technologies (Xu et al. 2018). These problems inevitably engender schedule delays of PBP in Hong Kong (Li et al. 2016).

There are various categorization method of SCR. Ritchie and Brindley (2007), for example, divided SCR into systematic risks and unsystematic risks; the former refers to the risks that occur as a function of the internal operating environment of companies, while the latter are organization-specific risks and are often within the control of the business. Jüttner et al. (2003) classified SCR according to environmental, network, and organizational sources, while Jüttner (2005) identified supply and demand as additional two sources of risk. Wagner and Bode (2008) categorized SCR into supply, demand, regulatory, infrastructure, and catastrophic types, while Kleindorfer and Saad (2009) considered operational contingencies, natural hazards, terrorism, and political instability as major sources of disruption risks. One of the popular categorization methods is dividing SCR into the following five types of risk: process, control, demand, supply, and environment (Christopher and Peck 2004). Since this method has been widely used to investigate uncertainty/risks in construction supply chains (Gosling et al. 2013; Pfohl et al. 2011), it was chosen as the method for this study with the following definitions for each type of risk: process risks disrupt the value-adding or managerial processes within the organizations; control risks affect stakeholders' abilities to transform the end user's order into raw material requests; supply risks refer to the disruption of the material or information flows resulting from within the upstream suppliers; demand risks are associated with the downstream order changes; and environment risks, which are also termed external risks as they happen outside the supply chain environment. From the perspective of stakeholders, process and control risks are internal to an organization while supply and demand risks are external to a firm but in the internal supply chain network. Although environment risks are external to the supply chain, they expose stakeholders in the network to potentially serious impacts (Thun and Hoenig 2011).

SCR sourced from different stakeholders have close interactions with each other, and such interactions influence the performance of the entire supply chain. For example, a design change originated from the client often leads to delayed assembly of precast components by the assembly sub-contractor, resulting in cost overruns and schedule delay of the whole project. Downstream installation errors/delays are likely to cause excessive inventory of components, bringing about poor layout management in both the factory and the construction site. Due to the compact area in Hong Kong, poor layout may trigger some safety problems. The mutual influence between the SCR makes SCM for PBP more difficult due to the multiple information and material/service/product transfer within the complex network.

SCR penetrate the entire construction processes and adversely influence the housing supply and sustainable development of Hong Kong. To fully address stakeholder-associated SCR in PBP, it is necessary to understand their interaction mechanism, from which effective mitigation measures could be developed.

1.2 Research aim and objectives

This study aims to examine the impacts of the dynamically interacting SCR on the performance of PBP in Hong Kong. The specific objectives of this research are listed as follows.

(1) To investigate the real situation of SCM for PBP, identify the embedded problems and analyze their root causes;

(2) To identify stakeholder-associated SCR and analyze their interactions in the context of PBP in Hong Kong;

(3) To develop a dynamic model for assessing the impacts of the SCR on the performance of PBP.

1.3 Research design

This research objectives are realized through the processes as illustrated in **Figure 1.1**. The steps and research methods used to achieve the objectives and expected outcomes are provided.

First, a comprehensive literature review and document analysis are conducted to understand the status quo of existing SCR research and identify the research problems.

Second, automated data collection technologies are adopted to trace the real-time status of a case supply chain. Document analysis is used to supplement data of the automated data collection system. Statistical analysis of the real-time data is conducted to quantitatively analyze the SCM for PBP and identify the problems involved. The root causes of the problems are analyzed by interviewing experts from the case project.

Third, the social network analysis method is applied to examine stakeholder-associated SCR and their cause-effect relationships in PBP in Hong Kong. A series of network indicators are adopted to identify the critical SCR and interaction links.

Fourth, a dynamic model using system dynamics (SD) theory is developed to assess the impacts of SCR on the performance of the supply chains of PBP. The inventory, schedule, and quality performance are considered in the model.

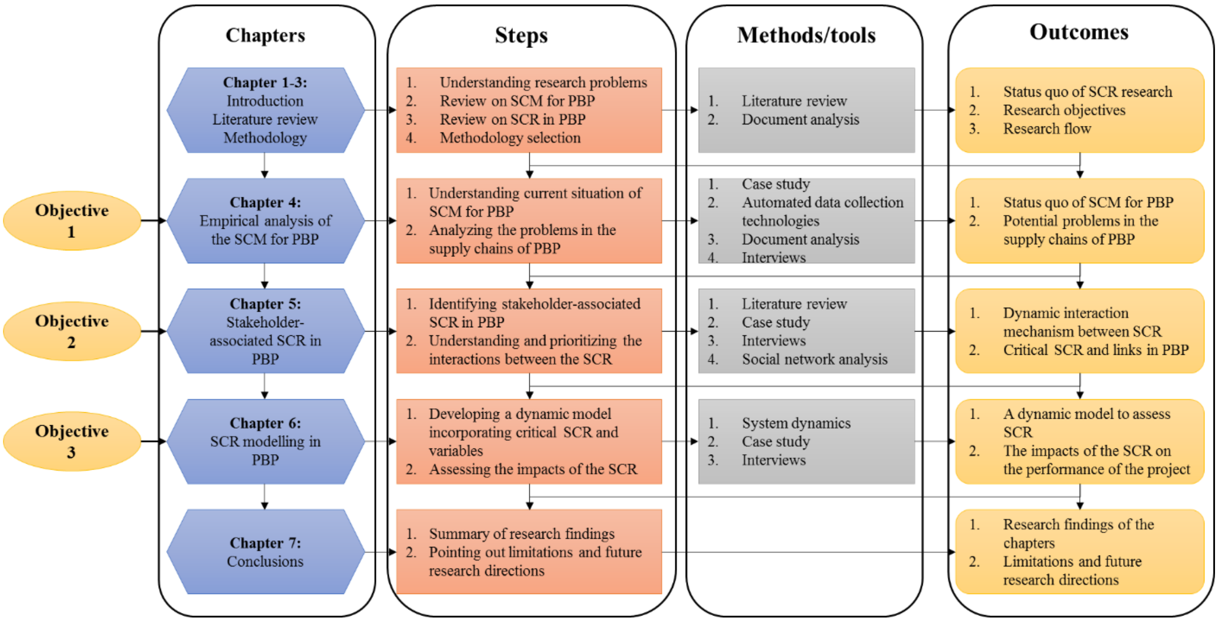


Figure 1.1 Research design

1.4 Structure of the thesis

This thesis is composed of seven chapters, the content of which is described as follows.

Chapter 1 provides a brief introduction of the thesis, highlighting major information of the research, including background, research objectives, research design, and the structure of the thesis.

Chapter 2 reviews existing research on SCM for PBP and finds that there are six major topics in this topic, including stakeholder relationships, supply chain structure, mass customization, benefits, challenges and promotional approaches. The research gaps are also provided.

Chapter 3 presents the methodologies adopted in this study to address the research objectives. The methods include literature review, document analysis, case study, interviews, system dynamics, and agent-based modelling, while the tools used for data collection and analysis include automated data collection technologies and social network analysis.

Chapter 4 shows empirical evidence and critique of the SCM for PBP in Hong Kong. Advanced technologies are adopted to reveal the real situation of the supply chain, providing in-depth understandings of the status and problems of SCM for PBP.

Chapter 5 develops a SCR network of PBP using social network analysis. SCR and related stakeholders together with dynamic risk interactions are considered in the chapter to tackle the limitations of traditional static risk analysis. Network and node/link measures are conducted to compute critical indicators of the network, including density, cohesion, nodal degree, betweenness centrality, status centrality, brokerage, and ego size, which could reflect the complexity of the supply chain network and identify critical SCR and their links.

Chapter 6 develops a model to evaluate the impacts of the SCR on the inventory, schedule and quality performance of PBP in Hong Kong.

Chapter 7 provides a summary of the research findings of the study. The theoretical and practical contributions are explained. The limitations and future research directions are also identified.

1.5 Chapter summary

This chapter briefly introduces essential information of the study, including research background, aim and objectives, research design and structure of the thesis.

Chapter 2 Literature Review

2.1 Introduction

Having a better understanding of existing knowledge and practices in SCM for PBP in both developed and developing countries is necessary before devising and implementing any measures to improve the performance of supply chains. Among the plethora of related studies, a systematic review that summarizes research on SCM for PBP is conspicuous by its absence. This chapter addresses that omission by providing a critical review of SCM for PBP research to map the knowledge framework of existing literature, identify major knowledge gaps, and provide suggestions for future research and practices. A careful review of journal articles in this field published from 2000 to 2018 is conducted. A total of six focus topics are identified, including stakeholder relationships, supply chain structure, mass customization, benefits, challenges, and improvement approaches.

2.2 Concepts of prefabrication

2.2.1 Various terms about prefabrication

Various terms related to prefabrication have been proposed in the literature with different scope and characteristics.

Tatum et al. (1987), for example, propose three terms, including prefabrication, pre-assembly, module in a report for the Construction Industry Institute (CII) of the USA, which are defined as follows, revealing the different industrialization levels by the terms.

‘Prefabrication is a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of the final installation.’

‘Pre-assembly is a process by which various materials, prefabricated components, and/or equipment are joined together at a remote location for subsequent installation as a sub-unit. It is generally focused on a system.’

‘Module is a major section of a plant resulting from a series of remote assembly operations and may include portions of many systems; usually the largest transportable unit or component of a facility.’

GROÁK et al.’s (1997) report for the Construction Industry Research and Information Association (CIRIA) defines pre-assembly as *‘For a given piece of work, the organization and completion of a substantial proportion of its final assembly work before installation in its final position’* with many forms of sub-assembly, taking place on or off-site, and often involving standardization.

Gibb (1999) uses the term “off-site fabrication” to cover both prefabrication and pre-assembly as mentioned in the CII and CIRIA reports and defines it as *‘a process which incorporates prefabrication and pre-assembly. The process involves the design and manufacture of units or modules, usually remote from the work site, and their installation to form the permanent works at the work site.’*

In addition, Gibb and Pendlebury (2006) classify off-site production into the following four levels: (1) Component and subassembly (i.e., elements always made in factory and never considered for on-site production, e.g., lintels); (2) Nonvolumetric preassembly (i.e., preassembled units that do not enclose usable space, e.g., precast concrete wall panels); (3) Volumetric preassembly (i.e., preassembled units that enclose usable space and are typically fully factory finished internally but do not form the building structure, e.g., bathroom pods); and (4) Modular building (i.e., preassembled modules that together form the whole building, e.g., hotel modules).

Richard (2010) proposes the term "industrialized building system" and defines it as *'a set of coordinated parts and rules where the same details / methods are re-used for a large number of different buildings located on different sites and meeting different programs.'* Industrialization is "product-oriented" and the product will generally be an industrialized building system.

The various terms reveal different natures of prefabrication which describe the multi-dimensional and diverse aspects of its development and strategies that have been explored throughout its evolution (Smith and Quale 2017). Also, as Gibb (1999) points out, in its fullest sense, off-site fabrication requires a project strategy that will change the orientation of the project process from construction to manufacture and installation. Those statements indicate that prefabrication is first a strategic decision before being a technological one even if there is a continuous interaction between strategy and technology.

The different degrees of industrialization have generated various physical sizes and volumetric or non-volumetric shapes at the scale of components, systems, and entire buildings (Smith and Quale 2017), resulting in different impacts on the supply chains, and the higher the industrialization level, the lower the supply chain risks. For example, as the first level of industrialization (Richard 2005), prefabrication refers to the components / sub-systems that are produced before and elsewhere i.e. off-site whatever the scale of the project. The supply chain risks will then be less predictable and greater for buildings using small and diverse components than for those built with larger and the same components. Industrialized construction is a strategy implemented by a generic organization grouping most of the participants to achieve a continuity of the production, and the purpose is to reach a high volume and therefore amortize the investment in processes capable of simplifying the production and reducing the costs at the same time (Richard 2005). The supply chain is a fundamental part of the strategy and will be tightly controlled over the whole sequence of operations. Building Systems are set of parts & processes where the details are standardized in order to reduce the number of components while being designed to allow for combinability, thereby generating variations and individualization (Richard 2010). As the number of components is reduced and as they are massively produced, the task of adjusting the supply chain is reduced accordingly and will be undertaken at the very outset due to the large economic issues involved.

2.2.2 Definition in this study

Although the abovementioned terms about prefabrication are different in scope, they have similar attributes about the technology implementation process. This study considers four attributes of prefabrication when limiting the research scope, including (1) manufacturing, (2) undertaken in the factory environment, (3) non-volumetric and volumetric pre-assemblies are manufactured as precast elements, such as floors, slabs, facades, staircases, beams and bathrooms, and (4) transporting precast components to projects site and installing them to form an entire building. As a result, prefabrication is defined as manufacturing precast elements in the factory and then transporting and installing them to form an entire building at a construction site.

According to Richard (2010), a building system is usually composed of six major sub-systems: structure, envelope, partitions, services, equipment and finishes, whereas the structural sub-system will normally play a transcendental role. In the specific context of Hong Kong, most precast concrete panels systems presently used by the Housing Authority are not generating completely finished buildings since the mechanical services, the installation of kitchen and bathroom fixtures, and the finishes need to be completed in situ with the conventional way.

2.3 Overview

The concept of SCM was initially used in the world-renowned Toyota production system as part of just-in-time (JIT) operation, which made a significant contribution to the overall development of manufacturing (Krafcik 1988). It is therefore suggested that those responsible for the process of prefabrication could learn from the advanced management experience of car manufacturers (Gann 1996).

As a result of efficient information sharing and the strong commitment of stakeholders, the building industry has already benefited from the significant merits of SCM including improved relationships between partners and enhanced integration of the construction process, (Emuze and Julian Smallwood 2014). Supply chain partnering and better relationships with suppliers are considered to be crucial elements for house builders to promote the application of prefabrication (Pan et al. 2008). House builders are therefore suggested to align product design in the early stages of the supply chain for the purpose of fully realizing the benefits of prefabrication (Pan et al. 2012).

Figure 2.1 illustrates the differences between supply chains of prefabrication and traditional cast-in-situ construction. As the figure shows, the prefabrication supply chain is much more complex than that of conventional construction due to additional flows and activities. This complexity leads to difficulties in prefabricated building projects regarding organization, planning, monitoring, and coordination. Therefore, a prefabrication supply chain is more sensitive to variations than a traditional construction supply chain.

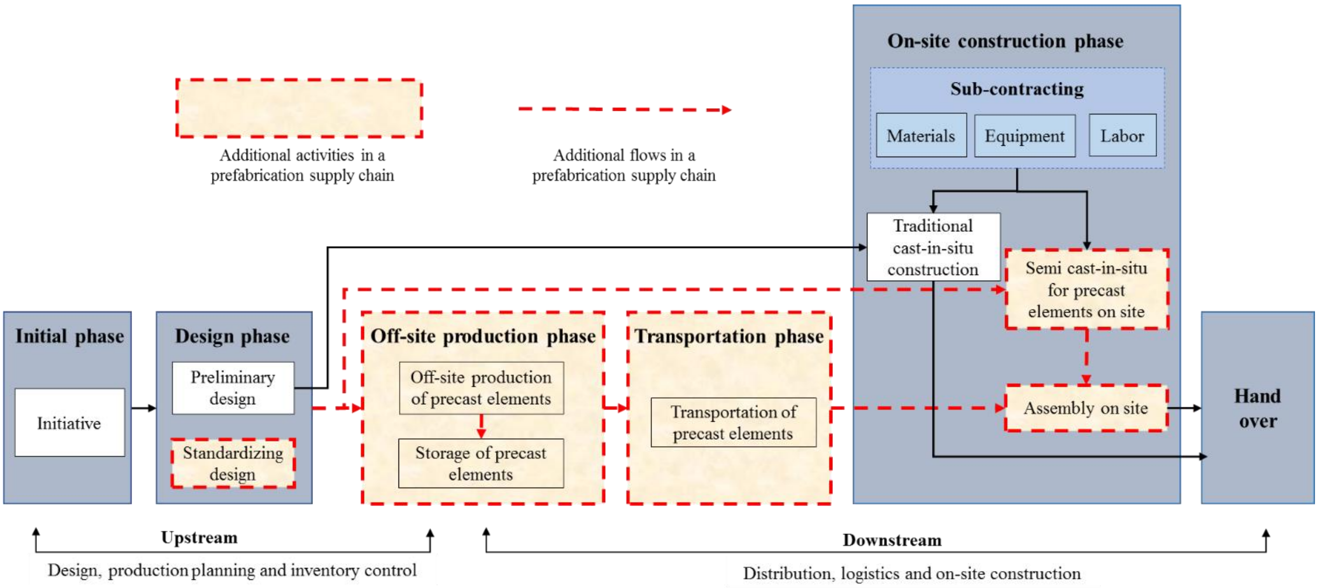


Figure 2.1 Comparison between prefabrication and traditional construction supply chains

2.4 Selection of reviewed papers

The present study collected SCM for PBP-related articles from three world-renowned indexed databases: Web of Science, Scopus, and Science Direct. The terms "prefabrication," "prefabricated construction," "prefabricated building," "precast concrete," "off-site construction," "modular building," "modular construction," "industrialized housing," "industrialized building," "housing industrialization," "building industrialization," "prefabricated housing," "manufactured housing," "manufactured building," "manufactured construction," "modular housing," "industrialized construction," "preassembly," "pre-assembly," and "prework" were used under title/abstract/keywords with a time span of 2000 to 2018 to identify prefabrication-related journal papers. The terms "supply chain," "logistics," "supply network," "supplier," and "supply" which reflect the characteristics of supply chain research, are then used to limit the search scope into SCM for PBP. This step generates approximately 200 results. Three steps are further taken to narrow down the list of the articles. First, the titles and abstracts of the collected papers are scanned one by one to filter those beyond the building industry (e.g. papers in the automotive, medical, or energy fields). Second, the full texts of the papers are carefully scrutinized to further omit those that are beyond the research scope (e.g. papers focusing on only one stage or single stakeholders without considering interactions between upstream and downstream supply chains), resulting in 66 papers remained for review. Third, a cross-referencing examination is conducted to browse the references cited by the selected papers. Then the titles, abstracts and full texts of potentially associated papers are scanned one by one, generating additional 9 results for further analysis. Therefore, a total of 75 papers are finally selected for an in-depth analysis since they match the scope of the paper. **Figure 2.2** shows the searching steps used for identifying related papers for the review. By implementing a careful searching process with the most frequently used terms in the literature and rigorous selection criteria of related articles, this chapter is able to provide a comprehensive review of SCM for PBP studies.

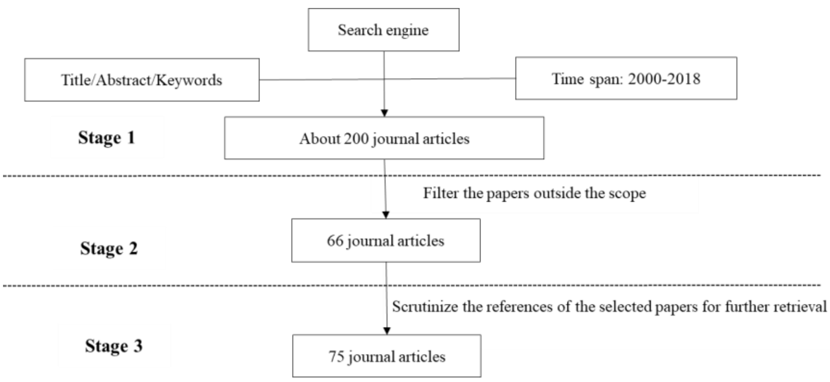


Figure 2.2 Searching steps

2.5 Common research themes on SCM for PBP

It is necessary to classify the reviewed papers into groups before doing detailed analysis. However, a common literature categorization method does not exist, although there is a large number of reviews to date. A good option to classify literature is to divide them into *what*, *why*, *how* and other aspects. For example, Zhang's (2015) work divides green real estate research into coverage and definition (what), measures (how), quantification of cost and benefit (why), and impacts (results). This method is proved effective for literature classification because it could help scholars easily identify critical research themes and clearly reflect the research main lines, ensure comprehensiveness of the categories since the *what*, *why*, and *how* and other aspects cover the major attributes and constitute the structure of a topic, and guarantee mutual exclusivity of the research themes due to their completely different natures. On this basis, the current study categorizes the reviewed literature into six research themes which are accordingly in line with six focus questions: (1) stakeholder relationships (what's the essence that should be managed in the supply chains of prefabricated buildings?), (2) supply chain structure (how could the supply chains of prefabricated buildings be managed?), (3) mass customization (what's the result of successful SCM for PBP?), (4) benefits (what benefits will be achieved by effective SCM for PBP?), (5) challenges (what challenges will be encountered in implementing SCM for PBP?), (6) promotional approaches (what measures could be conducted to tackle the problems involved and improve the performance of the supply chains of prefabricated buildings).

The common themes that provide answers to the research questions form a framework

(**Figure 2.3**) and are analyzed and synthesized as follows.

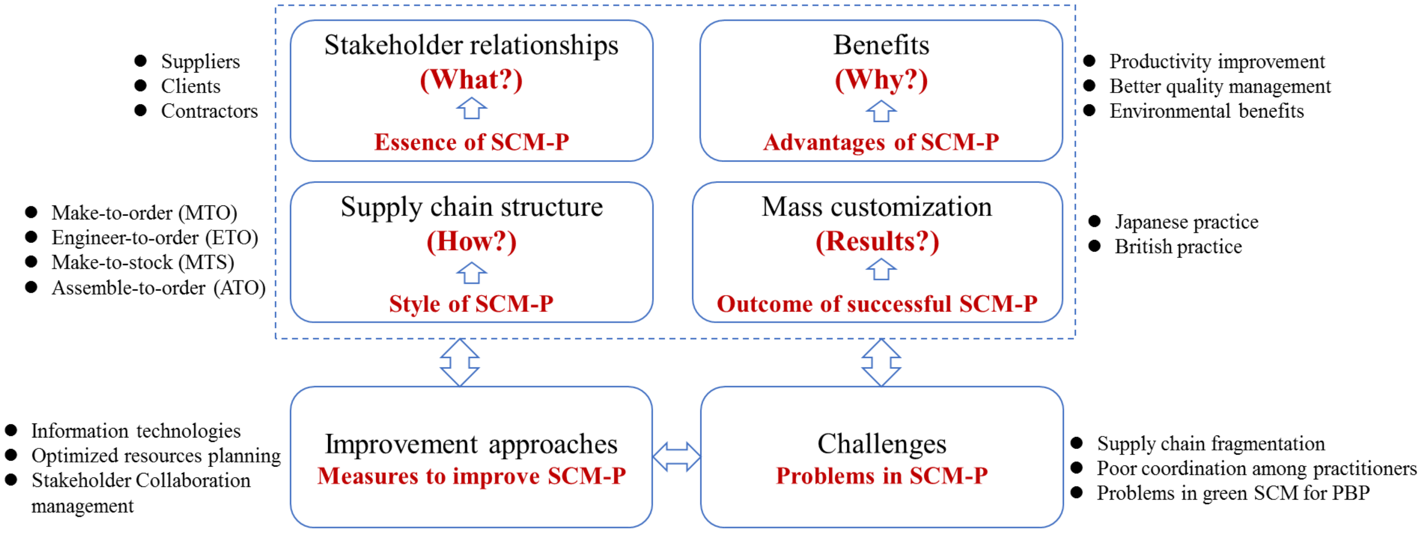


Figure 2.3 Review framework

2.5.2 Stakeholder relationships

Stakeholder relationships represent the essence of SCM for PBP, as indicated by Christopher (2005) who views SCM as the management process of the relationships between different customers and suppliers to deliver improved value at a lower cost, and Xue et al. (2007) who define a construction supply chain as a network of multiple organizations and relationships connected by information flow, materials, services or products flow, and fund flow between the stakeholders. Poor stakeholder relationships are likely to cause inferior results, such as cost overruns, time delays, and quality defects (Meng 2012). Therefore, a prefabrication supply chain should be controlled as a whole to coordinate entities and information to deliver satisfactory products to the client (Pero et al. 2015).

The relationships between major stakeholders are widely discussed in SCM for PBP research and the focus is found to be on the suppliers, clients, and contractors. Their relationships exist in different tiers within a particular supply chain (Meng et al. 2011). The manufacturer, specialist contractors, and material, equipment, and labor suppliers play the role of suppliers by providing precast components, resources, and services to the prefabrication supply chain; the main contractor is a coordinator who links the upstream client and the downstream suppliers; and the client is the end customer who provides financial investment for prefabricated building projects.

Suppliers

Supplier relationships are the most extensively analyzed relationships in the literature, which is attributed to their critical input into the supply chain, particularly in prefabrication where the capability requirements of suppliers are extremely high. Level of closeness and length of relationships are two indicators commonly used for assessing supplier relationships in the SCM for PBP research. Many studies suggest building supplier relationships with different levels of closeness based on the asset specificity of purchased items. Special solutions (e.g. electrical installations) are of high value with scarce supply, so close relationships with their suppliers should therefore be established, whereas suppliers who provide standardized parts mainly focus on logistics, thus requiring a looser supplier relationships in most cases (Bildsten 2014; Hofman et al. 2009). The monopolistic situation in the United Kingdom confirms the above conclusion, with close collaboration between an exclusive steel frame supplier and module manufacturers being observed (Doran and Giannakis 2011). Regarding the relationship duration, long-term relationships are widely advocated regardless of the attributes of the procured items considering its significance in ensuring supply stability and quality (e.g. Oral et al., 2003). More benefits are reflected in a study from Sweden, including improved knowledge sharing, joint decision making with specialist suppliers, and stable supply of standardized items (Bildsten 2014) as a consequence of long-term interaction with suppliers.

Despite the advantages of long-term collaboration with suppliers, short-term supplier relationships are currently the norm in both developed and developing countries, indicating the fragmentation of the entire industry (Pheng and Chuan 2001a; Zhai et al. 2014). In Sweden, such one-off type of procurement is viewed as impediment to information transactions about both time and quality when supplying uniquely designed joinery products (Forsman et al. 2012).

In view of suppliers' critical role in the supply chain operation, players who can provide advice about the best practices and procedures as well as product development for a specific market, are in high demand (Gibb and Isack 2003). The literature therefore proposes criteria to select proper suppliers (e.g. Safa et al. 2014)， makes efforts to improve supplier performance (e.g. Jeong et al. 2013; Zhai et al. 2016), and balances costs and supply capabilities to support optimal supply decision making (Arashpour et al. 2017b; Han et al. 2017).

Clients

Due to the client-oriented characteristic of the building industry (Akintoye and Main 2007), clients play the most important role in realizing supply chain integration in the building industry (Briscoe et al. 2004). Since it is clients' increasingly sophisticated demand that drives the building industry to adopt new technologies, quick responses to their requirements is considered important (Doran and Giannakis 2011). The client is expected to implicitly trust the selected supplier due to the limited options of alternative suppliers (Blismas et al., 2005) and the long lead time of prefabrication (Pan et al. 2007). Also, clients believe that suppliers should work with developers, contractors, and designers as early as possible to guarantee the integration of appropriate prefabrication techniques into the building design (Goodier and Gibb 2007). The necessity of high integration between clients and suppliers is confirmed by Doran and Giannakis (2011), since suppliers have to overcome the dimensional limitations related to architectural and transportation issues for the purpose of satisfying clients' increasing need for bespoke modular solutions.

Contractors

Compared with supplier and client relationships, contractors are rarely discussed in SCM for PBP research. This situation is different from traditional construction in which contractor relationships are the focus of SCM (Fernie and Thorpe 2007) while suppliers are largely ignored. Nevertheless, client-contractor relationships remain crucial because they are concerned with on-site productivity (Pheng and Chuan 2001a). Therefore, the contractor is suggested to closely and openly interact with the client to improve the efficiency of SCM for PBP through diminishing variations at the assembly stage (Doran and Giannakis 2011). Involving contractors in the design stage is also advocated in order to enhance the utilization of prefabrication in the early supply chain stage, which includes concreting, plastering, and form working (Tam et al. 2007).

In summary, diverse relationships among stakeholders make prefabrication supply chains complex. The literature explores stakeholder relationships and focuses on suppliers, clients, and contractors. Different closeness levels with suppliers are recommended according to the nature of the purchased items, and long-term connections with suppliers are advocated even though short-term relationships are currently the norm in the industry. Considering the significant role of suppliers, different methods are proposed to select suppliers, improve supplier performance, and support optimal supply decision making. Due to the characteristics of the industry, clients are of great importance in integrating the prefabrication supply chain and high integration between clients and suppliers is recommended to fully achieve customers' requirements. Even though contractors are rarely mentioned in SCM for PBP research, their close interaction with clients remains important in reducing variations at the assembly stage. In addition, contractors are suggested to enter the early design phase for better involvement of prefabrication techniques in the supply chain.

2.5.3 Supply chain structure

Supply chain structure refers to the way of managing supply chains and describes the diverse range of supply chain operations by showing how different parts of the supply chain interacts with customer orders (Gosling and Naim 2009). Supply chain structures are classified as: make-to-order (MTO), engineer-to-order (ETO), make-to-stock (MTS), and assemble-to-order (ATO) (Olhager 2003). These classifications are distinguished by the decoupling point at which a particular order enters the material flow of the chain, reflecting the effects of a customer order on production. Therefore, supply chain structures indicate different strategies used by different firms to develop products with different levels of customization. MTO and ETO are the major structures adopted in prefabrication. **Figure 2.4** illustrates the decoupling points of different supply chain structures. The "transportation" point is located in the last stage of the supply chain strategies rather than before the assembly phase. This is because the classical supply chain strategies are originally developed from the manufacturing industry (i.e. car production) where all the components are assembled in the factory and then finally transported for the end customers. Although the sequence of the supply chain stages are different from those of the construction industry, the strategies still widely apply to the housebuilding sector (e.g. Barlow et al. 2003).

Supply chain structures	Design	Production	Assembly	Transportation
Make-to-stock				DP
Assemble-to-order			DP	
Make-to-order		DP		
Engineer-to-order	DP			

Figure 2.4 Decoupling points (DP) of different supply chain structures (adapted from (Olhager 2003))

Make-to-order (MTO)

MTO refers to the supply chain in which a fully detailed design can be configured to suit a customer's particular requirements, and the material flow does not start until an order is received and validated (Winch 2003). The decoupling point of MTO is in the fabrication stage. MTO is a good option for suppliers to reduce potential risks of high inventory cost and product depreciation resulting from excessive stock due to inaccurate demand prediction of a particular design (Cheng et al. 2010b). Therefore, configuring or customizing products upon the arrival of a customer order is preferred by suppliers to provide standard or configurable products, such as happens with Sekisui House, the largest factory-based housing provider in Japan (Barlow et al., 2003). In addition, various production systems use MTO to support bespoke precast concrete production (Benjaoran and Dawood 2006), the logistics strategy in delivering different types of components (Court et al. 2009), and diminishment of waste from inventory (Wu and Low 2014).

However, the MTO structure in prefabrication has some problems that concur with those in the manufacturing industry where most controllability issues and changes in product specifications are caused by poor interaction among different organizations (Vrijhoef and Koskela 2000). Such issues reflect the weakness of the obsolete management principles, which should be addressed by developing control methods provided by the SCM for PBP theory.

Engineer-to-order (ETO)

The literature on the definition of ETO supply chains emphasizes their capability in offering customized products, for which totally new designs are developed (Gosling and Naim 2009). An ETO component is a prefabricated part of a building, whose form and function must be uniquely designed to suit its environment before it can be fabricated (Ergen et al. 2007a). The decoupling point of ETO is located at the design phase, therefore, ETO components are highly customized with long lead time (Song et al. 2005).

According to the point where the client enters the production information flow, Winch (2003) classifies ETO into concept-to-order (CTO) and design-to-order (DTO) modes, which reflect the two main contractual forms between client and suppliers: design-build and design-bid-build, respectively (Segerstedt and Olofsson 2010). CTO has stronger risk management capability than DTO because significant risks can be eliminated through detailed design development, and major clients in procurement therefore prefer the CTO mode. The DTO mode, on the other hand, is also considered appropriate for most buildings if supply turn-key service is supplied to customers by integrated teams (Winch 2003). A combination of CTO and DTO are employed in Sweden to supply joinery products (Forsman et al. 2012).

Johnsson's (2013) classification of ETO is more detailed, which includes DTO, adapt-to-order (ATO[1], differentiated from ATO which means assemble-to-order), and engineer-to-stock (ETS). ETS is a fully pre-engineered strategy that is similar to CTO. ATO[1] is between DTO and ETS in terms of the pre-engineering extent. Johnsson (2013) explored product development platforms to operationalize the pre-engineering strategy and found that the companies working with ETO could benefit from the platforms to increase their output and lower the costs.

High customization of ETO components produces a wealth of information about products and processes, such as installation instructions, the status, and the location of each component, which needs to be recorded individually and exchanged among stakeholders through frequent communication. Ergen et al. (2007a) pointed out that managing ETO components is a difficult task due to the complex information flow; consequently, many studies have focused on information management of ETO components (e.g. Ergen and Akinci 2008; Forsman et al. 2012; Pero et al. 2015). In addition, scholars also pay great efforts to improve collaborative planning and increase process transparency and flexibility based on project progress for planning and controlling design in ETO prefabrication systems (Wesz et al. 2018).

Make-to-stock (MTS)

In an MTS supply chain, production is initiated before an order is received, and items enter the finished goods inventory before they are sold to customers (Zhang et al. 2013). The decoupling point of MTS is at the shipment transportation phase. Therefore, MTS firms conduct production according to historical forecasts, which are likely to result in excessive inventory and high inventory costs (Lambert and Cooper 2000). The MTS mode is suitable for mass production where standardized products are required for great economies of scale and minimal lead time. In the United Kingdom, the MTS system is combined with MTO to design the component flows of a project, which brings in smooth supply of components for the final assembly without the need for a large central part warehouse (Court et al. 2009).

Assemble-to-order (ATO)

The ATO strategy is popular among manufacturing firms that seek responsiveness and cost efficiency (Benjaafar and ElHafsi 2006). The decoupling point of ATO is in the assembly phase. The ATO mode is of value when the supply lead time of components is long or when the supply is capacitated. However, managing the ATO system is difficult due to the correlation of demand for different components, different lead time of various components, and the availability of multiple components (Benjaafar and ElHafsi 2006). The ATO supply chain is used by Sekisui Heim which annually supplies over 20,000 houses in Japan, contributing significantly to Japan's classic notion of mass customized housing (Barlow et al. 2003).

In summary, different supply chain structures are utilized in prefabrication, which are distinguished by the decoupling point to reflect the specific stage at which the order enters the material flow. The decoupling points of ETO, MTO, ATO, and MTS are located in the design, production, assembly, and shipment transportation stages, respectively, indicating decreasing levels of customization. ETO and MTO are mainly adopted for SCM for PBP. MTO is a popular strategy for producing standardized components, which benefits suppliers by reducing inventory cost and product depreciation and enhancing the efficiency of the prefabrication supply chain. ETO can be classified into several sub-strategies and is widely used for customizing housing, which necessitates a high level of information exchange among stakeholders. Although limited research has focused on MTS, it can be combined with MTO to supply components for achieving economies of scale. Last but not least, ATO is a useful strategy for increasing the responsiveness and cost efficiency of prefabrication supply chains.

2.5.4 Mass customization

Mass customization is a competitive strategy which gives customers the freedom to define product specifications in order to provide a large variety of products and services (Pero et al. 2015). Effective information sharing and supply chain maturity are required for rapidly transforming customers' specifications into material requirements (Gann

1996; Yashiro 2014). Market factor is another key element to achieve efficient mass customization (Broekhuizen and Alsem 2002). Experience in the manufacturing industry (e.g. automobile, clothing, and computer), in which mass customization has been realized through efficient SCM and a large market demand (Fogliatto et al. 2012), shows that mass customization conversely facilitates supply chain integration by closely involving customers and suppliers (Pero et al. 2015). Given house builders' competitiveness and customers' ever-higher requirements for housing, efficient mass customization in the building industry is becoming increasingly important. Therefore, the ultimate result of successful SCM for PBP is to achieve mass customization, as confirmed by the experience of Japan with its mass customization of housing.

Industrialized housing can be mass-customized by mass-manufacturing housing components, as opposed to entire housing models, which can be combined to enable clients to customize houses individually (Noguchi 2003). Previous studies have explored mass customization of prefabricated buildings in developed countries, such as Japan, the United Kingdom, the United States, Finland, Canada, and Denmark. However, a careful review of the collected papers indicates that studies focusing on SCM for PBP are largely restricted to Japanese and British practices, while other research on mass customization of prefabricated buildings mainly concerns customization evolution, achievement approaches, and design issues. Studies that explore the customization evolution, mainly analyze the development pathways of Japan (e.g. Linner and Bock 2013; Yashiro 2014). From an achievement perspective, various product platforms (e.g. Bonev et al. 2015; Said et al. 2017), advanced configuration systems (Friedman et al. 2013), and different modularization methods (e.g. Kudsk et al. 2013b; 2013a) have been proposed to facilitate the success of mass customization. Design issues for mass customization of prefabricated buildings also feature prominently in the literature, including the use of vernacular design languages (Knight and Sass 2010) and axiomatic design (Marchesi and Matt 2017). Given that this study focuses on SCM for PBP, only those studies that consider supply chain issues of mass customized prefabricated buildings are analyzed in detail as follows to show the customization practices in Japan and the United Kingdom.

Japanese practice

The advanced car production industry in Japan provides valuable manufacturing principles for the housing industry to adopt in the production of customized housing. Mass customization of industrialized housing began to flourish in Japan in 1970 when substantial innovations were implemented in the customer interface, the supply chain, as well as the production processes (Barlow et al., 2003). Long-term concentrated urbanization generates a sufficiently large housing market to motivate housing manufacturers to provide mass customized systems with flexible housing designs. The efficient supply chains of industrialized housing drives mass customization development in Japan; the modularity design, well-organized assembly, and process engineering are involved in the integrated system to rapidly translate customers' preferences into material requirements for customization (Roy et al. 2003).

Manufacturing capability can also satisfy market demands in terms of both volumes and types of products (Gann 1996). Customization necessitates good relationships between housing suppliers and customers, implying the need for capable design and sales teams (Barlow and Ozaki 2001). Meanwhile, customization helps increase the popularity of industrialized housing, which was indicated by the doubling of the market share of prefabricated 2*4 timber panel housing in Japan from 1980 to 1992 (Gann 1996). Referring to the successful experience of Japan, the most significant issue in gaining such popularity is to balance the use of standard components to benefit from efficient operation of production lines and flexibility in assembly to provide a variety of customized options, since a high degree of customization means elevated costs and lead times.

Various suggestions, dominated by efficient SCM for PBP, have been put forward in the literature for developing mass customized housing. They include a number of supply chain strategies for Japanese house builders to deliver housing with varying degrees of customization and innovations in the production process in order to provide diverse choices in design and specifications, and to deliver high-quality housing on time (Barlow and Ozaki 2005).

British practice

The United Kingdom is attempting to promote the mass customization of industrialized housing by learning from the successful practice of Japan. However, British house builders hold a relatively negative view of customizing housing compared with Japanese house builders, which can be attributed to the different land development processes in these two countries. The United Kingdom’s house builders could gain expected profits from land development (Barlow et al., 2003), whereas Japan’s residential sector is not involved in land development since customers have ownership of plots (Barlow and Ozaki 2005). Japanese house builders therefore have to focus their competitive strategies on SCM and construction technologies to satisfy increasing customer expectations. Also, the supply chain in the United Kingdom is not sufficiently responsive to achieve an efficient engineering process of customization. Therefore, British house builders need to establish partnerships to replace the current adversarial relationships for improving supply chain performance of projects (Roy et al. 2003).

To improve their supply chain performance, UK housing suppliers are suggested to initiate new business models and innovative supply chain strategies (Barlow et al. 2003), adopt new technologies, and shift to efficient production processes (Roy et al. 2003). Court et al. (2009), on the other hand, proposes postponement as a useful approach to delivering responsive supply chains, thereby coping with the high uncertainty of customization demand, maintaining low operational costs, and ensuring shorter lead time.

In summary, mass customization is an important strategy to satisfy the increasingly diverse requirement of customers. Japan is experienced in producing mass customized housing, which is enabled by efficient supply chains and large market demand. Mass customization in the United Kingdom is less efficient than that in Japan because the land development practice in the former is speculative. Thus, Japan's practice implies that the United Kingdom should adopt different supply chain strategies concerning various levels of customization and redevelop the production processes.

2.5.5 Benefits

The benefits of SCM in improving time usage, cost control, and quality management of projects have been proven (Briscoe and Dainty 2005). These merits indubitably apply to prefabrication, and benefits to productivity, quality, and the environment from SCM for PBP are well documented in the literature.

Productivity improvement

Various studies have emphasized the capability of effective SCM for PBP to enhance productivity. As Doran and Giannakis (2011) pointed out, the building industry is able to reproduce the productivity gains generated in the automotive industry through a high level of process integration depending on how effectively the process is managed, from which production time can be relatively reduced as evidenced by the research in Australia (Moon et al. 2015) and Turkey (Demiralp et al. 2012). On the flip side, the decreased demand for laborers also indicates higher productivity as confirmed by Court et al. (2009) who observed 35% abatement of required on-site workers after adopting a construction system designed with a postponement function.

Better quality management

Quality management remains one of the major managerial targets in the building industry. The literature points out that quality problems in prefabrication supply chains are due to poor process resources (Moon et al. 2015) or poor logistics management capability (Roy et al. 2003), whereas effective quality management necessitates reliable and timely information sharing through the supply chain to reflect quality issues (Love 2002). Therefore, various control systems are established to instantly track real-time quality data of precast components to enhance the quality of components at a full level (Yin et al. 2009) and detect potential quality problems (Ikonen et al. 2013). On the other hand, Moon et al. (2015) correlated quality problems with waste generated in processes and designed a dynamic quality control structure to coordinate the supply chain. As a result, process waste decreased from 45.5% to 6.2%, indicating a significant improvement in quality.

Environmental benefits

The effective coordination of SCM for PBP also produces environmental benefits. For example, Kim and Bae (2010) utilized a lean supply system integrated with JIT principles for rebar supply and found that the energy use and carbon emissions resulting from frequent deliveries under the old system could be offset by the high productivity of the new system; thus revealing that the new system was environmentally friendly.

Kim et al. (2013) confirmed this finding by demonstrating that the prefab-JIT rebar delivery system results in a 8.36%, 6.96%, 6.65%, and 6.65% drop in global warming gases, acidification, eutrophication, and smog formation respectively, than the traditional delivery system. Lu and Yuan's (2013) investigation of an international supply chain showed the waste generation rate in the manufacturing and cross-border transportation processes to be 2% or lower by weight.

In summary, effective SCM for PBP considerably improves supply chain performance and helps to protect the environment. Significant time savings and reduction of labor demand can be observed, indicating improved productivity of prefabrication supply chains. Utilizing accurate and real-time information sharing to monitor quality issues considerably enhances quality control, and environmental benefits are obtained by abating unnecessary processes.

2.5.6 Challenges

SCM for PBP is considered to be a complex task that aims to coordinate the relationships between participants involved and frequent information exchanges. The various uncertainties and complexities that originate from the interfaces of different participants or functions make prefabrication supply chains fragmented (Behera et al. 2015). These challenges posed to SCM for PBP are thoroughly analyzed in the following.

Supply chain fragmentation

Fragmentation means the supply chain works like individual parts with poor coordination between stakeholders, the limited alternatives of suppliers in the market, and low efficiency of SCM. From the literature it is apparent that fragmentation of prefabrication supply chains is a global issue. Although many developed countries and regions adopt large-scale prefabrication practices, their supply chains remain inadequate and fragmented, including the lack of suppliers and contractors in providing technology, service and management work in the United Kingdom (Blismas et al. 2005b), limited capacity to supply prefabricated products (Blismas and Wakefield 2009) and poor process uptake (Sahin et al. 2018) in Australia, long lead time and scarcity of suppliers in Sweden (Larsson et al. 2013), lack of coordination before and during construction, inadequate planning preparations, and limited logistics concern in Singapore (Hwang et al. 2018), low concurrence of process and information (Niu et al. 2017) and inaccurate data collection and transfer (Zhong et al. 2017) in Hong Kong. Prefabrication in developing economies is not as mature as that in developed countries, which causes more fragmented supply chains. For example, in China, prefabrication lacks experienced practitioners, such as clients, designers, suppliers, contractors, and consultants, and supporting technologies (Mao et al. 2014). Large-scale production systems are also non-existent in the country (Zhang et al., 2014), which indicates the insufficiency of the supply chains. Transportation is also a critical issue in China because stakeholders face uncertain site locations, complex distribution process, and other logistics problems (Zhai et al., 2014). In Malaysia, the lack of communication between multidisciplinary stakeholders (Pozin et al. 2016) and inefficient transportation, logistic and material delivery processes (Azwanie et al. 2016) reveal the fragmentation and disconnection of the prefabrication supply chains. Such fragmentation is considered as the dominant hindrance to the utilization of prefabrication in both developed (Pan et al., 2007) and developing countries (Kamar and Hamid 2011), since it increases the difficulty in coordinating the design, production, and delivery processes, thus significantly affecting the performance of SCM for PBP.

Poor coordination among practitioners

Poor coordination among practitioners, which results in limited information sharing, is another challenge faced by SCM for PBP. This situation occurs because most of the participants involved in a prefabrication supply chain only bear their own targets in mind without considering the overall benefits of the chain due to the one-off characteristics of the industry (Zhai et al., 2014). However, a high degree of trust and interaction are required for coordinating supply chains, particularly in a monopolistic market with limited alternative suppliers (Blismas et al., 2005). Therefore, a low awareness of the necessity for participants to integrate and coordinate the prefabrication supply chain is likely to reduce production efficiency and result in a series of problems.

Problems in green SCM for PBP

As green developments proliferate, green SCM has become a goal pursued by the building industry. However, problems exist at different stages that consequently affect the achievement of green SCM for PBP. Singapore has been the focus of recent research in this respect and the country's practices have been found to have a lot of limitations. For example, a large inventory, lack of sufficient care, improper staffing arrangements, and unclear identification marks are considered the most undesirable barriers at the stock management stage (Wu and Low 2014), while at the site layout and delivery management stages, large storage areas, large quantity supply base, the lack of JIT sourcing with the suppliers, and a lean workforce are the most significant non-value-adding activities (Wu and Low 2012).

Therefore, fragmentation of supply chains and poor integration of stakeholders are significant challenges for SCM for PBP, and non-value-adding activities cause difficulties to realize green supply chains.

2.5.7 Improvement approaches

Effective improvement approaches are urgently needed to tackle the challenges involved in supply chain. The need for effective interactions and coordination between partners involved is frequently highlighted for developing useful measures to improve SCM for PBP (e.g. Sandberg and Bildsten 2011). Detailed planning of factory and on-site activities can also be enabled by coordinating supply chain processes and material resources (Čuš-Babič et al. 2014). The literature proposes various approaches to enhancing SCM for PBP through the use of information technology, optimized resources planning, and cooperative processes management, as described in the following sections.

Information technologies

Information technologies are the most frequently mentioned approaches in the literature to improving SCM for PBP since frequent information exchange is required to keep all the parties updated with information about the project status and to make the supply chain work as a coordinated entity to detect potential problems (Ergen and Akinci 2008). The information technologies that are discussed in the literature related to SCM for PBP include radio frequency identification (RFID) technology, building information modelling (BIM), and cloud computing.

RFID has been widely adopted in prefabrication to provide targeted quality management data, bidirectional information flow, and accurate logistics data (Ikonen et al. 2013), as well as locating precast components in the storage area (Ergen et al. 2007b). Based on RFID, different SCM for PBP systems can be set up to support quality control and inventory and transportation management, thereby achieving remarkable time savings, cost and quality benefits, and better process control (Yin et al. 2009). Wang et al.'s (2007) research quantifies the benefits of a RFID-based dynamic system in tracing and monitoring precast components by updating the information in the web portal, which is proven to reduce data entry mistakes by 12% and save 16% of time with 8% of cost abatement.

BIM is primarily recommended for information management and has been acknowledged as an adequate context for information mapping to more effectively monitor progress, and carefully plan and manage material flows (Čuš-Babič et al. 2014). BIM is also confirmed to be a major determinant for facilitating coordination between on-site and off-site working packages (Said 2016).

Cloud computing is another valuable technology which delivers proper and up-to-date information via the Internet and a remote central server. BIM server could be integrated with cloud computing to enhance collaboration in supply chains (Abedi et al. 2016). Abedi et al. (2014) adopt cloud computing to effectively mitigate poor planning and scheduling, production lead time, and poor on-site coordination in a Malaysian prefabrication supply chain, while Xu et al. (2018) develop a cloud asset-enabled IoT platform to enhance lean prefabrication in Hong Kong.

Optimized resources planning

Optimized resources planning for supply chains means reasonable arrangements of resources and sound coordination between the various stakeholders to tackle the problems in supply chain operation, such as poor consistency between the upstream component production and the downstream on-site installation. Enterprise resource planning (ERP), which is a comprehensive advanced planning system that involves various information processing abilities, is proposed for optimized resources planning in supply chains. ERP inputs all the data into one database to achieve information transparency and velocity through the elimination of information distortion and delay (Akkermans et al. 2003). An investigation of ERP use in small-size and medium-size companies in Sweden demonstrated that ERP not only can match the needs of industrialized timber frame housing, but also enhance the re-engineering of enterprises to improve the efficiency of internal and external supply chains (Bergström and Stehn 2005a). These firms obtain operational and managerial benefits, including improved material management and better information processing capability, but reflect limited strategic benefits of core business due to the high requirement of ERP for information technologies (Bergström and Stehn 2005b). Modelling methods are widely used in the literature to optimize production planning and resource allocation across the supply chains, from which improved production schedule (Li et al. 2010; Wang and Hu 2017) and increased corporate profits (Chen et al. 2017) are achieved.

Stakeholder Collaboration management

Collaboration management, which relies on effective cooperation and interactions between stakeholders of construction projects, is recognized as a solution to tackle the increasing uncertainty and complexity of supply chains (Saad et al. 2002). A prefabrication supply chain consists of multiple processes and organizations, different measures are therefore put forward in the literature to enhance stakeholder collaboration. For example, Forsman et al. (2012) identified long-term procurement relations and efficient information-sharing as the major domains of innovation for increasing the efficiency of ETO joinery-products supply. Blismas et al. (2010) pointed out that cooperative innovation which combines process and product innovation management plays the critical role of maintaining long-term sustainability for prefabricated housing in Australia. Feng et al. (2017) establish a cooperation mechanism between stakeholders to indicate the necessity of governmental punishment and incentive schemes for the purpose of sustaining solid partnership between stakeholders.

In summary, effective approaches have been proposed in the literature to enhance SCM for PBP. Various information technologies, such as RFID, BIM, and cloud computing, are recommended to streamline the information flow along the supply chains to shorten time, reduce mistakes, improve quality, and enhance project planning and coordination. Optimized resources planning is advocated for reasonably arranging and optimizing resources throughout the supply chains. Stakeholder collaboration management measures are also proposed to improve SCM for PBP.

2.6 Discussions and suggestions for future research

A critical review of the SCM for PBP research shows that existing studies are largely restricted to qualitative analysis with only a few papers providing quantitative research on supply chain issues, and there is a lack of systematic studies that demonstrate the status of an entire supply chain. The reason for this fragmentation is because SCM for PBP research is complex, time-consuming, and data-intensive due to the multiple stages, long project duration, and the large number of stakeholders involved. The research gaps are identified and future research directions are suggested for better industry development (see **Figure 2.5**).

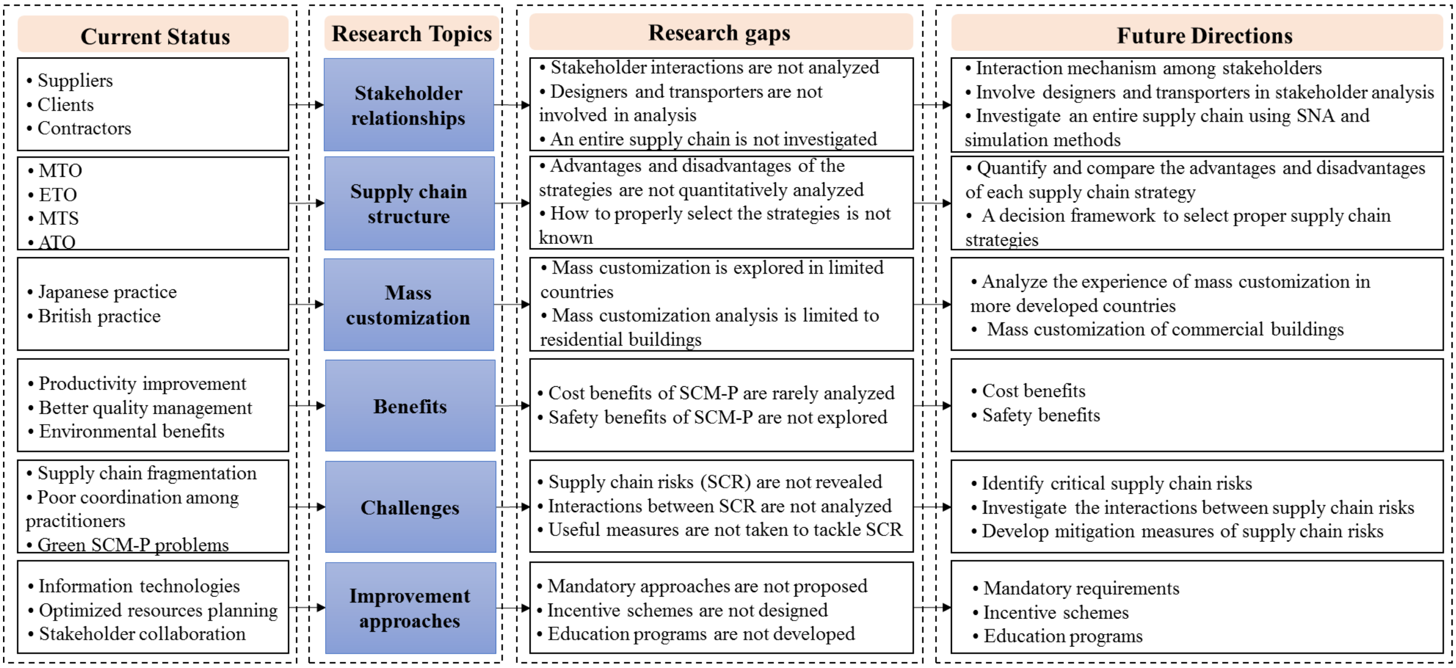


Figure 2.5 Framework for future directions

2.6.1 Comprehensive supply chain analysis

Although the literature has investigated stakeholder relationships focusing on suppliers, clients, and contractors, it is not enough to reflect the real relationship networks of prefabrication supply chains. The following research gaps have been identified. First, current studies only reflect the importance and situation of the abovementioned relationships, while the interaction among partners is rarely considered. However, the fact is that stakeholders do not act independently, but form a social network through formal (e.g. contract terms) or informal (e.g. trusts among stakeholders) interactions.

Therefore, this gap needs to be filled by exploring the interaction mechanism among stakeholders, from which proper coordination measures can be developed to enhance the mutual interaction among participants. Second, designers and transporters that are located upstream are ignored in existing analysis, which should be addressed in future studies. This is because prefabrication is moving value-adding activities to the upstream to indicate the increasing value of the design stage, while component damage is most likely to occur in the transportation phase to potentially influence the on-site schedule and increase total cost. Therefore, designers and transporters should also be included in stakeholder analysis to identify and mitigate potential problems resulting from them. Third, existing research fails to analyze the network of an entire prefabrication supply chain, with only a few stakeholders in the upstream or the downstream being investigated. However, a supply chain network comprises all stakeholders whose attributes and interactions work together to influence the performance of the supply chain dynamically. Therefore, it is of value to build a comprehensive network involving all the participants to reflect the status of a whole supply chain, from which the root cause of potential problems can be identified. This can be assisted with social network analysis (SNA) and simulation methods considering the dynamic features and complexity of prefabrication supply chains.

2.6.2 Selection of supply chain strategies

MTO, ETO, MTS, and ATO are the major supply chain structures that indicate strategies of different firms with various sizes and market targets. Existing research on supply chain structure is restricted to descriptive and qualitative analysis of employed strategies, while quantitative and comparative studies are limited. As supply chain strategies are the critical element that influences the business development of companies, it is very important for firms to select the most suitable strategy. Therefore, future research needs to investigate supply chains using different strategies to quantify their advantages and disadvantages, which can provide direct implications for practitioners when comparing these modes. A decision framework to select proper supply chain strategies is also in need of development for the purpose of assisting practitioners with decision making.

2.6.3 Mass customization analysis in a wider scope

Existing research on mass customization of prefabricated buildings is limited to the practices of Japan and the United Kingdom, although many other countries also have mature experience in developing mass customizations. Recent years have observed increasing demand for customized housing. In China, for example, many developers are pursuing mass customization to satisfy customers' sophisticated demands. However, mass customization requires a highly mature supply chain, which is still relatively difficult to achieve in developing countries. Learning from the valuable experience of other countries is necessary before being able to quickly transform materials into customers' requirements. Therefore, analysis of mass customization practices in experienced countries needs to be further developed. In addition, while current studies on mass customization are largely restricted to residential projects, seldom-explored commercial buildings have even more unique appearances, indicating potential demand for customizing commercial buildings. Thus, the drivers of and barriers to mass-customized commercial buildings should be more thoroughly investigated to identify implications for future studies.

2.6.4 Cost and safety benefits

The benefits of SCM for PBP for productivity improvement, quality management, and environment protection are well documented in the literature; while the cost and safety benefits from closely integrated and coordinated supply chains are rarely discussed. Although Fang and Ng (2011) developed a model to lower logistics costs without affecting project schedules, and Kim et al. (2016) proposed a metric-based cost model to identify activities that require process re-engineering to reduce supply chain costs, while Demiralp et al. (2012) provided a cost-sharing approach among supply chain members, research on cost-related issues is still limited. These studies on SCM for PBP are confined to cost reductions at one stage or a few activities, and cost sharing among stakeholders, while systematic cost analysis of SCM for PBP is lacking. Cost benefits are one of the largest motivations for participants to implement SCM for PBP. Therefore, the extent to which cost can be saved by full SCM for PBP execution should be explored. Also, while the risks of injuries are claimed to be reduced by SCM for PBP, quantitative analysis of the reduction is lacking. Therefore, safety benefits can be further analyzed to convince stakeholders of potential injury abatement through the use of SCM for PBP.

2.6.5 Dynamic SCR analysis

As a consequence of various uncertainties and complexities embedded in supply chains, supply chain fragmentation and poor integration of stakeholders are determined as the main challenges to SCM for PBP. Such problems pose potential risks to hinder the efficient flow of information, materials and products among stakeholders in a supply chain, which will greatly affect project performance as a whole. Existing research, however, fails to cover supply chain risk issues. Therefore, it is necessary to bridge this gap by identifying critical supply chain risks, which do not exist individually but are interrelated and interact with each other to influence project objectives (Yang and Zou 2014a). Investigating risk interactions enables scholars and practitioners to better understand and evaluate supply chain risks, and thus needs to be conducted in future studies. Corresponding mitigation measures can be developed based on a comprehensive understanding of supply chain risks.

2.6.6 Exploration of more improvement approaches

Various approaches have been proposed based on the use of information technology, optimized resources planning, and cooperative processes management, which play an important role in supporting SCM for PBP. However, these measures, to a large extent, are implemented voluntarily based on the willingness of stakeholders. Considering that most participants involved in projects often work individually with their own benefits and disregard the integration of the entire supply chain, more mandatory and incentive measures are needed in addition to the voluntary approaches. Therefore, it is of value to design mandatory requirements and incentive schemes to stimulate the adoption of proper approaches to SCM for PBP implementation. Moreover, since most stakeholders are unaware of the significance of SCM for PBP, education programs should be provided to increase the participants' awareness of information sharing and cooperation among partners.

2.7 Chapter summary

This chapter presents a systematic review of current research in the field of SCM for PBP. There are six focus topics in the SCM for PBP domain: stakeholder relationships, supply chain structure, mass customization, benefits, challenges, and improvement approaches. Research on these issues has been largely restricted to qualitative analysis while only a few studies have used quantitative methods. Also, there is a lack of systematic studies that demonstrate the status of an entire supply chain. While the latter is worthy of research to help identify the root cause of the problems associated with SCM for PBP, it is complex, time-consuming, and data-intensive due to the multiple stages, long project duration, and the large number of stakeholders involved. SCR in PBP and associated stakeholders are also in demand for further analysis for the purpose of developing useful mitigation measures.

Chapter 3 Research Methodology

3.1 Introduction

This chapter demonstrates the scientific methodologies used in this study to achieve the research objectives in detail. The tools that are used for data collection and analysis are also presented.

3.2 Addressing Objective 1

To address Objective 1, a combination of case study, document analysis, and interviews are adopted. Advanced information technologies are used to collect a vast amount of empirical data within the supply chain of a real-life project. This is followed by document analysis that is 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 is developed to show the real-time status of the supply chain. Statistical analysis of the dataset is conducted to reveal the actual situation of the SCM for the project and identify the embedded problems. Experienced stakeholders of the case project are then interviewed to analyze the root causes of the problems. **Figure 3.1** shows the research framework to tackle Objective 1.

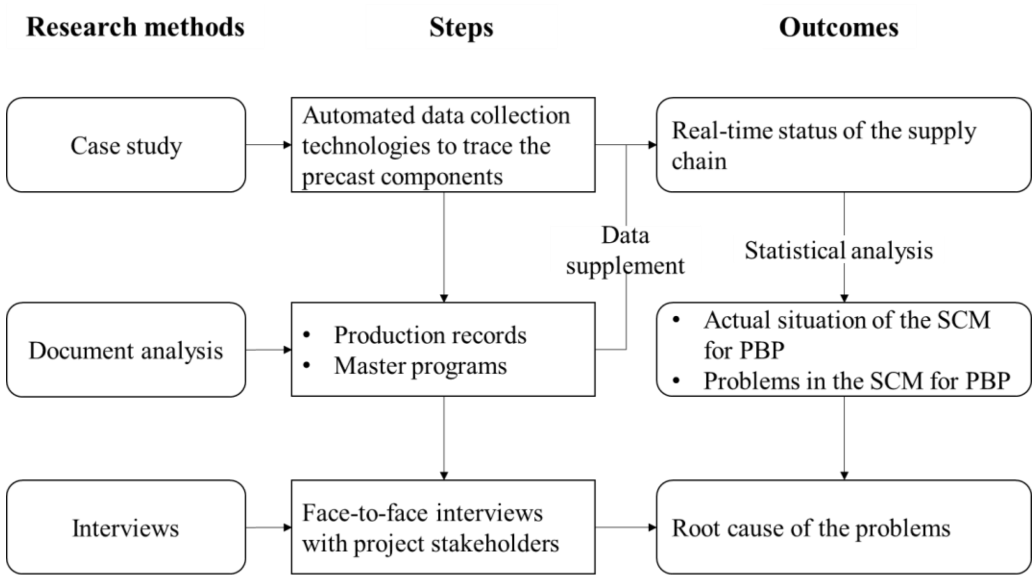


Figure 3.1 Research framework to address Objective 1

3.2.1 Case study

Case study is one of the five common research strategies in social sciences that provides a unique way to generate case-based understanding of research questions (Yin 2013). This method has been widely adopted in construction research, such as the study by Mok et al. (2017a) who explore the key challenges in major public engineering projects using a case study. In the specific context of PBP, Gibb (2001) investigate the application of standardization and preassembly by using a case study approach. 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 cases (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. Longitudinal case studies are commonly used in process analysis with the data collected by continuous collection methods, such as long-term actor shadowing or participant observation (Pettigrew 1990).

In order to guarantee theoretical generalization of the case study, a public housing project located in Tuen Mun is selected, which is considered to be representative of PBP in Hong Kong for the following reasons. First, the project is 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 PBP. 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 project ran from June 2015 to September 2017, with the aim of constructing five buildings of 34-38 stories to provide approximately 5,000 units and accommodate 14,000 people. This study conducts real-time data collection from one of the buildings which has a total of 37 floors; Floor 1-34 each has 46 façades, while the 3 top floors each has 37 façades. Therefore, a total of 1675 precast façades were traced throughout the supply chain for data analysis. The building has four wings with eleven types of precast components, including water tank, semi-precast slab, secondary beam, façade, parapet, staircase, partition wall, tie beam, and bathroom, refuse chute, and water meter cabinet, comprising 29% concrete volume of the building.

A longitudinal study is conducted to provide an in-depth analysis of the SCM for the project. This is 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 is finally collected to form a dataset of the project, which illustrates the SCM principles within the case study project.

Although it is recognized that investigating several cases would be more meaningful for revealing the true situation of SCM for PBP, information privacy in the construction industry makes it very difficult to obtain large amounts of data from more than one project. Nevertheless, the case study project recruited for this study provides valuable insights regarding the actual situation of SCM for PBP.

3.2.2 Automated data collection technologies

Automated data collection technologies are adopted to trace the status of the supply chain. An integrated system combining RFID and BIM technologies is 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. 2007b) 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. For example, Li et al. (2018b) develop an Internet of Things-enabled platform integrating BIM and RFID to collect real-time data across the assembly process, which provides decision support for managers and workers. Qi et al. (2018) also propose a framework to integrate BIM and RFID for prefabricated component management, showing satisfactory results of information capturing and sharing in prefabrication supply chains.

This study tracks the status of the precast facades using data collected by RFID, which is then automatically uploaded via gateway to the BIM system for visualization. Because of cost considerations, Housing Authority applies RFID in four types of building components, including precast facades, timber doorsets, aluminum windows, and metal gatesets, among which only facades are produced using prefabrication way while other components are non-precast elements. Tracing precast components could show the production, transportation and assembly processes of the supply chain, thereby providing valuable implications about the operation of the supply chain and potential problems involved. By contrast, tracking non-precast elements could not reveal the production process of precast components in the factory, resulting in a lack of the upstream data. Therefore, only real-time information of precast façades is collected for analysis to represent the status of the project supply chain. Precast façades are performing as structure and envelope sub-systems whereas the structure sub-system normally plays a transcendental role (Richard 2007). Also, the investigated building has up to 1675 facades, while other types of precast components (i.e. bathrooms, staircases and beams) number much less. Therefore, tracing facades would generate a more comprehensive database. However, the assembly sequence has impacts on the supply chain operation. The assembly of volumetric components (i.e. bathrooms) is more complex than that of facades. Therefore, facades often have to wait for assembly of those components, resulting in long waiting time in the construction site. Despite that, real-time data of precast facades could still provide valuable implications regarding the status of the supply chain.

Passive RFID is 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.

3.2.3 Document analysis

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

3.2.4 Interviews

Interviews with stakeholders from the case project are 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. **Table 3.1** shows their background information. Since they attend the case study project from the beginning, they know the project situation very well and therefore are able to provide deep insights into the problems in the supply chain and their root causes. Requiring the experts to carry out the analysis objectively is 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 are invited to answer three questions with which to analyze the problems and their sources embedded in the SCM: (1) Does the described problem really occur in the SCM for the PBP? (2) How does the problem occur in the supply chain? and (3) What is the root cause of the problem? They are asked to provide as many details as possible. By doing this, how and why the problems occur in the project is discussed in detail, ensuring that all possible occurrence and their sources are considered. Each interview lasts at least three hours during which time the stakeholders are 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.

Table 3.1 Background information of the four experts

	Role	Working/researching years in PBP in Hong Kong	Educational background	Position
Expert 1	Client	12	Master	Senior engineering manager
Expert 2	Manufacturer	10	Master	Production manager
Expert 3	Main contractor	15	Master	Assistant engineering manager
Expert 4	Assembly sub-contractor	11	Master	Assistant engineering manager

3.3 Addressing Objective 2

The classical risk management processes developed by the Project Management Institute (2013) is incorporated in the SNA research steps as illustrated in **Figure 3.2** to address Objective 2.

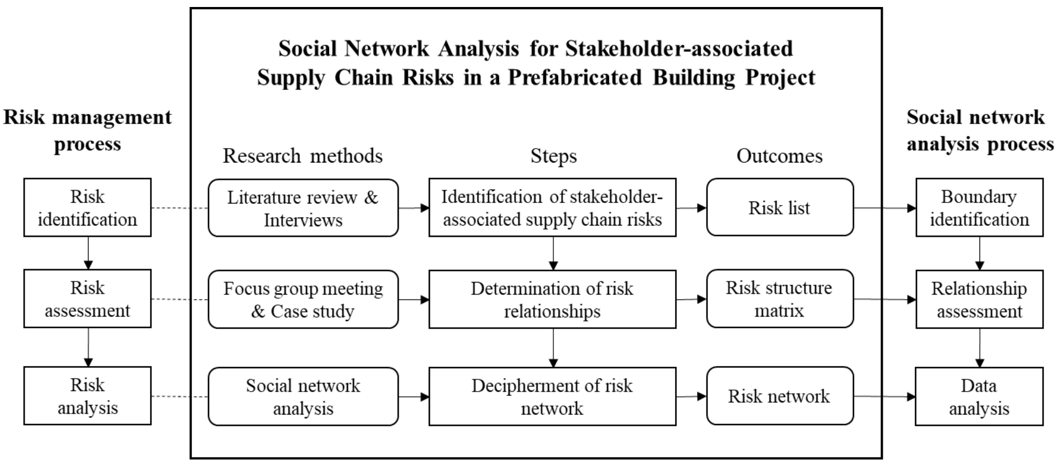


Figure 3.2 Research framework to address Objective 2

3.3.1 Literature review

A comprehensive literature review is conducted to identify stakeholder-associated SCR. Using Scopus database and the Google engine, research papers, reports and surveys are searched for topics related to risks, uncertainty, constraints, barriers, and challenges in construction/prefabrication supply chains. The collected documents are then fully reviewed to summarize stakeholder-associated SCR in PBP in Hong Kong. This method has been widely adopted for factor identification by previous studies, such as Yu and Shen (2015) and Mao et al. (2015).

3.3.2 Case study

This section recruits the same case project in Section 3.2.1 to generate case-based understandings and for data collection.

3.3.3 Interviews

Three experts are interviewed to evaluate the comprehensiveness and appropriateness of the identified risks. The experts are selected based on their knowledge and working background regarding PBP implementation in Hong Kong. **Table 3.2** illustrates the background information of the experts participating in the interviews. They have worked in or researched on PBP in Hong Kong for over ten years and are therefore able to provide valuable comments for SCR identification. Face-to-face interviews with the experts are carried out to discuss the occurrence of SCR in real projects, ensuring that such SCR really exist and could potentially affect supply chain performance. The experts also propose more SCR in addition to the risks identified from the literature and explain them in detail based on their working and research experience in PBP. Each interview lasts three to four hours to guarantee that all the SCR are analyzed and rationalized in the context of Hong Kong. Finally, a proper list of SCR is generated after detailed discussions with the experts. These SCR represent nodes in the social network and are denoted as *SaRb*, referring to the b^{th} risk associated with the a^{th} stakeholder in the supply chain.

Table 3.2 Background information of the three experts

	Role	Working/researching years in PBP in Hong Kong	Educational background	Position
Expert 1	Client	12	Master	Senior engineering manager
Expert 2	Contractor	15	Master	Assistant engineering manager
Expert 3	Academician	16	PhD	Professor

Stakeholders from the same case project recruited to address Objective 1 are invited to attend an interview to quantify the interrelationships between SCR. The stakeholders are selected from the full-time front-line workers and managers of the project team who work for the project from the beginning and know the project very well. Therefore, they are able to provide valuable implications of SCR from both the front-line and the managerial levels. The background information of the stakeholders participating in this step is shown in **Table 3.3**.

Table 3.3 Background information of the stakeholders involved in SNA

Stakeholders	No.	Position	Working years in PBP in Hong Kong
Client	-	Senior engineering manager	12
Manufacturer	1	Production director	8
	2	Shop-floor worker	5
Transporter	-	Front-line transporter	6
Main contractor	1	Assistant engineering manager	15
	2	Foreman	8
Assembly sub-contractor	1	Assistant engineering manager	11
	2	Front-line worker	5

3.3.4 SNA

The social network theory considers a project as a system that is linked by diverse relationships, with the aim to examine the impacts of relationship structure on behavior and identify the causes and effects of the relationships (Scott 2000). SNA has already been successfully used to investigate stakeholder-related risks and their interactions in complex green building projects (Yang et al. 2015), major public engineering projects (Mok et al. 2017b), and housing demolition projects (Yu et al. 2017), indicating that SNA is an effective method for exploring risks and their cause-effect relationships. As the application of SNA in SCR remains unexplored, this study fills this knowledge gap by adopting SNA to examine stakeholder-associated SCR and their interactions in PBP in Hong Kong.

This study collects data for SNA in accordance with the method suggested by Yu et al. (2017) that involves asking the stakeholders to answer three questions to evaluate the impact of one risk on the other: (i) Does *SaRb* have an impact on *ScRd* (the influence direction)?; (ii) If yes, what is the likelihood of the impact?; (iii) To what extent does *SaRb* influence *ScRd* ? Two parameters are adopted to quantify the impact, namely, *likelihood of the influence* and *level of the influence*. A five-point Likert scale is used to assess the parameters, where "1" and "5" mean the lowest and the highest *likelihood of the influence* or *level of the influence* respectively. The impacts between SCR are represented by links with the direction from the source nodes to the target nodes, and the overall influence level is calculated by multiplying these two parameters. For example, if S1R2 has a medium likelihood (denoted as "3") to affect S2R3 and the influence level is relatively high (denoted as "4"), there will be a link from S1R2 to S2R3 with an overall influence level of 12. The directions and impact levels of the links are continuously discussed by the stakeholders until they reach a consensus. Finally, a risk structure matrix is generated in this step, where all the possible links between the nodes are identified and assessed by the stakeholders.

The risk structure matrix is imported into the Netminer 4 Software (Cryam Netminer 2000) to visualize the SCR network for the case project. The node colors and shapes stand for the stakeholder and the risk categories respectively, while the thickness of the arrows shows the overall influence degrees between the nodes.

Network and node/link measures are conducted to compute critical indicators of the network, including density, cohesion, nodal degree, betweenness centrality, status centrality, brokerage, and ego size, which could reflect the complexity of the supply chain network and identify critical SCR and their links.

3.4 Addressing Objective 3

SD is adopted to develop a dynamic model for simulating the impacts of SCR on the performance of project supply chains. Case study and interviews are combined to collect data to quantify the relationships between the variables in the SD model. **Figure 3.3** shows the framework to tackle Objective 3.

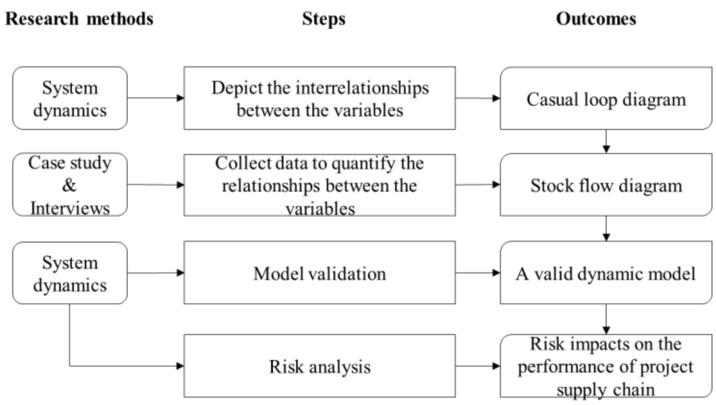


Figure 3.3 Research framework to address Objective 3

3.4.1 SD

SD is proposed by Forrester (1958) to handle large-scale and complex systems where different types of feedbacks exist. With the basic principle of exploring the interaction mechanism between the major objects in a system, SD has been widely applied to understand the relationships between the behaviors within a system with time, and its underlying structure and decision rules (Wolstenholme 1990). The use of SD is observed in various areas, including strategic management (Warren 2005), construction waste management (Yuan 2012), and land use planning (Shen et al. 2009).

As supply chains are complex systems that always work dynamically, system thinking with dynamic considerations are needed to analyze supply chain issues. In recent studies, the SCM field extensively adopts SD to address the problems in complex supply chain systems. For example, Piri et al. (2018) develop multiple SD models to depict the cause and effect of interconnectivity, adaptability and transformability of a biocomposite production system to facilitate guided decision-making towards a more robust and resilient supply chain. Aivazidou et al. (2018) provide a strategic SD model to capture the impact of different water management policies on the supply chain profitability. Similarly, Gonul Kochan et al. (2018) build a SD framework to explore the impact of cloud-based information-sharing on the supply chain performance of healthcare products. The abovementioned research shows that SD is suitable for investigating supply chains and analyzing the dynamic interaction mechanism involved.

SD describes the structure of complex systems using intuitive tools, including causal loop diagrams and stock-loop diagrams, which play an important role in revealing the causal relationships for quantitative analysis. According to Yuan (2012), five steps should be taken to build a SD model, including (1) develop the causal loop diagram for system description, (2) transform the causal loop diagram into the stock-flow diagram to obtain the feedback mechanism within the system, (3) build confidence in the model by a series of tests, (4) conduct base run simulation, and (5) develop scenarios for further analysis.

3.4.2 Case study

This section recruits the same case project in Section 3.2.1 to generate case-based understandings and for data collection. Quantitative data of the production, transportation and assembly stages in the case project is collected from historical project documents to depict the supply chain in the proposed model.

3.4.3 Interviews

Interviews with three stakeholders from the case project are conducted to collect qualitative data about the relationships between the variables. **Table 3.4** shows the background information of the stakeholders involved. This method is frequently used in previous research, such as Yuan (2012), to quantify the relationships within SD models. The three experts are from the client, the manufacturer, and the main contractor respectively. Their background information is provided in Table 3.2. They are invited to quantitatively describe the relationships between the variables with as many details as possible to keep consistency of the data.

Table 3.4 Background information of the stakeholders involved in the SD model

Stakeholders	No.	Position	Working years in PBP in Hong Kong
Client	-	Senior engineering manager	12
Manufacturer	1	Production director	8
Main contractor	1	Assistant engineering manager	15

3.5 Chapter summary

This chapter explains the research methods and tools used to address the three objectives in details. The research methods used in this study include literature review, case study, document analysis, interviews and SD, while the tools include automated data collection technologies and SNA.

Chapter 4 An Empirical Analysis of SCM for PBP

4.1 Introduction

A supply chain can be said to comprise two basic processes: production planning and inventory control, and distribution and logistics (Beamon 1998); a prefabrication supply chain also includes on-site assembly. The supply chain of a prefabricated building project involves a client, a designer, a manufacturer, a transporter, a main-contractor, and several service/product suppliers. Because of the multiple processes and stakeholders involved, coordinating the information, material/service/product, and capital flows in the supply chain is a complex task. Poor SCM for PBP 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 PBP. For example, various production planning systems or models have been developed using an intelligence approach (Benjaoran and Dawood 2006), radio frequency identification (RFID) technology (Yin et al. 2009; Zhong et al. 2013), and genetic algorithms (Li et al. 2010). Inventory control systems for materials have also gained wide attention as a way of reducing associated costs (Ingrao et al. 2014; Pan et al. 2011), while long lead time is mitigated by designing coordination mechanisms (Zhai et al. 2016).

However, research into SCM for PBP has achieved only limited breakthroughs due to the following limitations: (1) only single processes (e.g. production, logistics) have 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, and therefore most research has used simulated data or modeling methods. These restrictions have prevented studies from revealing the true picture of SCM for PBP for the following reasons. First, the upstream and the downstream processes do not exist independently but frequently interact with each other to influence performance of the supply chain (Luo et al. 2018). The supply chain should not therefore be seen as individual parts but instead should be inspected and managed as a whole to see how the supply chain actually operates through the dynamic interactions of different processes. Second, data collection and sharing across the supply chains of PBP are often found to be inaccurate, incomplete, and insufficient (Zhong et al. 2017) due to the inadequate use of information technologies (Xu et al. 2018). However, valid and accurate data is a critically important element in SCM for PBP because of its significant role in supporting stakeholders' decision-making and process improvement (Lewis and Cooke 2013). Thus, improving the quality of data within supply chains is an important first step toward exploring the actual situation of SCM for PBP.

Tackling the aforementioned limitations will contribute significantly to a fuller understanding of SCM for PBP, thereby generally enhancing the performance of supply chains. This study therefore posits the following research questions: (1) What is the current situation of SCM for PBP in Hong Kong? (2) What problems exist in SCM for PBP? (3) What are the root causes of the problems in SCM for PBP? This study uses automated data collection technologies to obtain real-time information of precast components in the production, transportation, and assembly processes of a prefabricated building project in Hong Kong. The valid and accurate data collected by the advanced information technologies lays a solid foundation for analyzing the problems embedded in the SCM and their root causes.

4.2 Findings and discussions

First, this section explores the production and transportation situation of the whole project (including five buildings) using documents analysis to show the true picture of the two stages. Because of data inaccessibility of the assembly stage of all the five buildings, only production and transportation analysis is conducted in this part.

Second, the real-time data of precast components of Block 5 is analyzed to accurately reflect how the supply chain of the building is operated and managed. This section presents a statistical analysis of the dataset to show the actual situation of the SCM for the case building, 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.

4.2.1 Production and transportation management of the whole project

The production record of the factory is analyzed to find that fluctuating production schedule, high inventory, long stock time are potential problems that indicate the poor resource planning and negatively influence the supply chain performance of the project. The fluctuating transportation schedule is also observed in this project. It should be noted that the analysis in this section is based on measurement of facades by number.

The whole project has a total of 7849 facades which could be divided into 22 types. Those facades with similar appearance and size are produced by similar molds which could be adapted for manufacturing another type of facades. Therefore, the types of facades manufactured by similar adaptable molds are considered as one category. For example, facades of types TX1, TX1r, TX1A, TX1B, TX1C, TX1Ar, and TX1Br are within the TX1 category. **Table 4.1** shows façade information of the project.

Table 4.1 Façade information of the project

Façade category	Façade type	No.
TX1	TX1	327
	TX1r	352
	TX1A	34
	TX1B	34
	TX1C	25

	TX1Ar	34
	TX1Br	34
TX2	TX2	570
	TX2r	570
TX4	TX4	1206
TX8	TX8	1216
	TX8r	1223
TX9	TX9	607
	TX9r	607
	TX9A	350
TX11	TX11	165
	TX11r	165
TX12	TX12	100
	TX12r	131
	TX12A	65
	TX12Ar	13
	TX12Br	21

Analyzing the production rhythm of facades from the same category could reveal the manufacturing rules followed by the factory. Considering that the amount of facades is up to thousands, those types of facades number less than 100 are relatively meaningless in showing the production trend and are therefore not considered in analyzing the manufacturing of facades from the same category. **Figure 4.1** shows the design information of facades considered in production analysis of the same category, while **Figure 4.2**-**Figure 4.8** illustrate the number of facades from the same categories (TX1, TX2, TX4, TX8, TX9, TX11 and TX12 categories) produced daily. The figures seem to reveal limited implications regarding the rule of production arrangement of facades from similar types, and instead show that the manufacturing of facades is conducted randomly without reasonable resource consideration and planning.

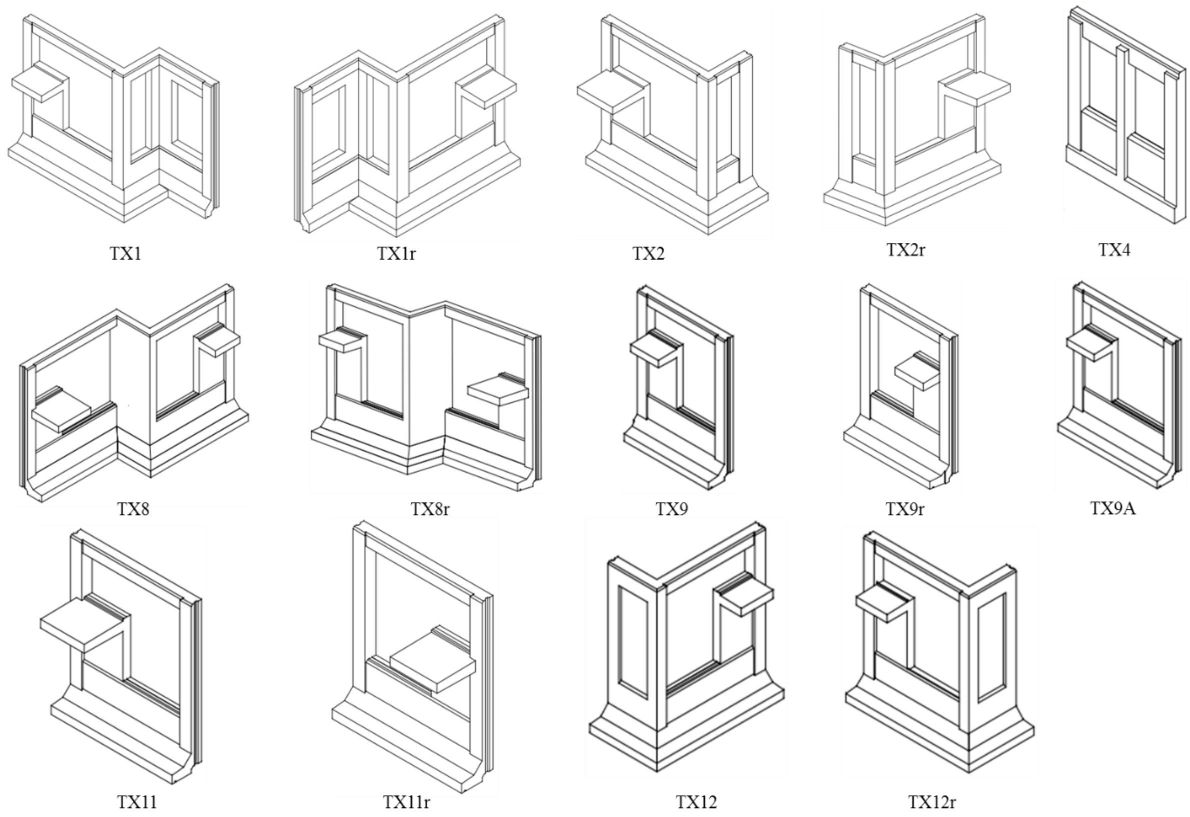


Figure 4.1 Design information of facades considered in production analysis of the same category

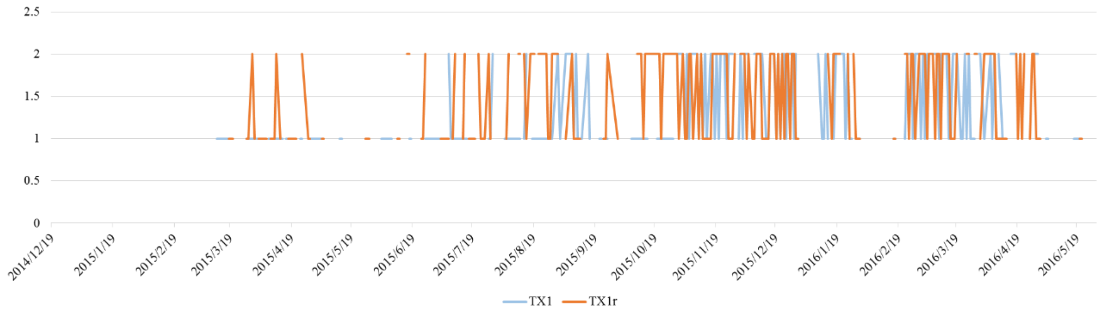


Figure 4.2 The number of facades (TX1 and TX1r types) produced daily

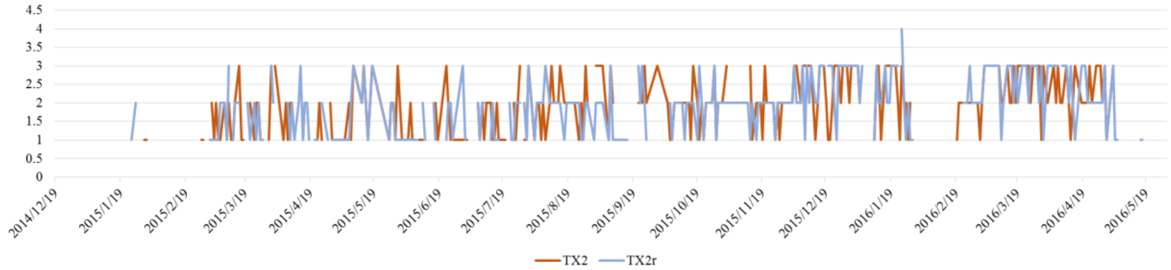


Figure 4.3 The number of facades (TX2 and TX2r types) produced daily

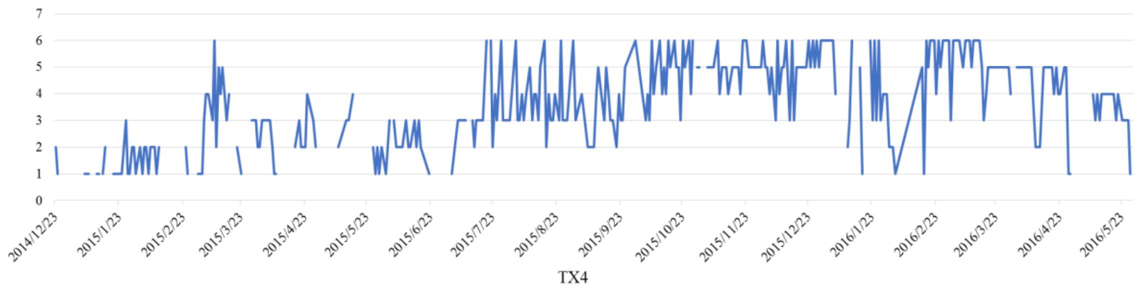


Figure 4.4 The number of facades (TX4 type) produced daily

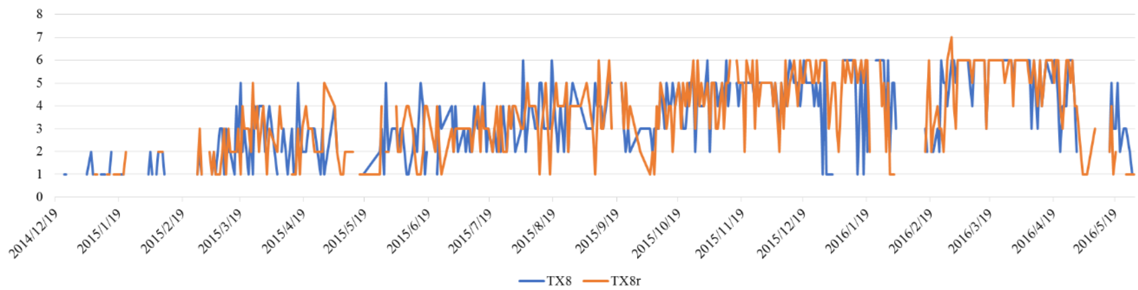


Figure 4.5 **The number of facades (TX8 and TX8r types) produced daily**

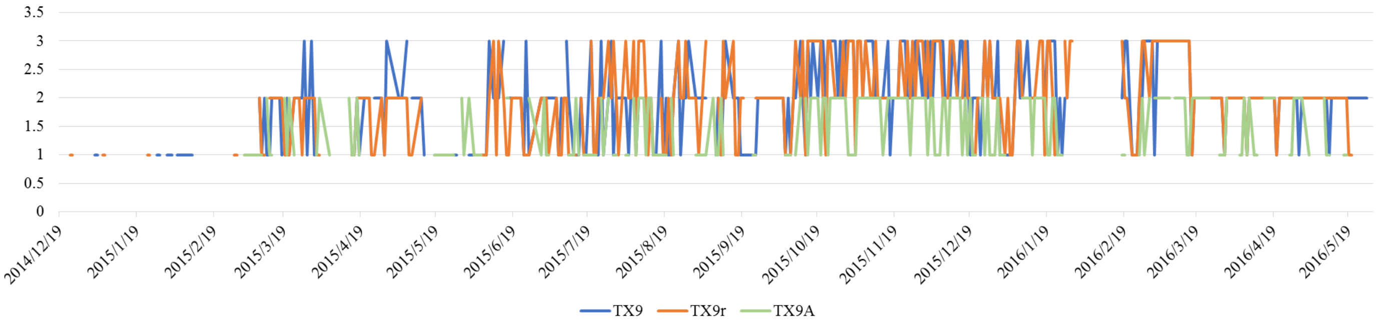


Figure 4.6 **The number of facades (TX9, TX9r and TX9A types) produced daily**

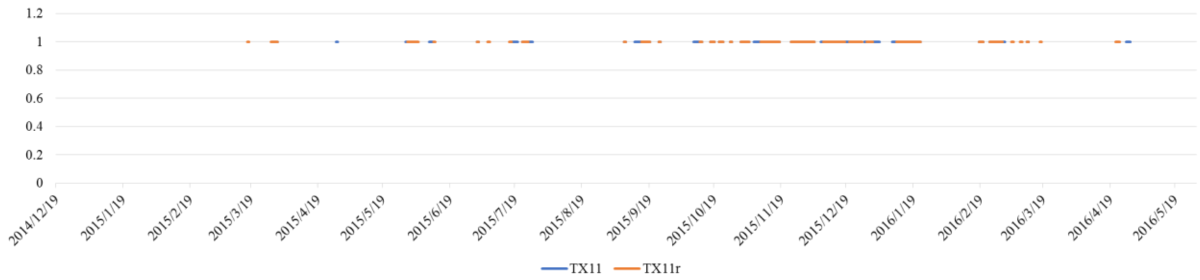


Figure 4.7 **The number of facades (TX11 and TX11r types) produced daily**

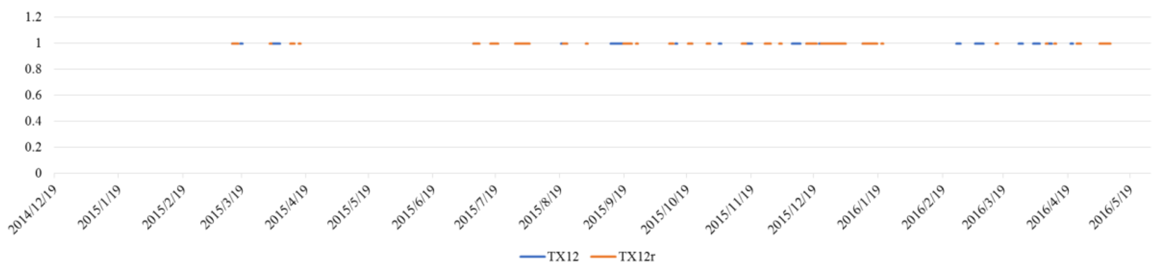


Figure 4.8 **The number of facades (TX12 and TX12r types) produced daily**

Figure 4.9 shows the daily production schedule of the whole project, revealing that the number of daily produced facades varies significantly and frequently in the factory. The production speed generally increases gradually since the very start of the project, and then rapidly decreases at the late stage. The factory produces 20 facades on average every working day with 20 facades being most frequently manufactured daily. The largest number of daily fabricated façade is 40. According to the project documents, the factory has a total of 45 molds for the project, indicating that most molds stand idle during the production stage, resulting in huge resource waste.

Figure 4.10 illustrates the monthly production situation of the whole project, showing an upward trend of manufacturing schedule. The largest and smallest numbers of monthly fabricated facades are 909 and 24 facades respectively, indicating an unbalanced resource arrangement during the production stage.

Figure 4.11 reveals the daily inventory of precast facades for the whole project in the factory. It can be seen that the inventory is always at a very high level throughout the production stage. The largest inventory reaches 1249 facades in the middle of project implementation, which is almost higher than the total number of facades of Block 2 (1056 facades) while the average inventory is as high as 719 facades. Such situation reveals significant resources waste in the factory and poor coordination between upstream and downstream supply chains

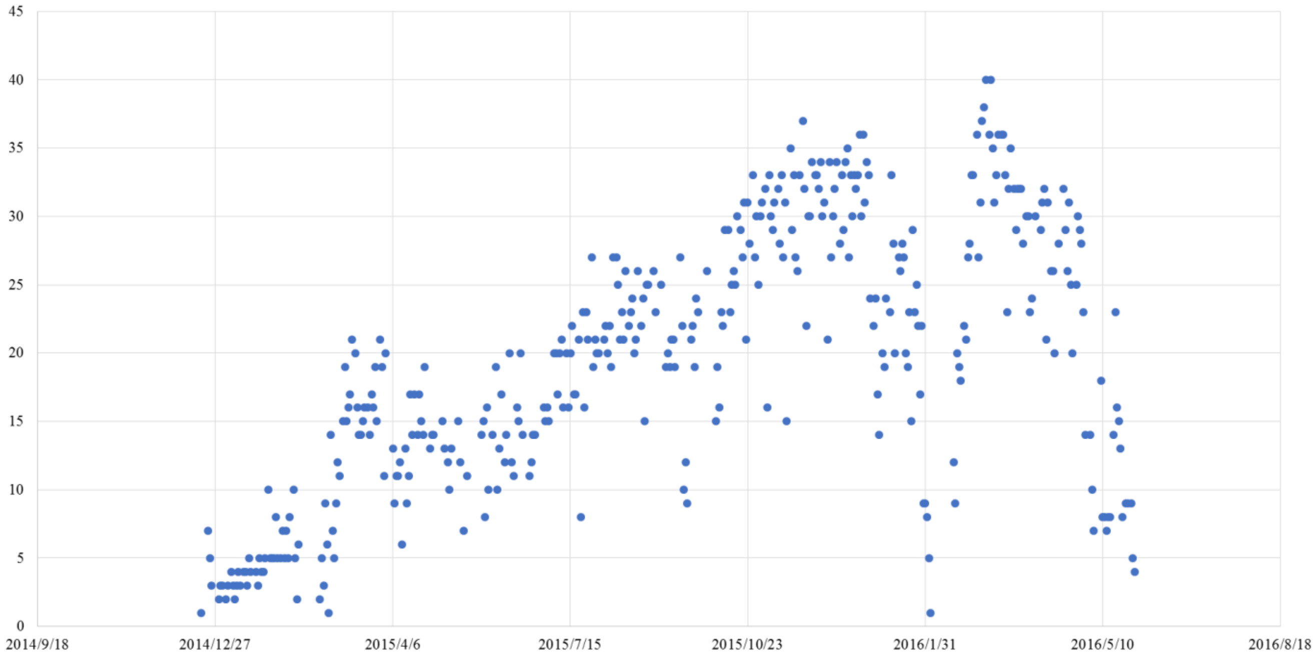


Figure 4.9 Daily production schedule of the whole project

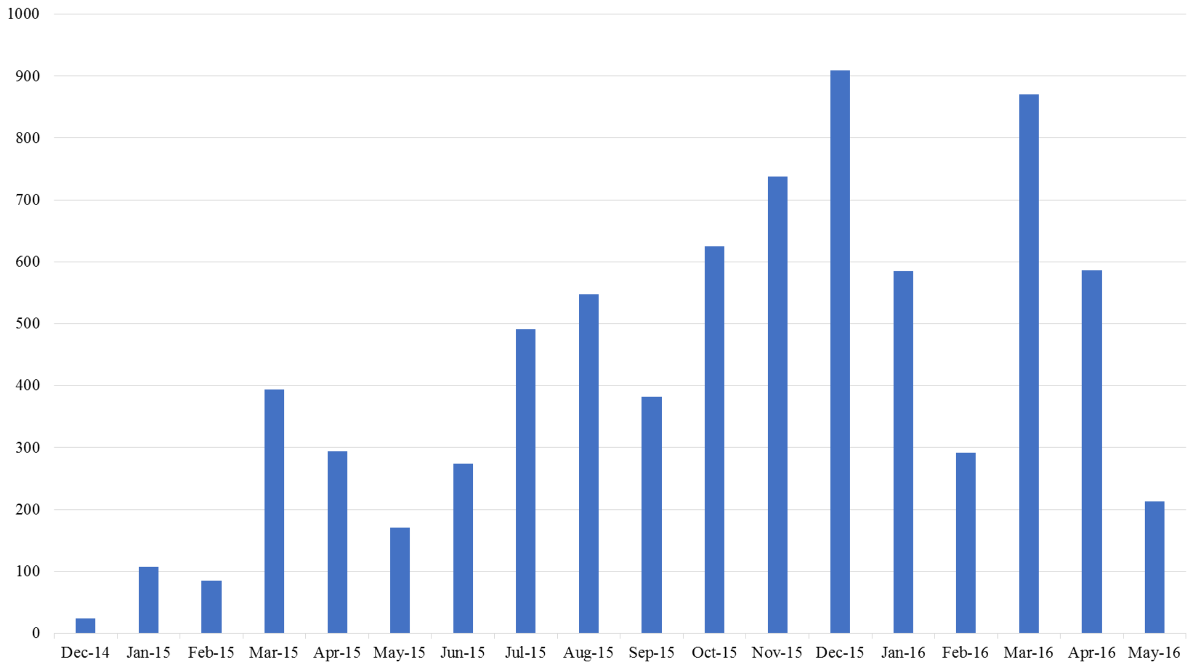


Figure 4.10 Monthly production schedule of the whole project

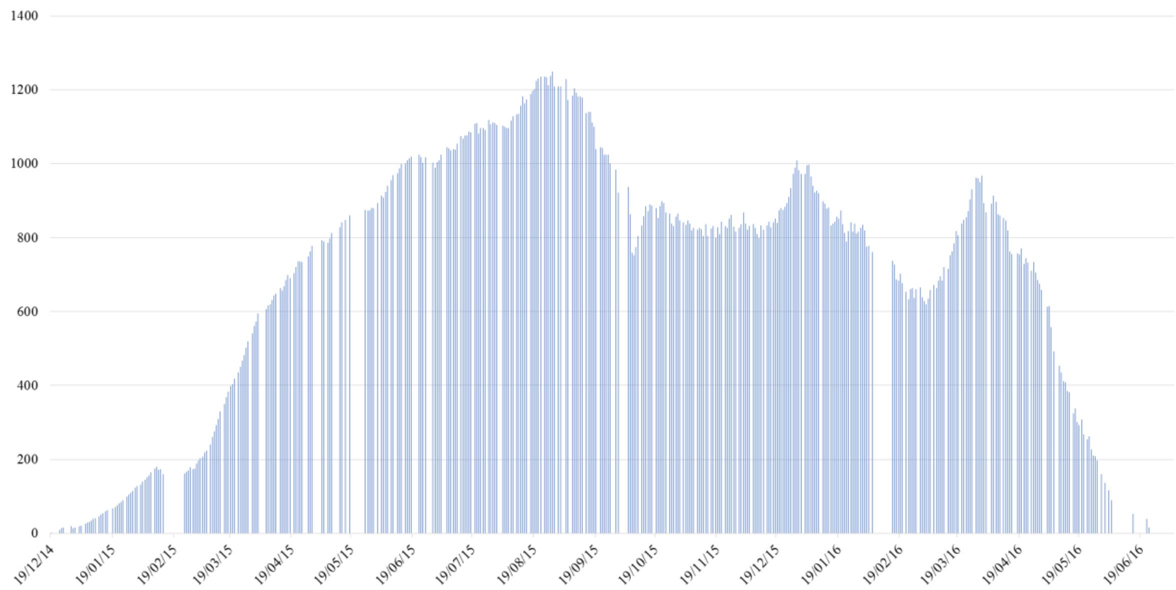


Figure 4.11 Daily inventory of facades for the whole project in the factory

Figure 4.12 demonstrates the stock time of each floor's facades of the five blocks in the factory, showing similar pattern of facades' waiting time among the different buildings. Generally, the stock time of the five buildings is relatively high and then decreases rapidly, averaging out at 42 days.

The long stock time and large number of inventory are likely to cause a series of problems in the factory, such as poor layout management, components damages, and difficulty in finding the proper components.

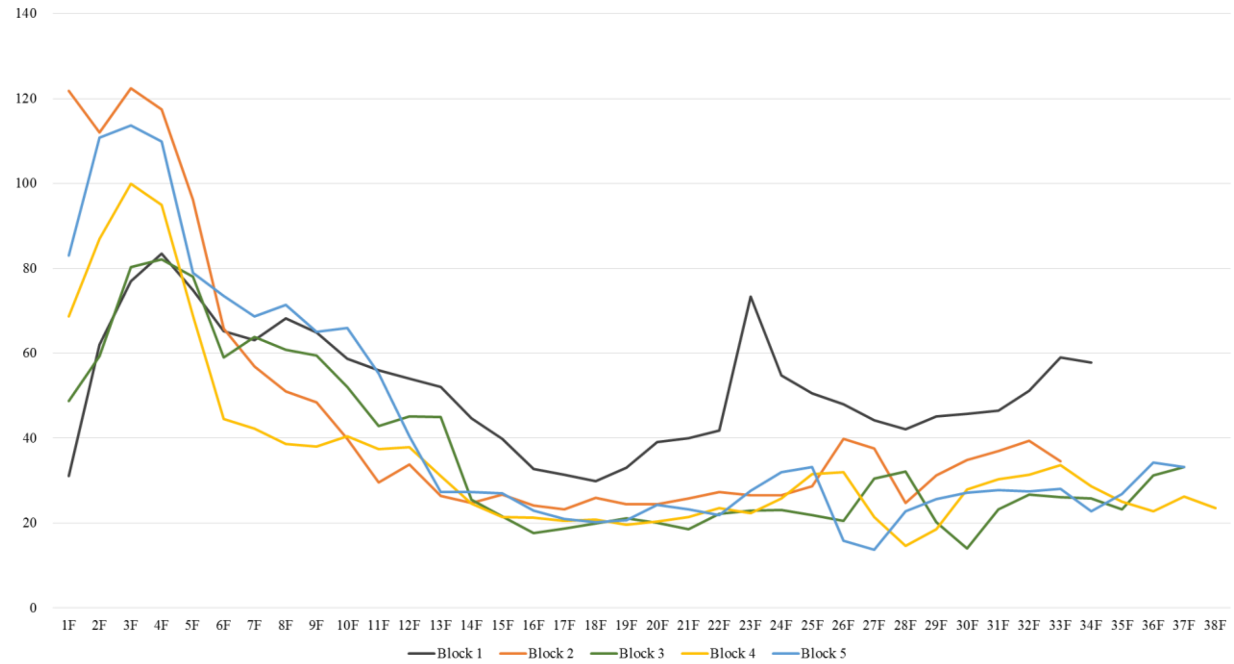


Figure 4.12 Stock time of each floor's facades of the five blocks in the factory

Figure 4.13 shows the number of facades delivered by the transporters daily, revealing a significant fluctuating trend throughout the transportation stage. The largest number of facades transported in a batch is 119, while 23 facades are transported most frequently during the transportation phase. The highly fluctuating situation indicates the unstable demand for precast components in the downstream chain.

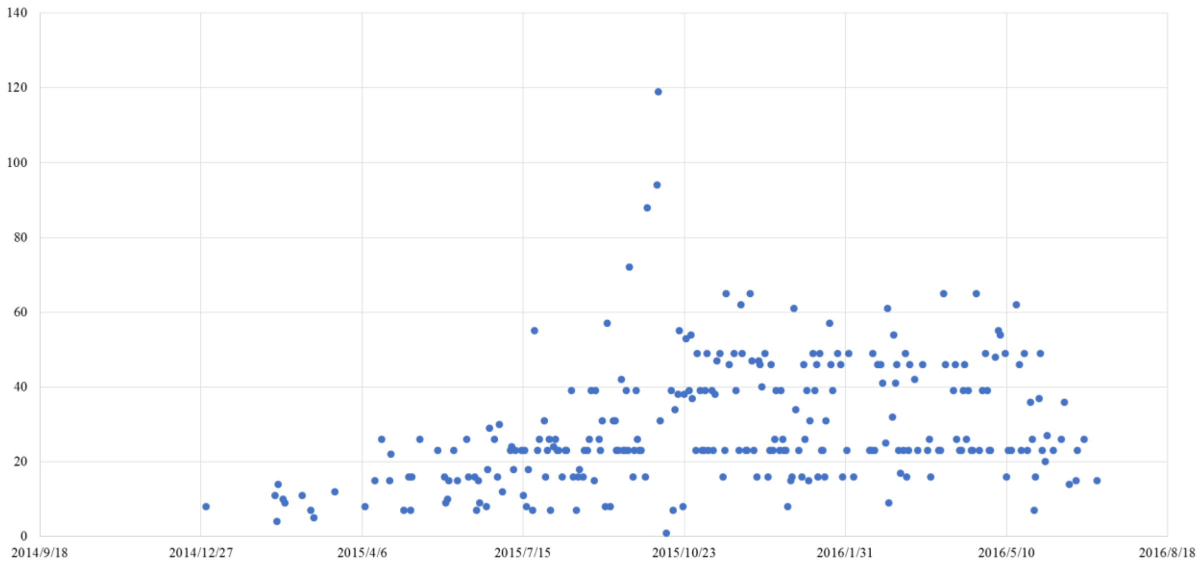


Figure 4.13 Number of facades delivered daily

4.2.2 Supply chain operation of the investigated building

The operation of the production, logistics, and on-site assembly stages constitute a major part of the supply chain. **Figure 4.14** and **Figure 4.15** show the production and on-site construction processes respectively. Each process of the case building displays considerable fluctuations, indicating significant variations in the supply chain. The analysis in this section is based on measurement of facades by number.

Figure 4.14 Production process in the factory

Figure 4.15 On-site construction process

Production stage and embedded problems

The production of precast components is restricted by the factory's resource constraints. It is therefore important to reasonably plan the production 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 building shows unbalanced resource deployment across the production phase, indicating limited considerations of resource planning.

As can be seen in **Figure 4.16**, daily manufacturing records of façades show a highly fluctuating production schedule. Although façades are generally fabricated by floor sequence, there are considerable production disorders amongst the floors. For example, after beginning to work for Floor 7, the production line is found to go back to manufacture several façades of previous floors (e.g. Floor 5), which suggests that the factory conducts fabrication individually rather than by complete batch. This situation frequently happens during the manufacturing stage. Also, the distribution of the total amount of daily produced façades is 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.

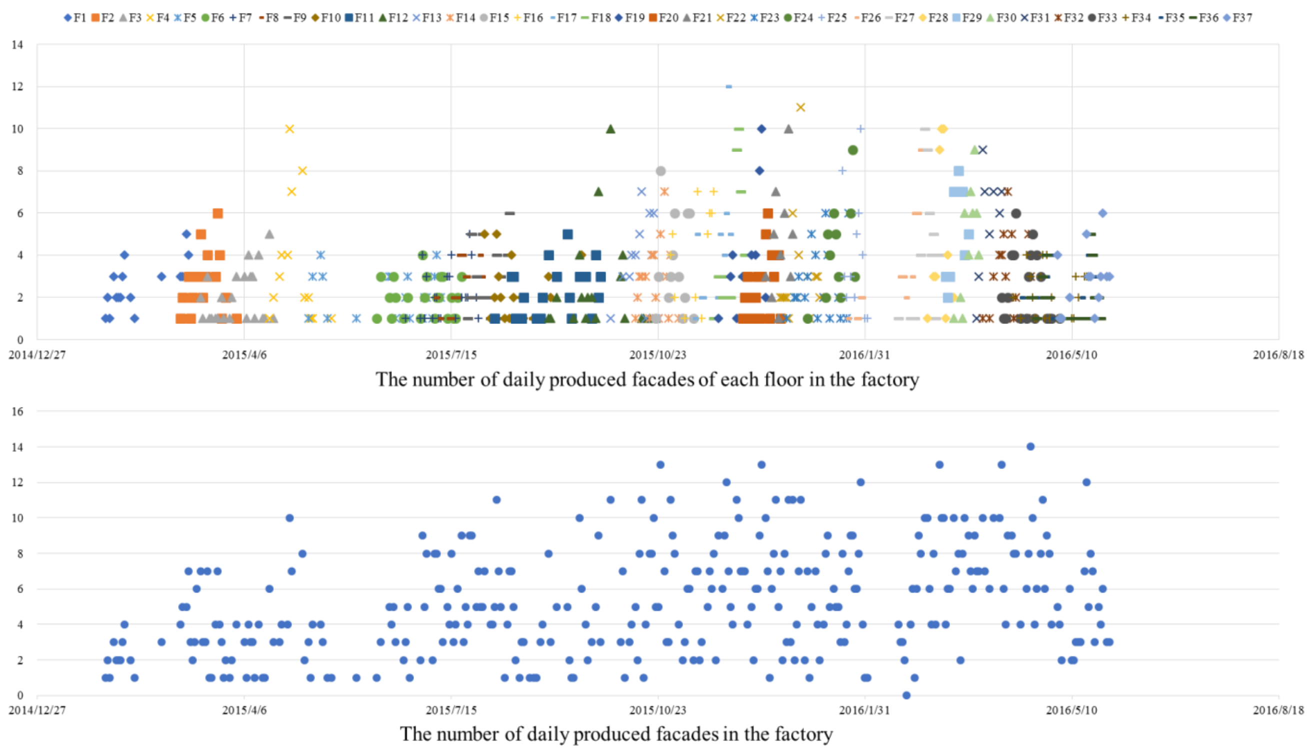


Figure 4.16 Daily production schedule of the investigated building

The scatter plot shown in **Figure 4.16** below demonstrates that a minimum of one façade and a maximum of 14 façades are manufactured daily with five façades being produced on average every working day, which is far from reaching the realistic production capability of the factory. As the project documents illustrate, 36 façade molds are prepared for this building, implying that the factory is able to produce 36 façades daily. Most molds and equipment therefore stand idle during the manufacturing phase, causing significant waste and revealing poor planning of resources.

By contrast, the number of monthly manufactured façades has an upward trend with relatively lower fluctuations as shown in **Figure 4.17**. This implies that the manufacturer is likely to produce more precast components in the later stage of the supply chain. Minimum and maximum amounts of façades produced monthly are 22 and 187 respectively, which reveals a great gap between manufacturing efforts devoted to different supply chain stages.

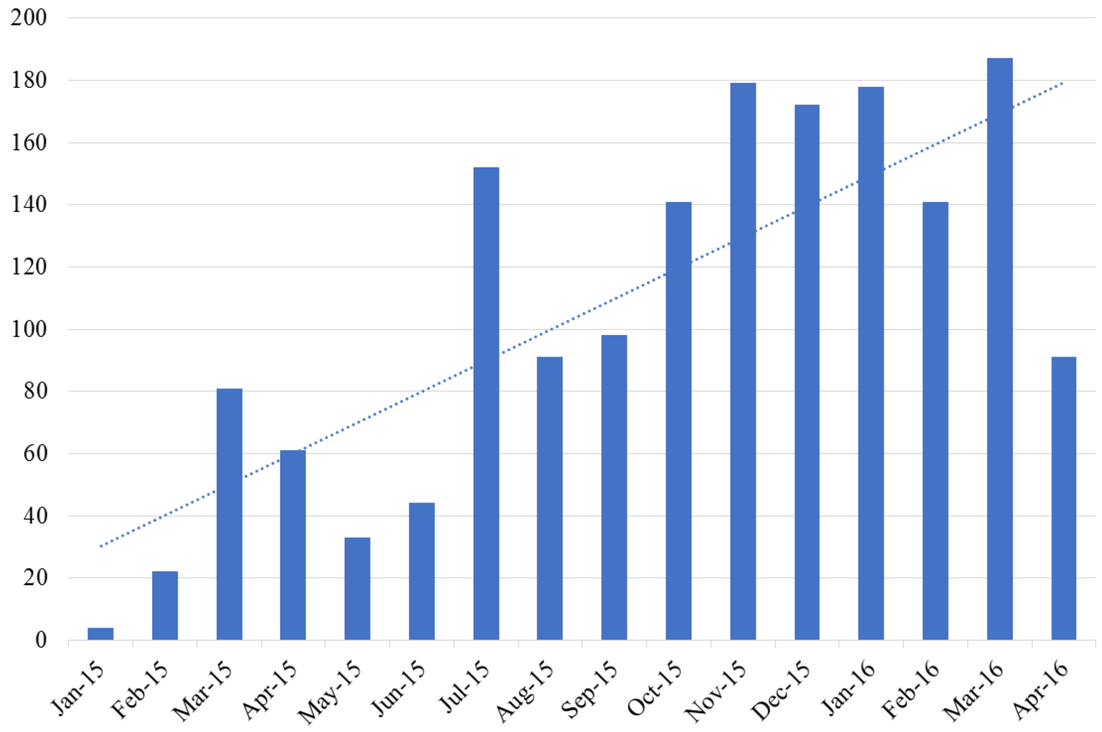


Figure 4.17 Monthly production schedule of the investigated building

The production duration of façades for each floor is shown in **Figure 4.18**, which displays a downward trend of fabrication time for each floor, indicating that the manufacturing speed accelerates with the building construction schedule. Specifically, the longest time (65 days) and shortest time (10 days) is spent on fabrication for Floor 5 and Floor 30 respectively. On average, 30 days are used to complete the production of façades for each floor. Furthermore, several days' interruption frequently takes place during the manufacturing phase, resulting in significant time buffers. This is because the manufacturer is working for multiple projects at the same time and fails to balance the production resources for different projects.

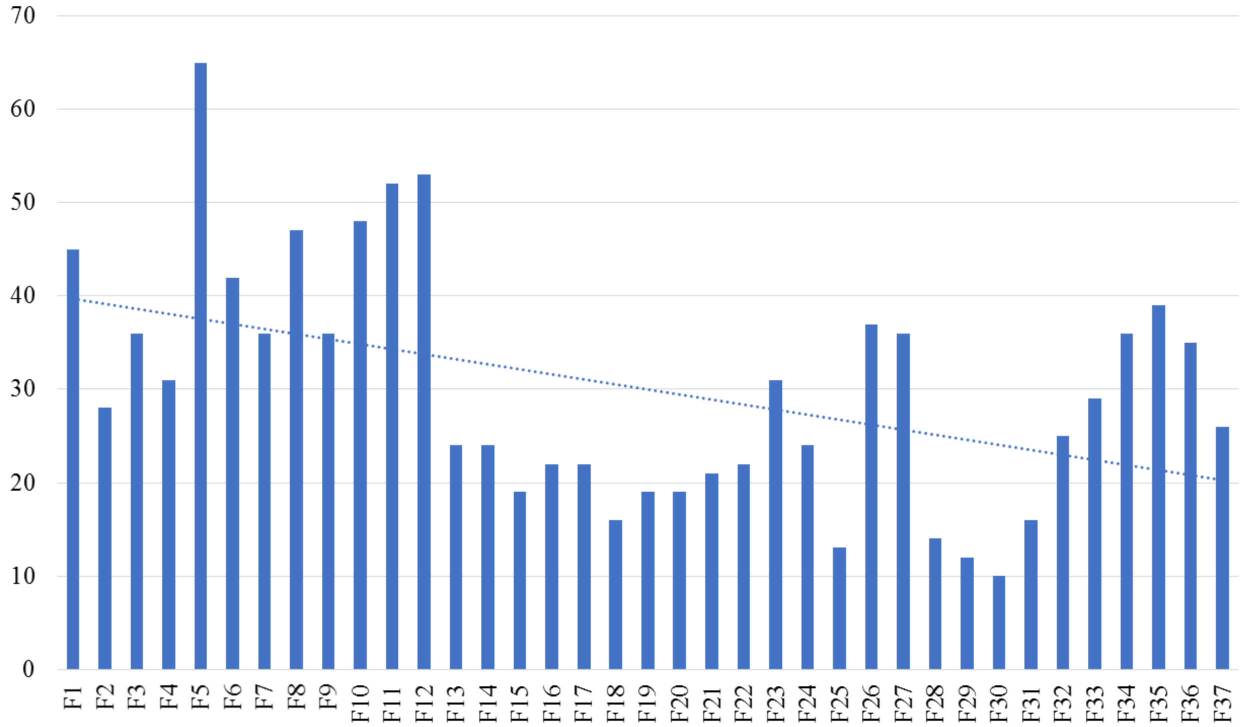
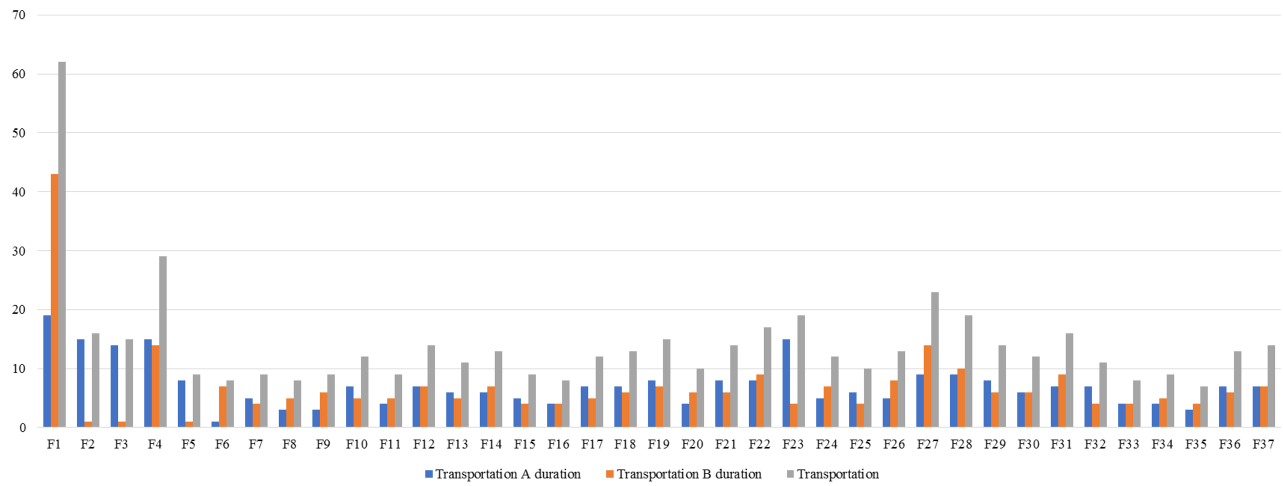


Figure 4.18 Production duration of each floor of the investigated building

Transportation stage and embedded problems

The transportation process consists of two sub-processes: cross-border transportation from the factory to the buffer (Transportation A) and local transportation from the buffer to the construction site (Transportation B). Transportation arrangements are subject to the schedule of on-site assembly in order to ensure the arrival of precast components in time. The transportation time of each floor's facades and the number of facades conveyed each time remains relatively stable during the transportation phase, indicating the well control of the transportation task in the case building.

The transportation durations of each floor's façades are shown in **Figure 4.19**, which demonstrates that time used for the transportation decreased with the building's progress. The transportation of façades for the initial floors takes more time than the subsequent floors, indicating that schedule of the building construction is relatively slow at the beginning of the supply chain. Transportation of the first floor's façades spend the longest time on both of the two sub-processes; transportation A and B last 43 days and 19 days respectively. The shortest time used for these two processes is only one day, implying that the transporter does 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 is 7.1 days and 6.9 days respectively.



Remarks:
Transportation A: From factory to buffer; Transportation B: From buffer to site

Figure 4.19 Transportation duration of facades of each floor (days) of the investigated building

The number of façades shipped each time by cross-border transportation (Logistics A) is illustrated in **Figure 4.20**. According to the manufacturer, heavy trucks are used for the transportation with each truck capable of conveying 7 or 8 façades at a time. The entire logistics task is 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.

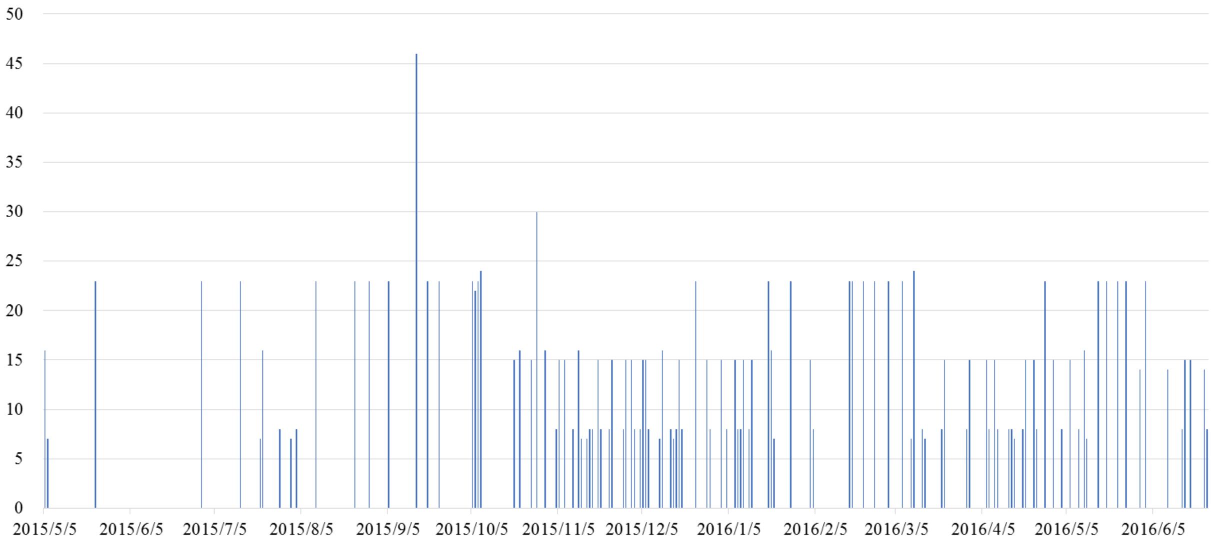


Figure 4.20 Number of components transported in each batch of the investigated building

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 maximize cost, time, and resource benefits. However, significant assembly delays are observed at the assembly stage of the case building, resulting in various problems in the supply chain.

The actual assembly duration of typical floors (Floor 2-34) is shown in **Figure 4.21** with significant schedule delays across the assembly stage despite long-term efforts devoted to good on-site construction practice. The second floor takes 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 is relatively faster with the erection duration of typical floors averaging out at nine days. A sharp increase in the assembly time occurs 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 (details described in Section 4.2.2). Only Floor 5 and Floor 6 realize the goal of completing the assembly within the cycle time, while other floors lag behind the expected schedule resulting in a delay of 102 days and considerable cost overruns. This situation reveals poor control of the assembly process.

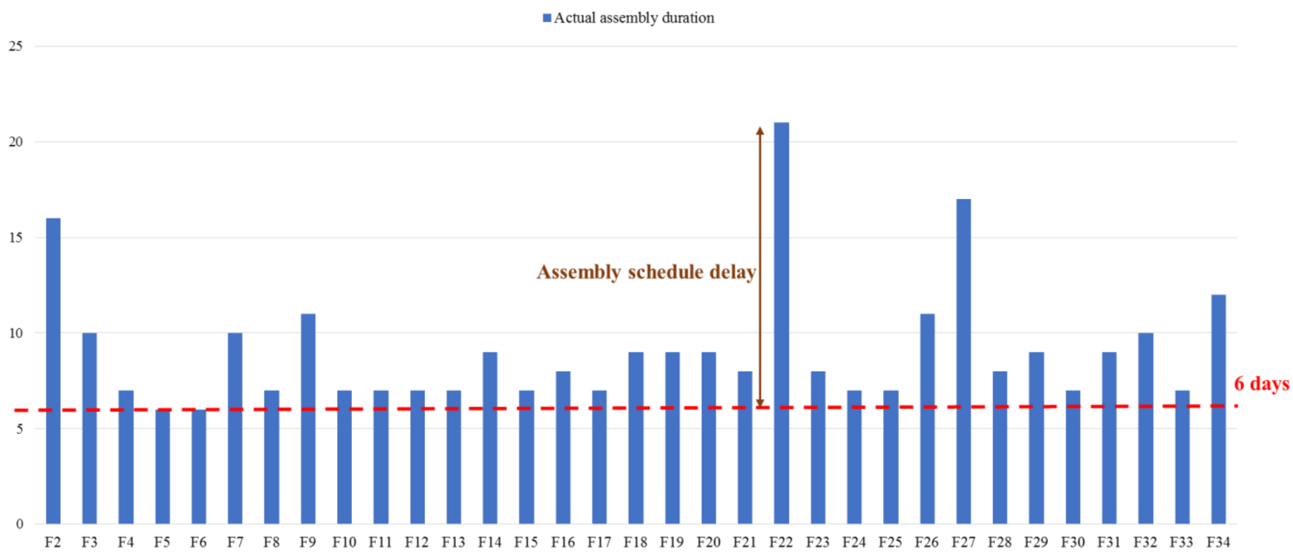


Figure 4.21 Erection duration of typical floors (days) of the investigated building

Inventory and lead time management

The overall progress of the supply chain is illustrated in **Figure 4.22**. It can be seen that there is 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 2001a), while long lead time is associated with schedule delay and extra costs. This section describes the inventory and lead time situation of the case building to show overproduction, excessive inventory, and long lead time in the SCM.

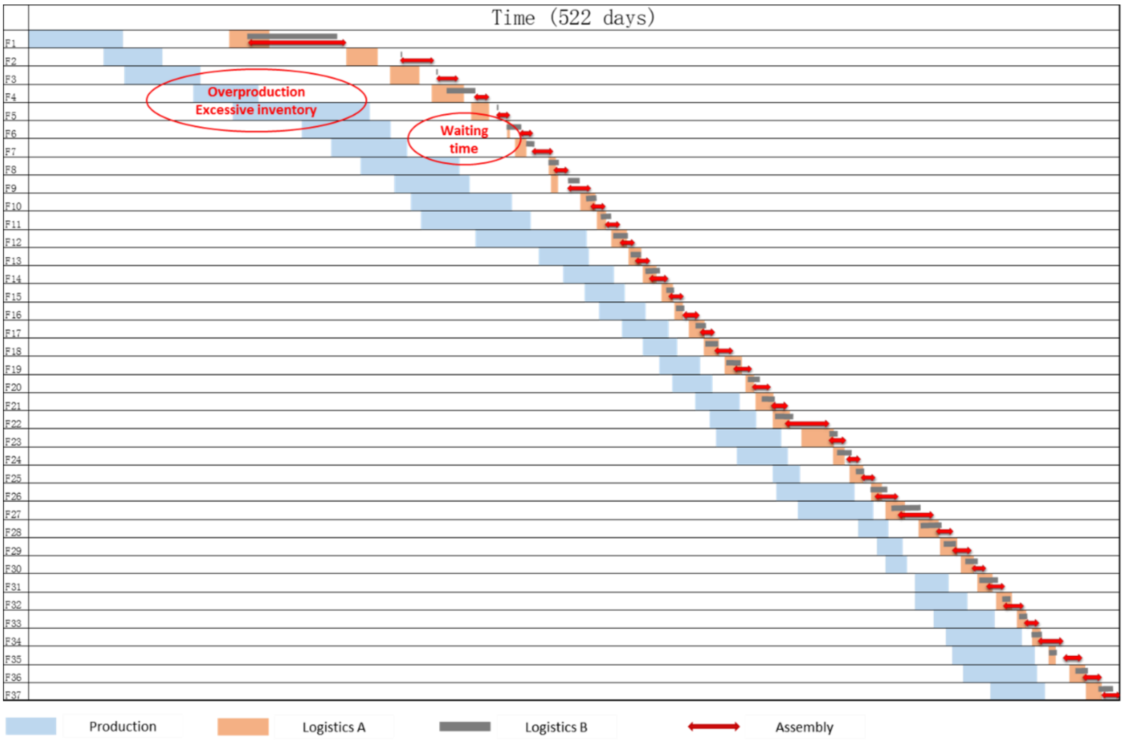


Figure 4.22 Overall progress of the supply chain of the investigated building

Inventory management and embedded problems

Excessive inventory exists 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 building.

The inventory amount in different supply chain stages is shown in **Figure 4.23**. 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 prefers to store large quantities of components before they are really needed. Initially, the amount of factory inventory demonstrates an upward trend, increasing to 300 façades in the 227th day. 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. 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 is two floors of façades (92 façades). However, the quantity of façades in stock far exceeds the safety inventory with up to 321 working days of excessive inventory, which indicates severe overproduction by the manufacturer.

The average stock time of different floor façades in the factory, the buffer, as well as the site is shown in **Figure 4.24**. 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 construction 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.

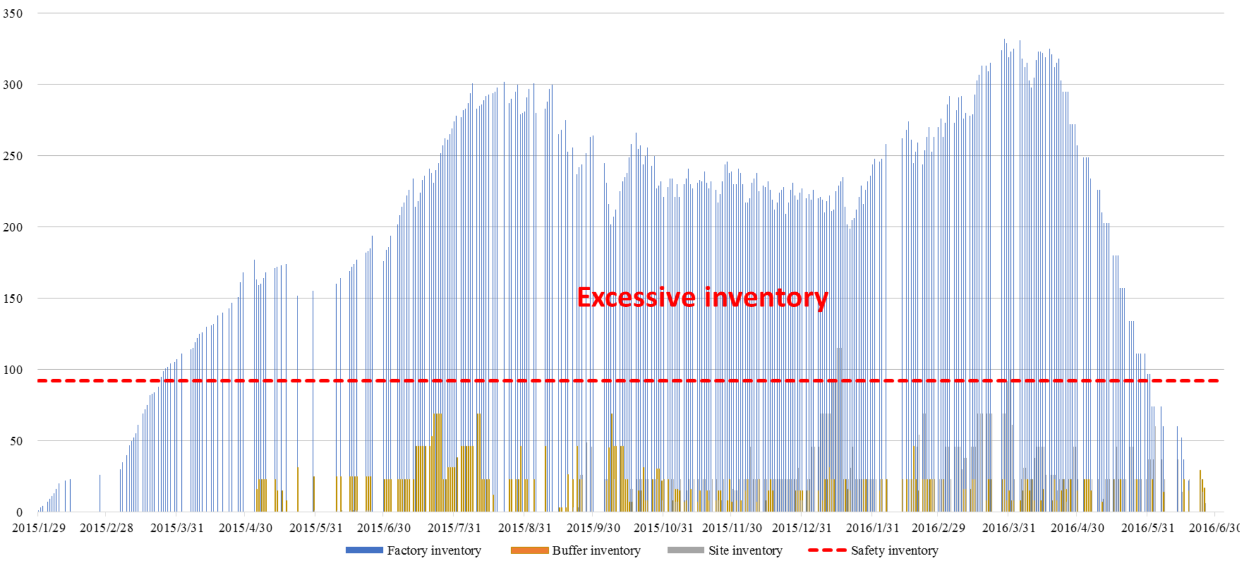


Figure 4.23 Inventory amount in different supply chain stages of the investigated building

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 adopts 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 prefers to store large quantities of components on the construction site. This situation results in a lot of waste and extra costs in the supply chain.

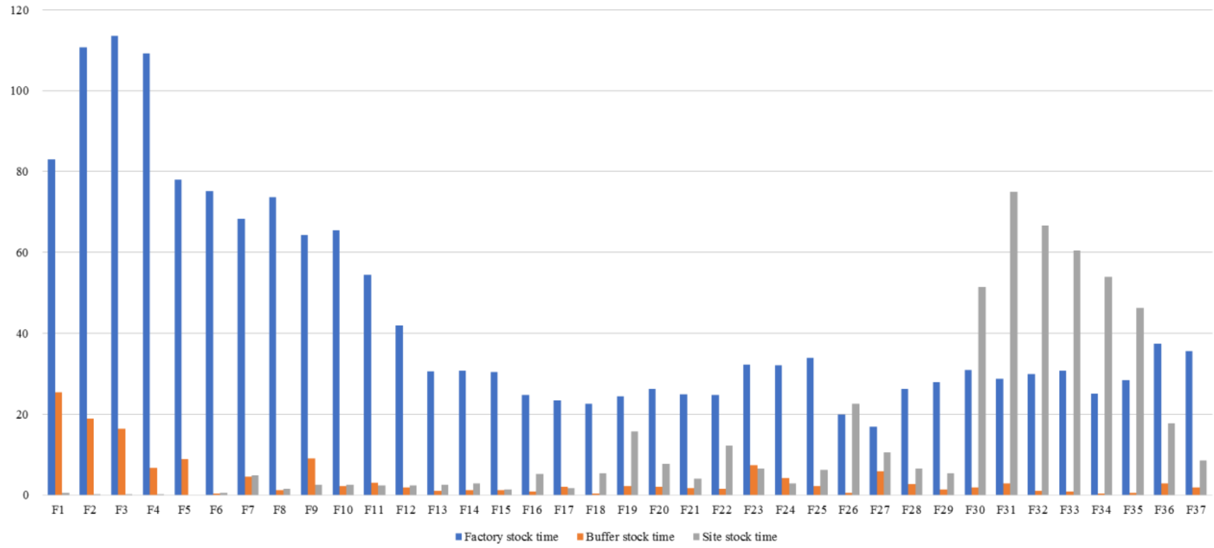


Figure 4.24 Stock time of different floors' facades of the investigated building

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 are to be directly delivered to the construction site from either the factory or the buffer. **Figure 4.25** 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 building progress can be seen, implying better supply chain performance in the later stages. Vrijhoef and Koskela (2000) point out that a considerable lead time in the beginning, particularly because of inventory and delays, is caused by uncoordinated planning and inter-organizational problems.

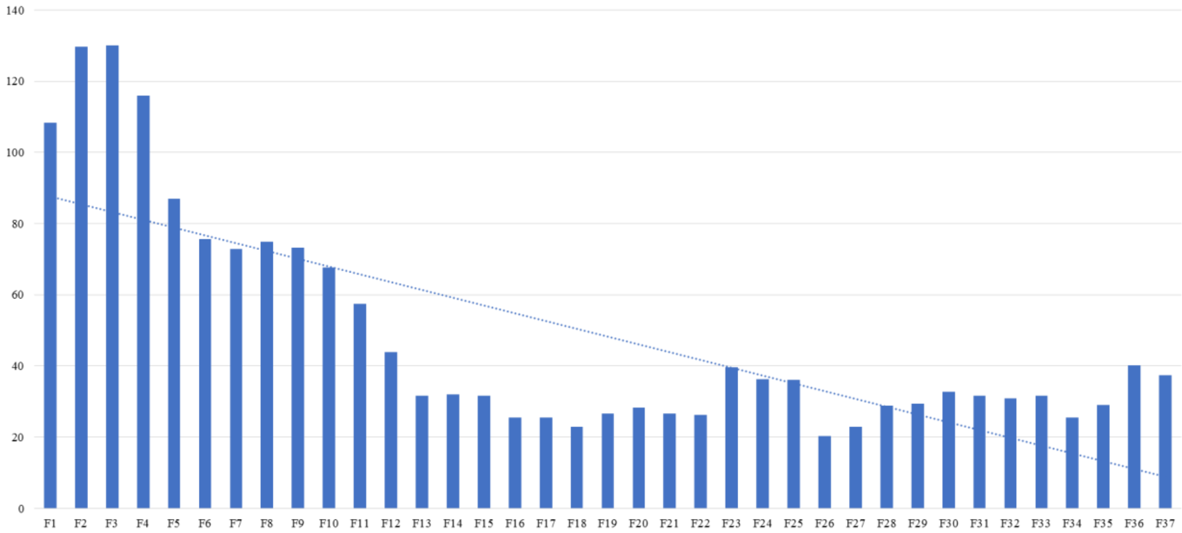


Figure 4.25 Lead time of different floors' facades of the investigated building

It is surprising to see such a long lead time since the factory adopts an over-early production principle and therefore has enough time to plan the production and control the lead time. This phenomenon suggests that the manufacturer lacks 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. 2005a) and is considered to be a barrier affecting the development of PBP.

Extra cost analysis

The poor operation of the multiple stages and the problems involved generate extra cost to the supply chain. This section provides a simple estimation of the extra cost of the investigated building resulting from overproduction, excessive inventory in the factory and the site, and assembly delay.

Overproduction is an important source of extra cost because facades are produced before they are really needed. Therefore, capital is invested into production in advance, resulting in loss of cash value. According to the interviews with the manufacturer, the production cost of a façade is approximately HK$1,500. This study assumes that the annual return rate of investment was 4.5% during the production stage of the investigated building. **Figure 4.26** shows the extra cost from overproduction in the factory, which finally leads to HK$10,914 loss of the manufacturer.

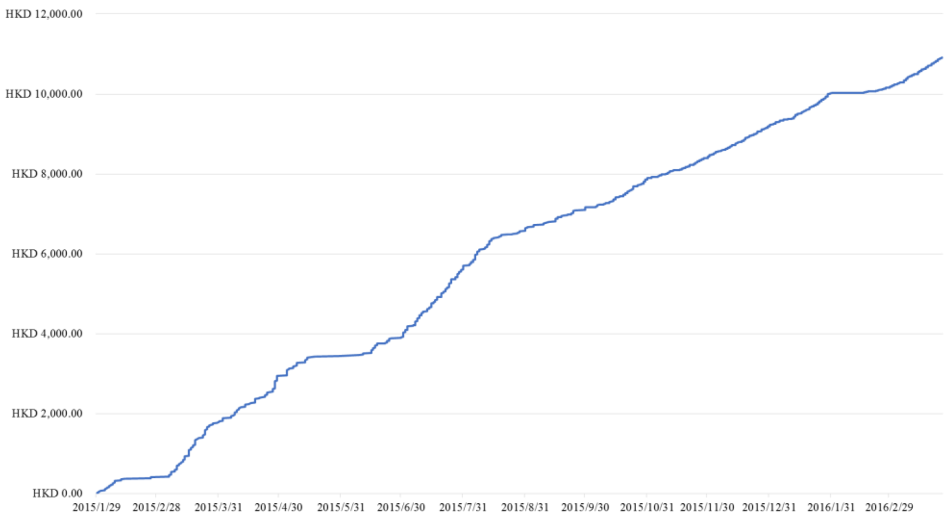


Figure 4.26 Extra cost from overproduction in the factory

Excessive inventory also generates extra cost because the factory has to provide space for storage and extra staff for management. According to the warehouse rental cost and labor cost in the mainland and Hong Kong respectively, this study assumes that daily inventory management fee of one façade is HK$0.3 and HK$1.8. **Figure 4.27** demonstrates the extra cost caused by excessive inventory in the factory and the site respectively. It can be seen that the overall costs resulting from excessive inventory in the factory and the site are HK$22,788 and HK$414,536 respectively. A huge gap exists between the extra costs in mainland and Hong Kong due to their very different consumption level and labor costs.

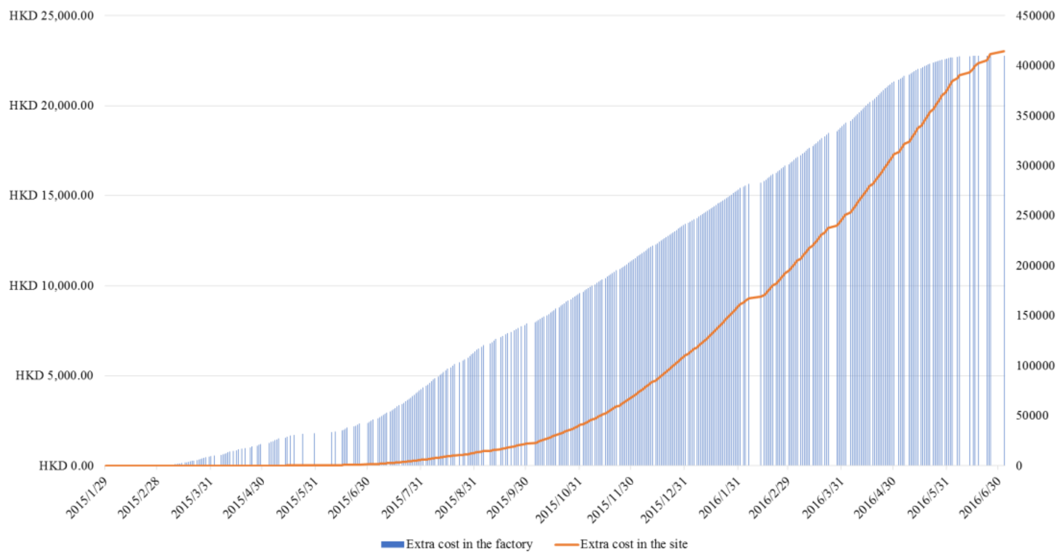


Figure 4.27 Extra cost from excessive inventory in the factory

Assembly delay in the site is also an important source of extra cost because of the consumption of more resources (i.e. labor, equipment). According to the financial report of Housing Authority, the overall cost of one unit is approximately HK$800,000. As the investigated building has 996 units, the total cost of the project is HK$796,800,000.

According to the manufacturer, the production cost of all the precast elements of the project is HK$250,000,000 that of the investigated building is calculated to be approximately HK$50,000,000. Therefore, the construction cost of the investigated building in the site of Hong Kong is HK$746,800,000. Considering that the construction time of the investigated building is 522 days with 152 days delay, daily construction cost in the construction site is calculated to be approximately HK$1,430,700. **Figure 4.28** shows the extra cost from assembly delay in the site, indicating that the loss from the delayed schedule is as high as HK$217,466,400.

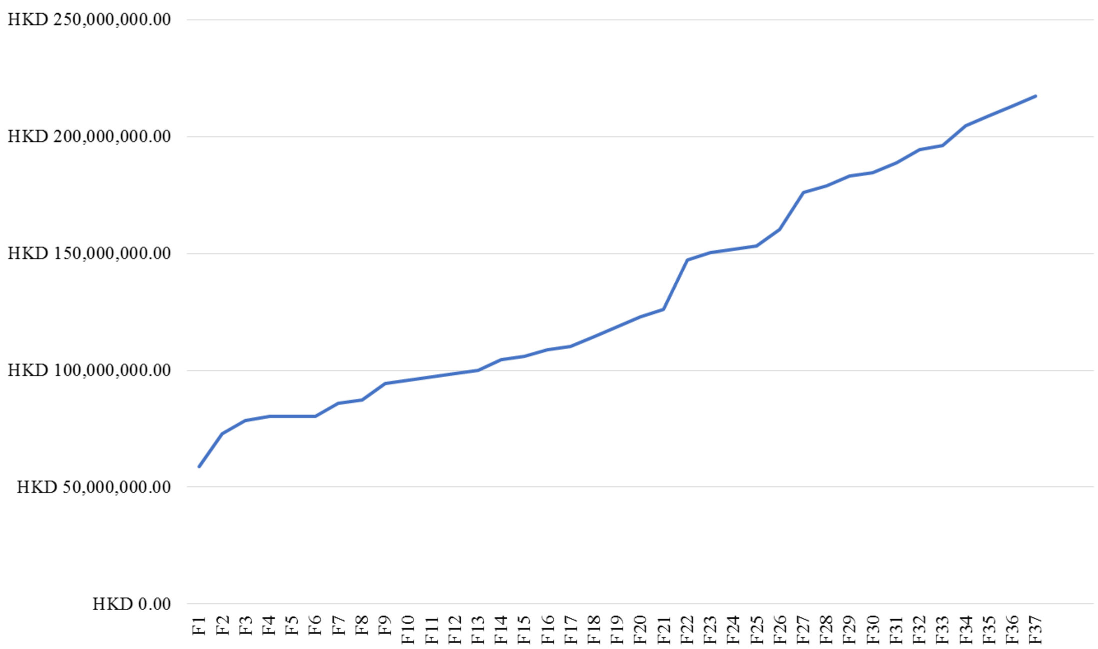


Figure 4.28 Extra cost from assembly delay

The above analysis reveals that assembly delay in the construction site has the most significant impacts on the cost performance of the supply chain because of the extremely high construction costs in Hong Kong. Excessive inventory in the site also causes high loss while extra cost in the factory is relatively low because of the relatively cheap land and labor costs in the mainland. Therefore, the assembly schedule in the site should be monitored more carefully to reduce the wastes caused to the whole supply chain.

4.2.3 Root cause of the problems

Experts from the case study project are interviewed to solicit their opinions regarding the problems and their root causes embedded in the SCM. The occurrence of the problems is analyzed in detail to gain an understanding of their source factors. Finally, the interviewed experts reach a consensus that poor supply chain planning, poor communication between stakeholders, and poor control of working flows are the root causes of the problems. These three issues also widely exist in the PBP of other countries, such as Singapore (Hwang et al. 2018), Australia (Sahin et al. 2018), and Malaysia (Pozin et al. 2016), indicating their significant impacts on the performance of the global prefabrication sector.

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 that need detailed planning to arrange the intensive work. However, as pointed out by the interviewed stakeholders, on-site construction often does not go according to plan and so disturbs original resource arrangements due to frequent variations. Such mismatches between the plan and the actual implementation has 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. On the other hand, the production profile shows that the factory followed the traditional rule of earliest due date regardless of resource considerations. However, this common trial and error approach to production planning by pre-cast firms, does not guarantee a good result (Zhai et al. 2006).

The main contractor is 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 is revised up to seven times, which greatly disrupts the plan across the supply chain. Although the enterprise resource planning (ERP) system used by the main contractor plays an important role in integrating the internal and external information flows, it mainly focuses on the managerial level of decision-making while the shop-floor schedule is only weakly connected to the system. According to the assembly sub-contractor, the shop-floor supervisors adopt a paper-based schedule that is often disrupted by engineering changes. There is 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. 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 2001a) and variation reductions in the assembly phase (Doran and Giannakis 2011). Unfortunately, the main contractor from the case study fails 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 complains that they do not receive the latest on-site information quickly since the main contractor often informs the factory of their demand very late without prior communication. The factory therefore has to use the earliest due date principle in case any sudden orders arrived, which generates huge overproduction and excessive inventory with long waiting times. Also, because the main contractor is deficient in communicating with the transporter about the latest delivery schedule of precast components, the transporter often conveys components to the buffer several days in advance, causing excessive inventory and long lead time in the buffer.

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 complains that the changes in the master program and the design are 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 does not believe that the project could be implemented as planned, and therefore produces large amounts of components in advance and keeps them in stock to address those problems caused by the poor information transfer by the main contractor.

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.

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 reach a consensus that delayed assembly schedules have a considerable propagation impact on supply chain operations. The main contractor attributes excessive installation time to low productivity and multiple errors that break the construction rhythm. Choi et al. (2017) identified site access, on-site storage area, site operations and labor productivity as the barriers impeding PBP implementation in Hong Kong. This is echoed by the case project where the poor site layout management, due to the compact area and large inventory, limits site access and on-site storage, while low productivity significantly affects site operations to cause delay and errors at the manufacturing, transportation, and installation stages. 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. 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 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, problems may occur on the construction site, such as tower crane breakdown, safety accidents, and design change, 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 has insufficient control of the various working flows, which considerably affects component quality and delivery schedule. Although the components are produced in a controlled off-site environment, they may still have some defects and therefore do 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 delays delivery of components. It is also observed that the case study project mistakenly takes delivery of components from the factory, which significantly affected installation implementation. Although all the components have a serial number marked on the surface to show their identity information, workers often make mistakes by marking wrong serial numbers or making the label ambiguous, which impedes component identification during installation.

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

4.3 Conclusion

This chapter investigates the state of a supply chain of a prefabricated building project in Hong Kong by tracing precast components across the production, logistics, and on-site assembly processes. Automation collection technologies are adopted to obtain real-time data of precast facades across the supply chain. The findings show that overproduction, excessive inventory, long lead time, limited considerations of resource planning, and significant delay in assembly schedule are serious problems which add considerable non-value-adding wastes to the supply chain and lead to cost overruns and schedule delay of project. Extra costs from the supply chain problems are simply estimated. The root cause of the problems includes poor supply chain planning, poor communication between stakeholders, and poor control of working flows.

Chapter 5 Stakeholder-associated SCR and Their Interactions in PBP

5.1 Introduction

Various supply chain risks (SCR) exist in PBP due to the technical and organizational complexities. SCR disturb and interrupt the material, information, and fund flows, and are likely to have negative impacts on the objective achievement of each firm as well as the whole supply chain with respect to the client's cost, quality and schedule advantages (Pfohl et al. 2011). High interconnectedness exists in the supply chain, and SCR can therefore be manifold (Pfohl et al. 2011), and are likely to result in many serious problems in PBP, such as late deliveries, inappropriately supplied components, and component damage (Pheng and Chuan 2001b) and redesign and extra cost (Kamar and Hamid 2011).

Understanding the cause-effect correlation between the SCR is of crucial importance, as the hidden impacts of a certain risk connected with the others would result in considerable harm to the entire supply chain (Chopra and Sodhi 2004). However, studies on SCR have mainly focused on the static perspective of risks while few of them have considered the dynamic interactions between SCR and their associated stakeholders. Since SCR are ascribed to stakeholders from design to the final assembly phase, it is important to examine SCR from their perspectives. This research adopts social network analysis (SNA) to develop the risk network of the supply chain of a prefabricated building project in Hong Kong in order to prioritize the stakeholder-associated SCR. The research findings show that poor planning of resources and schedule, poor control of working flows, and poor information sharing between stakeholders are the major challenges to the supply chains of PBP.

5.2 Results

A total of thirty SCR related to seven stakeholder groups are identified. The stakeholders (denoted as S1-S7) considered in this study include client, designer, main contractor, manufacturer, transporter, assembly sub-contractor, and government. **Table 5.1** shows stakeholder-associated SCR.

Table 5.1 A list of stakeholder-associated supply chain risks

Risk ID	Stakeholder node	Related Stakeholders	Risk node	Risks	Sources	Risk category
S1R1	S1	Client	R1	Design change	Jaillon and Poon (2010); Jaillon and Poon (2014)	Demand
S1R2	S1	Client	R2	Inefficient design approval	Hossen et al. (2015)	Process
S1R3	S1	Client	R3	Delayed payment	Cheng et al. (2010b)	Demand
S3R3	S3	Main contractor				Demand
S2R4	S2	Designer	R4	Design errors	Hossen et al. (2015)	Process
S2R5	S2	Designer	R5	Poor communication with other project participants	Taylan et al. (2014); Xu et al. (2018); Hwang et al. (2018); Pozin et al. (2016)	Control
S3R5	S3	Main contractor				Control
S4R5	S4	Manufacturer				Control
S4R6	S4	Manufacturer	R6	Delayed delivery of precast elements to the site	Pheng and Chuan (2001b); Xu et al. (2018); Liu and Lu (2018)	Supply
S4R7	S4	Manufacturer	R7	Component identification marking errors	Interview	Process
S4R8	S4	Manufacturer	R8	Unclear component identification marks	Wu and Low (2014)	Process

S4R9	S4	Manufacturer	R9	Precast components mistakenly delivered	Pheng and Chuan (2001b)	Supply
S4R10	S4	Manufacturer	R10	Poor factory layout management	Luo et al. (2015)	Process
S4R11	S4	Manufacturer	R11	Component damages	Pheng and Chuan (2001b); Azwanie et al. (2016)	Process
S5R11	S5	Transporter				Process
S4R12	S4	Manufacturer	R12	Poor quality of components	Luo et al. (2015)	Process
S4R13	S4	Manufacturer	R13	Long component lead time	Luo et al. (2015); Zhai et al. (2016); Larsson et al. (2013)	Supply
S3R14	S3	Main contractor	R14	Inaccurate initial time and resources estimation	Taylan et al. (2014)	Demand
S4R15	S4	Manufacturer	R15	Slow response to design change	Interview	Process
S3R15	S3	Main contractor				Process
S3R16	S3	Main contractor	R16	Lack of skilled labor	CIC (2014)	Process
S4R16	S4	Manufacturer				Process
S6R16	S6	Assembly sub-contractor				Process
S3R17	S3	Main contractor	R17	Safety accidents	Fard et al. (2017)	Process
S4R17	S4	Manufacturer				Process
S5R17	S5	Transporter				Process
S6R17	S6	Assembly sub-contractor				Process
S6R18	S6	Assembly sub-contractor	R18	Inefficient verification of precast components due to unclear labels	Demiralp et al. (2012); Li et al. (2017a)	Process
S3R19	S3	Main contractor	R19	Labor dispute	Aibinu and Odeyinka (2006)	Process
S6R19	S6	Assembly sub-contractor				Process
S3R20	S3	Main contractor	R20	Poor site layout management	Luo et al. (2015)	Process
S3R21	S3	Main contractor	R21	Tower crane breakdown	Li et al. (2016)	Process
S6R22	S6	Assembly sub-contractor	R22	Installation error of precast elements	Li et al. (2017b)	Process
S6R23	S6	Assembly sub-contractor	R23	Delayed assembly schedule	Li et al. (2016)	Demand
S3R24	S3	Main contractor	R24	Inadequate professional pre-planning studies for project	Hossen et al. (2015); Hwang et al. (2018)	Control

S4R24	S4	Manufacturer				Control
S5R25	S5	Transporter	R25	Transportation vehicle damage	Interview	Process
S5R26	S5	Transporter	R26	Traffic accidents	Interview	External
S5R27	S5	Transporter	R27	Prolonged custom declaration	Lu and Yuan (2013)	Control
S3R28	S3	Main contractor	R28	Bad weather	Hossen et al. (2015)	External
S6R28	S6	Assembly sub-contractor				External
S7R29	S7	Government	R29	Excessive approval procedures	Taylan et al. (2014)	Control
S7R30	S7	Government	R30	Governmental policy change	Yang and Zou (2014b)	Control

Network and node/link measures are conducted to compute critical indicators of the network, including density, cohesion, nodal degree, betweenness centrality, status centrality, brokerage, and ego size, which could reflect the complexity of the supply chain network and identify critical SCR and their links. The network analysis results are summarized as follows.

5.2.1 Network measures

Graph G (43, 195) is generated to represent the SCR network (See **Figure 5.2**), reflecting that the network comprises 43 nodes linked by 195 weighted arrows. Density and cohesion of the network are 0.108 and 0.309 respectively. The cohesion value is higher than the density value, and the mean geodesic distance between nodes is 2.303 walks, implying complex SCR interactions due to risk propagation impacts across the network.

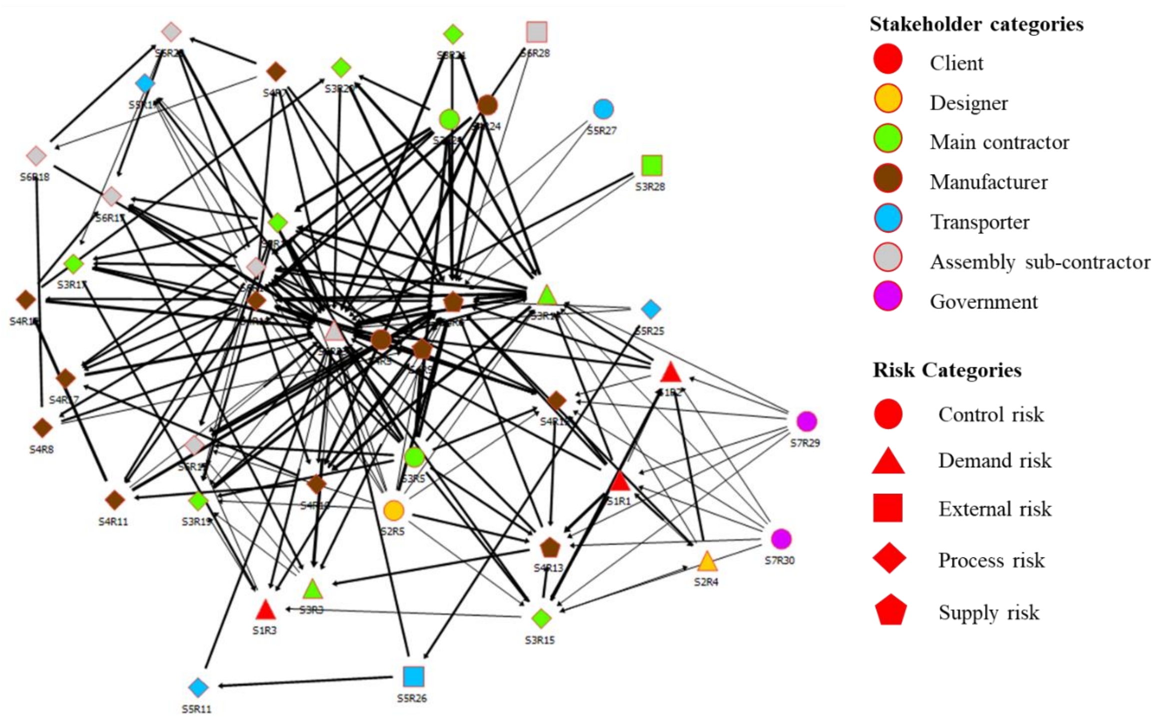


Figure 5.1 SCR network of the case project

5.2.2 Node/link measures

Nodal degree

This reflects the immediate connection features of a node. "In-degree" indicates the incoming relations (impacts received) while "out-degree" shows the outcoming relations (impacts exerted) (Loosemore 1998). Nodal degree is computed by the weighted sum of links with the immediate successors or predecessors.

Table 5.2 lists the top ten SCR with high out-degree and degree difference values. These risks have direct impacts on a large number of SCR or have higher impacts on other SCR in comparison with the impacts they receive. S3R14 ("Inaccurate initial time and resources estimation" related to the main contractor) with the highest out-degree value of 144, has the strongest direct impacts on the other risks. S3R5 (“Poor communication with other project participants” derived from the main contractor) and S4R5 (“Poor communication with other project participants” derived from the manufacturer) with high degree different values of 143 and 126 respectively; both have an in-degree value of 0, indicating that they exert strong direct influences on other risks but receive no impacts from the others. S6R23 (“Delayed assembly schedule” related to the assembly sub-contractor) and S4R6 (“Delayed delivery of precast elements to site” associated with the manufacturer) are special nodes that they have high out-degree values of 136 and 73 respectively; in the meanwhile, they are greatly affected by other risks in a direct way with extremely high in-degree values of 369 and 332 respectively, indicating that these two nodes are in the sensitive locations of the network and significantly lead to the overall network complexity.

Table 5.2 The top ten risks with high out-degree and degree difference values

Ranking	Risk ID	Out-Degree	Risk ID	Degree difference
1	S3R14	144	S3R5	143
2	S3R5	143	S4R5	126
3	S6R23	136	S3R24	72
4	S4R5	126	S2R5	70
5	S4R16	126	S3R14	68

6	S6R16	99	S1R1	63
7	S3R24	88	S4R16	40
8	S1R1	80	S4R7	39
9	S4R6	73	S4R24	32
10	S3R16	72	S2R4	24

In terms of the node type, most of the SCR are ordinary nodes, while nine of them are transmitters, including S2R5, S3R5, S4R5, S5R25, S5R27, S3R28, S6R28, S7R29, and S7R30. These risks are in need of attention since they increase the complexity of the network.

Betweenness centrality

This reflects the occurrence with which a node/link connects two other nodes/ links (Pryke 2012).

Table 5.3 demonstrates the top ten critical risks and links with high betweenness centrality. S6R23 ("Delayed assembly schedule" related to the assembly sub-contractor), S4R16 ("Lack of labor resource" related to the manufacturer), and S6R16 ("Lack of labor resource" related to the assembly sub-contractor) with the highest betweenness centrality are the hubs in the network to connect many pairs of nodes and consequently lead to risk propagation. Meanwhile, these three risks are included in nine of the most important links as shown in **Table 5.3**. Therefore, these risks should be well addressed to reduce the complexity of the network.

Table 5.3 The top ten risks and links with high betweenness centrality.

Ranking	Risk ID	Node Betweenness Centrality	Link ID	Link Betweenness Centrality
1	S6R23	0.330002	S6R23→S4R16	237.867
2	S4R16	0.158037	S6R23→S6R16	119.641
3	S6R16	0.066172	S4R16→S4R12	65.156
4	S4R6	0.049055	S4R16→S4R7	64.406
5	S3R14	0.043984	S4R16→S4R8	62.406
6	S3R16	0.021366	S6R23→S3R16	57.272
7	S4R15	0.020535	S6R23→S4R10	39.234
8	S4R10	0.019357	S6R16→S6R22	37
9	S4R12	0.018064	S4R15→S4R13	36.25
10	S4R7	0.013012	S4R16→S4R15	33.906

By comparing **Table 5.2** and **Table 5.3**, it is found that four risks including S4R15 ("Slow response to design change" related to the manufacturer), S4R10 ("Poor factory layout management" related to the manufacturer), S4R12 ("Poor quality of components" related to the manufacturer) and S4R7 ("Component identification marking errors" related to the manufacturer) are important nodes that build connections between risks although they do not have strong immediate impacts on the others, indicating that the manufacturer plays the important role of a hub in connecting the stakeholders across the supply chain.

Status centrality

This indicates the relative influence of a node through considering the links with its immediate neighbours as well as all other nodes that could be connected with the node via the immediate neighbours (Katz 1953).

Table 5.4 shows the top ten risks with high out-status centrality. S3R5 ("Poor communication with other project participants" derived from the main contractor) is the most important risk that has the highest out-status centrality value of 1.278, indicating its significant impacts on the risk level of the whole network. It is noted that all the risks in **Table 5.4** have already been identified in **Table 5.2** or **Table 5.3**, indicating their significant effects on the overall interactions in the network.

Table 5.4 The top ten risks with high out-status centrality.

Ranking	Risk ID	Out-Status Centrality

1	S3R5	1.278149
2	S3R14	1.271659
3	S4R5	1.127089
4	S6R23	1.109298
5	S4R16	0.915882
6	S3R24	0.842859
7	S6R16	0.746787
8	S1R1	0.69263
9	S4R6	0.622822
10	S2R5	0.599011

Figure 5.3 illustrates the status centrality map of all the risks in which the node colors and shapes stand for the stakeholder categories and the risk types respectively. The more central status a risk locates in, the higher impacts on the network interactions the risk has. Obviously, the risks related to the main contractor, the manufacturer and the client locate in the very central status of the circle, indicating their significant roles in coordinating the supply chains of PBP. The demand and control risk categories are located more centrally than other risk types, providing two implications: (i) the downstream supply chain managed by the client and the main contractor is a significant

risk source in the network, and plays an important role in the overall network interactions, and (ii) the control risks that determine the transformation of the client's order into raw material requests are important source nodes that have great potential to generate more risks, thereby leading to the complexity of the entire risk network.

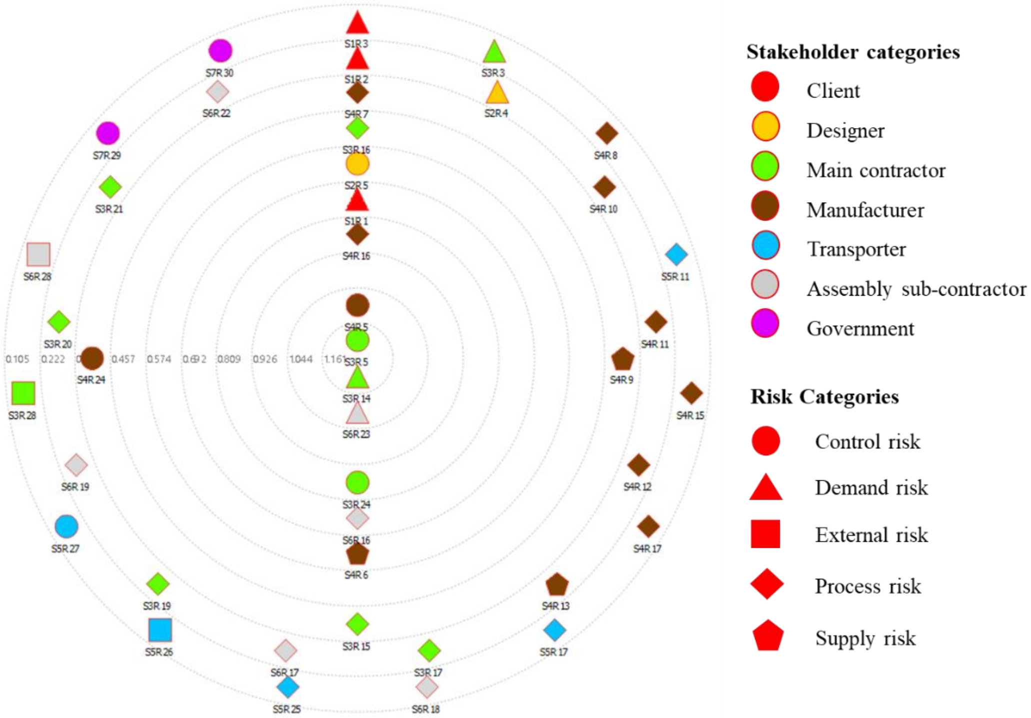


Figure 5.2 Status centrality map

Brokerage

This measures the number of times a node is involved in the five kinds of brokerage relationships (Coordinator, Gatekeeper, Representative, Itinerant, and Liaison) given a partition vector being analyzed in all the triads (Gould and Fernandez 1989). The stakeholder category is selected as the partition vector in this study.

Table 5.5 shows the top ten risks with high brokerage value. These risks are recognized as significant risks because of their important functions in linking different stakeholders. This can also be explained by the fact that the influence between different stakeholder categories would not exist if these risks were deleted. S6R23 (“Delayed assembly schedule” related to the assembly sub-contractor) is the most critical risk mainly because of its gatekeeper and liaison functions. Two risks, including S4R13 (“Long component lead time” associated with the manufacturer) and S3R15 (“Slow response to design change” associated with the main contractor) that are not included in above analysis, are also identified as critical risks due to their brokerage roles in the network. In addition, the main contractor, the manufacturer, and the assembly sub-contractor are found to be responsible for most of the risks in **Table 5.5**, indicating their important roles in communication with other stakeholders embedded in the supply chain to address the risks.

Table 5.5 The top ten risks with high brokerage value.

Ranking	Risk ID	Partition Value	Coordinator	Gatekeeper	Representative	Itinerant	Liaison	Total
1	S6R23	S6	12	74	37	45	109	277
2	S4R6	S4	8	36	18	10	29	101
3	S4R16	S4	13	34	6	3	11	67
4	S3R14	S3	3	19	3	1	21	47

5	S6R16	S6	1	13	5	7	17	43
6	S3R16	S3	5	3	11	1	7	27
7	S4R13	S4	1	3	1	2	6	13
8	S3R15	S3	0	0	3	2	8	13
9	S4R10	S4	5	6	0	0	0	11
10	S1R1	S1	0	0	0	0	10	10

Ego size

This measures the number of direct successors or predecessors of a node (Wasserman and Faust 1994).

Table 5.6 illustrates the top ten nodes with high ego size, indicating their direct influence on large numbers of nodes. These nodes are also identified by calculating the abovementioned metrics, thus reflecting the multiple impacts sourced from them.

Table 5.6 The top ten risks with high ego size.

Ranking	Risk ID	Size
1	S6R23	37
2	S4R6	28

3	S4R16	19
4	S3R14	17
5	S6R16	16
6	S3R5	13
7	S3R16	13
8	S2R5	12
9	S4R5	11
10	S4R15	11

5.3 Critical challenges in PBP

The SNA indicators provide a comprehensive profile of stakeholder-associated SCR and their interactions, which enables us to understand critical SCR and links from four aspects, including degree of nodes, betweenness centrality, status centrality, and brokerage, from which different functions of SCR in the network are fully considered.

Critical risks are identified based on the SNA metrics analyzed above. The rankings of SCR, however, differ in different SNA metrics calculation due to their different roles in the network. Previous research often identified the top 3 or 5 risks from each metric perspective as critical factors (e.g. Yang et al. 2015; Yu et al. 2017) since they have the most significant impacts on the complexity of the network. Therefore, this study identifies the top 5 risks in each ranking list as the critical SCR. Meanwhile, the SCR that are included in three or more ranking lists are also considered as significant risks given their multiple roles in influencing network interactions. As a result, a total of nine critical SCR in the case project are finally identified.

Those links ranking top 10 in link betweenness centrality are identified as critical links. It is found that the critical nodes are associated with nine of the critical links identified in **Table 5.3**, indicating their crucial roles in influencing the network. For the purpose of better understanding the critical risks and links, they are categorized into three major challenges. Those risks and links in the same category share similarities and could therefore be tackled by similar strategies. Critical SCR, links and challenges are summarized in **Table 5.7**. The major challenges include poor supply chain planning, poor control of working flows, and poor information sharing between stakeholders.

Table 5.7 Major challenges.

Critical nodes/links	Associated stakeholders	Primary challenges
S3R14	Main contractor	1. **Poor supply chain planning**.
S4R16	Manufacturer	• Frequent revisions of the master program reflect poor planning of resources and schedule by the main contractor.
S6R16	Assembly sub-contractor	

		• Resources deployment in the factory and the site is largely disrupted as a result of poor master planning, which causes severe problems with significant propagation impacts, such as lack of labor.
S4R6	Manufacturer	2. **Poor control of working flows**.
S6R23	Assembly sub-contractor	• The poor management and inspection of internal working flows result in significant schedule and quality problems in both the production and assembly stages.
S6R23→S4R16	Assembly sub-contractor	
S6R23→S6R16	Assembly sub-contractor	• Delays in the delivery and the assembly phases caused by poor internal flow management do not exist individually but interact with each other directly.
S6R23→S3R16	Assembly sub-contractor	
S6R23→S4R10	Assembly sub-contractor	
S4R16→S4R15	Manufacturer	
S4R16→S4R12	Manufacturer	
S4R16→S4R7	Manufacturer	
S4R16→S4R8	Manufacturer	
S6R16→S6R22	Assembly sub-contractor	
S2R5	Designer	3. **Poor information sharing between stakeholders**.
S3R5	Main contractor	• The obsolete communication ways between stakeholders make it hard to obtain real-time information of the project.
S4R5	Manufacturer	
S4R15→S4R13	Manufacturer	

S1R1	Client	• The unawareness of frequent information exchanges results in outdated informing of variations occur in the supply chain to stakeholders.

5.4 Network analysis after removing the key nodes and links

The significant role of the key nodes and links identified in **Table 5.7** has been recognized by the SNA indicators, but does not reveal the extent to which they influence the network complexity. This section uses the examination method suggested by Yu et al. (2017) and Yang et al. (2015) to build a new network that eliminates all the critical risks and links in order to analyze their influence on the network through re-calculating the major SNA indicators.

The calculation results show that the new risk network is transferred into a graph with 34 nodes linked by 46 arrows as shown in **Figure 5.4**. The density of the network is brought down by 62.04% from 0.108 to 0.041, while the cohesion is abated by 79.31% from 0.309 to 0.063, implying that the complexity of the network is remarkably decreased. Also, the betweenness centrality values of nodes and links are both reduced considerably as shown in **Table 5.8**, reflecting that the risk propagation impacts throughout the network are significantly lessened. In addition, four risks become isolated nodes and can therefore be tackled individually without considering their propagation impacts, which largely alleviates the difficulties in dealing with the SCR.

Therefore, the complexity of the entire risk network after removing the key nodes and links is greatly reduced, indicating that useful strategies are worthy of development to fully address the challenges.

Table 5.8 Comparison of critical indicators between the original and new networks

Ranking	Node Betweenness Centrality			Link Betweenness Centrality		
	Original network	New network	Reduction	Original network	New network	Reduction
1	0.330002	0.020833	93.69%	237.867	25	89.49%
2	0.158037	0.017045	89.21%	119.641	18	84.95%
3	0.066172	0.017045	74.24%	65.156	16	75.44%
4	0.049055	0.014205	71.04%	64.406	14	78.26%
5	0.043984	0.011364	74.16%	62.406	14	77.57%
6	0.021366	0.00947	55.68%	57.272	13	77.30%
7	0.020535	0.00947	53.88%	39.234	12	69.41%
8	0.019357	0.008523	55.97%	37	12	67.57%
9	0.018064	0.007576	58.06%	36.25	10	72.41%
10	0.013012	0.006629	49.05%	33.906	10	70.51%

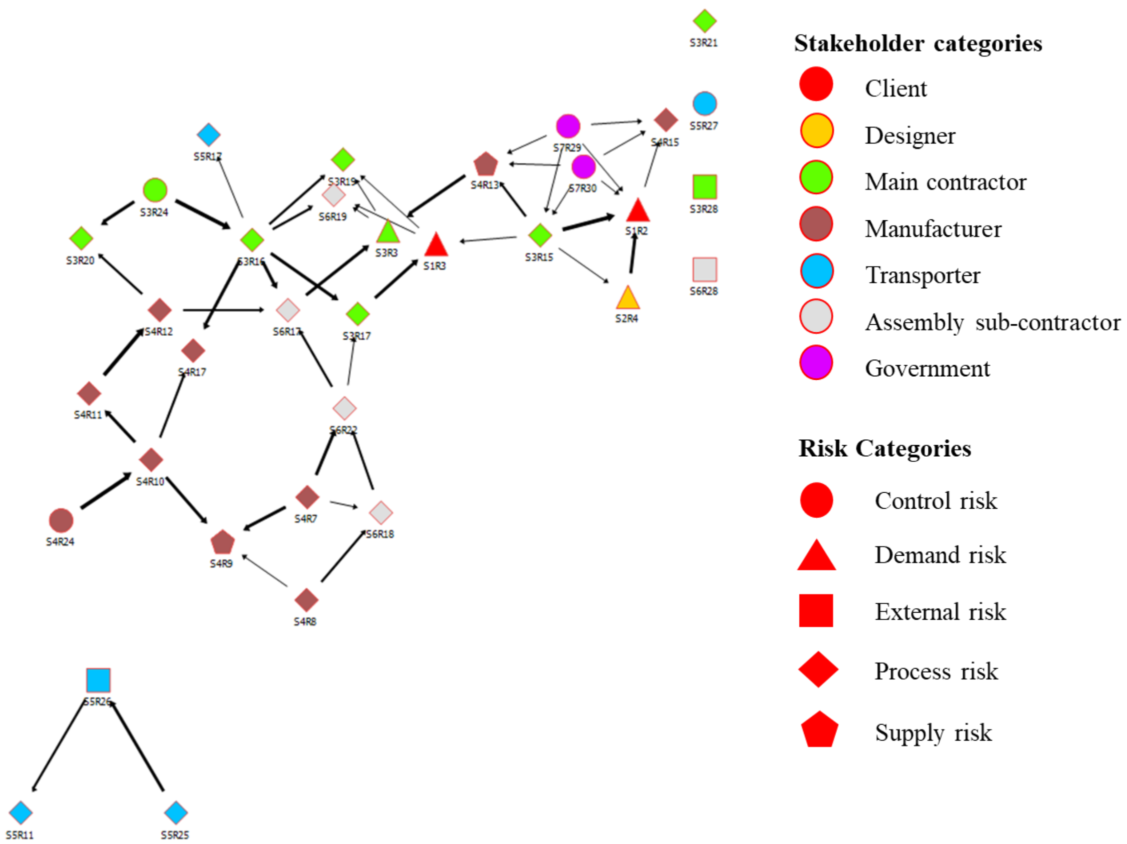


Figure 5.3 SCR network after removing the key nodes and links

5.5 Chapter summary

This chapter adopts mixed methods to identify and analyze the stakeholder-associated SCR in PBP in Hong Kong. Thirty risks associated with seven stakeholders are identified. A social network of the SCR in a case project is established to prioritize the SCR. As a result, nine critical risks and eleven critical links are identified, from which three major challenges to PBP in Hong Kong are drawn, including poor planning of resources and schedule, poor control of working flows, and poor information sharing between stakeholders.

Chapter 6 A Model for Simulating SCR in PBP

6.1 Introduction

This chapter provides a SD model to evaluate the impacts of the critical SCR on the supply chain performance of PBP in Hong Kong. First, the model development details, including the variables involved and their cause-effect relationships are explained. This is followed by model validation to test the confidence of the model. Finally, base run simulation and scenario analysis are carried out to assess the impact of SCR on the performance of the supply chain.

6.2 Model development

The developed model uses SD to model the supply chain with the critical SCR being considered. The model will be used to measure the impacts of the SCR on the performance of the project, which majorly include inventory, quality and schedule aspects. Specifically, component inventory reveals the number of components kept in stock in both the factory and the construction site throughout the supply chain, which, on the other hand, could indicate the overproduction and cost concerns. Quality problems are associated with the number of produced components and the quality defective rate, and therefore will be modelled considering these two parameters. Schedule delay is majorly ascribed to the delay due to design change, delayed delivery time of precast components and reinstallation time of precast components, which therefore will be highlighted in the modelling process. In addition, these problems caused by the SCR require extra labor to deal with them and thereby reduce their impacts on the project supply chain. Therefore, the demand for the input of additional labor resources will also be modelled.

6.2.1 Conceptual model of the supply chain

The supply chain is modelled using the SD model. To determine the system boundary, this study views the model as two subsystems, including the supply chain subsystem and the SCR subsystem.

The supply chain subsystem includes the design, manufacturing, transportation, and assembly processes. The client usually directly recruits a consultant for design work and a main contractor for supply chain coordination. The design drawings will then be provided for the factory and the main contractor for precast component production and on-site engineering construction respectively. According to the on-site construction schedule, the main contractor will send order information of demanded precast components to the factory. Accordingly, the transporter then conveys the components to the buffer or the site directly as required by the main contractor. Finally, all the components will be installed to form an entire building.

The SCR subsystem depicts the impacts of SCR on the performance of the supply chain. Multiple SCR are embedded in different processes of the supply chain and disrupt the information, material and service flows. Construction supply chain research often categorizes SCR into process, control, demand, supply, and environment risks (Gosling et al. 2013; Pfohl et al. 2011). SCR do not exist independently, but have close cause-effect relationships with each other, resulting in considerable impacts on project performance, such as excessive inventory, schedule delay and quality defects.

6.2.2 Causal-loop diagram

The causal-loop diagram is a conceptual tool that portrays the structure of a SD model to capture the feedback mechanism. It could dynamically trace the chain effects of a cause via a series of associated variables back to the original cause (Sterman 2000). **Figure 6.1** shows ten feedbacks within the causal-loop diagram to reveal the SCR impact mechanism in PBP, including one positive and nine negative feedbacks. It reveals the major variables in the supply chain of PBP, some of which represent critical risks, such as delayed delivery of precast elements to the site, installation errors, and component quality problems. The relationships between the variables are shown with feedbacks. The plus sign means the value of the target variable increases with the source variable, while the minus sign has the opposite meaning. This figure aims to reveal how the critical risks interact to affect the supply chain performance.

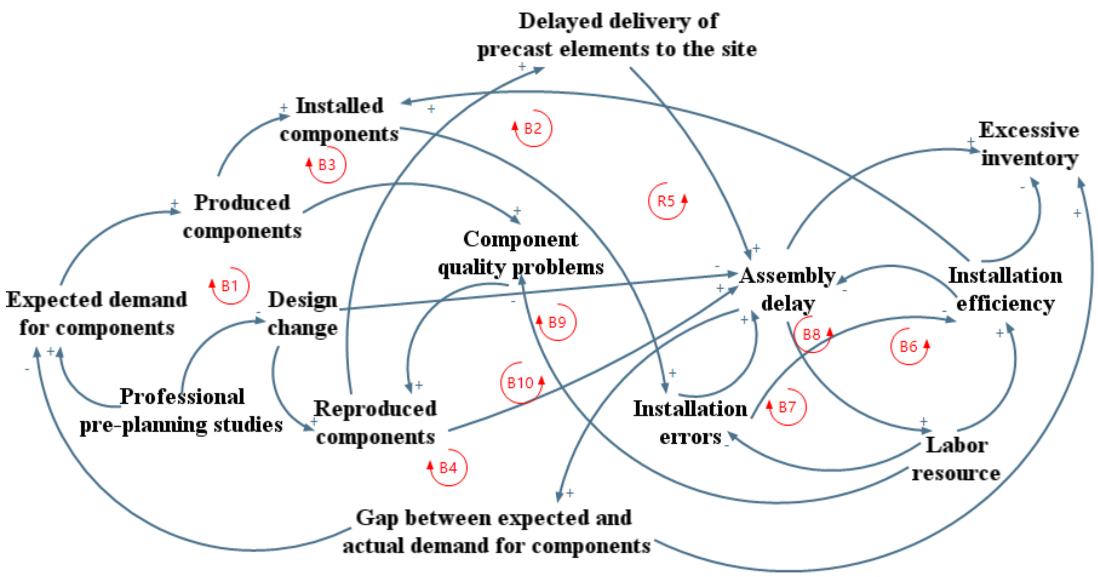


Figure 6.1 Causal-loop diagram of the model

Feedback 1 is a balancing (negative) loop showing the chain impacts of component quality problems and assembly delay. Specifically, expected demand for components drives the production in the factory, and the more produced, the more quality problems are likely to be identified, thereby requiring reproduction of the elements. As a consequence, assembly delay will be caused, resulting in a gap between expected and actual demand for precast components. This gap is negatively related to the expected demand for components.

Feedback 2 is a balancing (negative) loop and has similar chain effects with Feedback 1. An additional variable in Feedback 2 is delayed delivery of precast elements to the site. The reproduction of precast components will engender delayed delivery which is an important cause of assembly delay.

Feedback 3 is a balancing (negative) loop and has common variables with Feedback 1 and 2. Additionally, it shows that the more components produced, the more installed. As a result, more installation errors are expected to occur. The errors are an important source of assembly delay which will cause a gap between expected and actual demand for precast components.

Feedback 4 is also a balancing (negative) loop with many variables in common with Feedback 3. The additional variable is installation efficiency which will be negatively affected by installation errors, resulting in assembly delay.

Feedback 5 is a reinforcing (positive) loop having some same variables with Feedback 3 and 4. Additionally, assembly delay requires more labor resource to catch the expected schedule. The more labor, the higher the installation efficiency. The improved installation efficiency will generate more elements to be installed, in which more installation errors are likely to occur.

Feedback 6 is a balancing (negative) loop with three variables, namely, assembly delay, labor resource and installation efficiency. Apart from the interconnections included in Feedback 5, more labor resource could effectively mitigate assembly delay.

Feedback 7 is a balancing (negative) loop having similar cause-effect relationships with Feedback 6. It shows that assembly delay could be caused by installation errors which can be reduced by inputting more labor resource.

Feedback 8 is a balancing (negative) loop that covers the four variables of Feedback 6 and 7, illustrating the negative effects of installation errors on installation efficiency which is negatively associated with assembly delay. Labor resource is a significant element that could mitigate the delay.

Feedback 9 is a balancing (negative) loop with five variables, including delayed delivery of precast elements to the site, assembly delay, labor resource, component quality problems, and reproduced components, describing the chain effects of schedule and quality issues in the supply chain.

Feedback 10 is a balancing (negative) loop with similar interaction mechanism with Feedback 9. More labor resource contributes to the reduction of component quality problems which subsequently influence the remanufacturing of components and assembly delay, indicating the significant impacts of resources in mitigating supply chain problems.

6.2.3 Stock-flow diagram

Figure 6.2 shows the stock-flow diagram of the model, and Table 6.1 demonstrates the variables in the model.

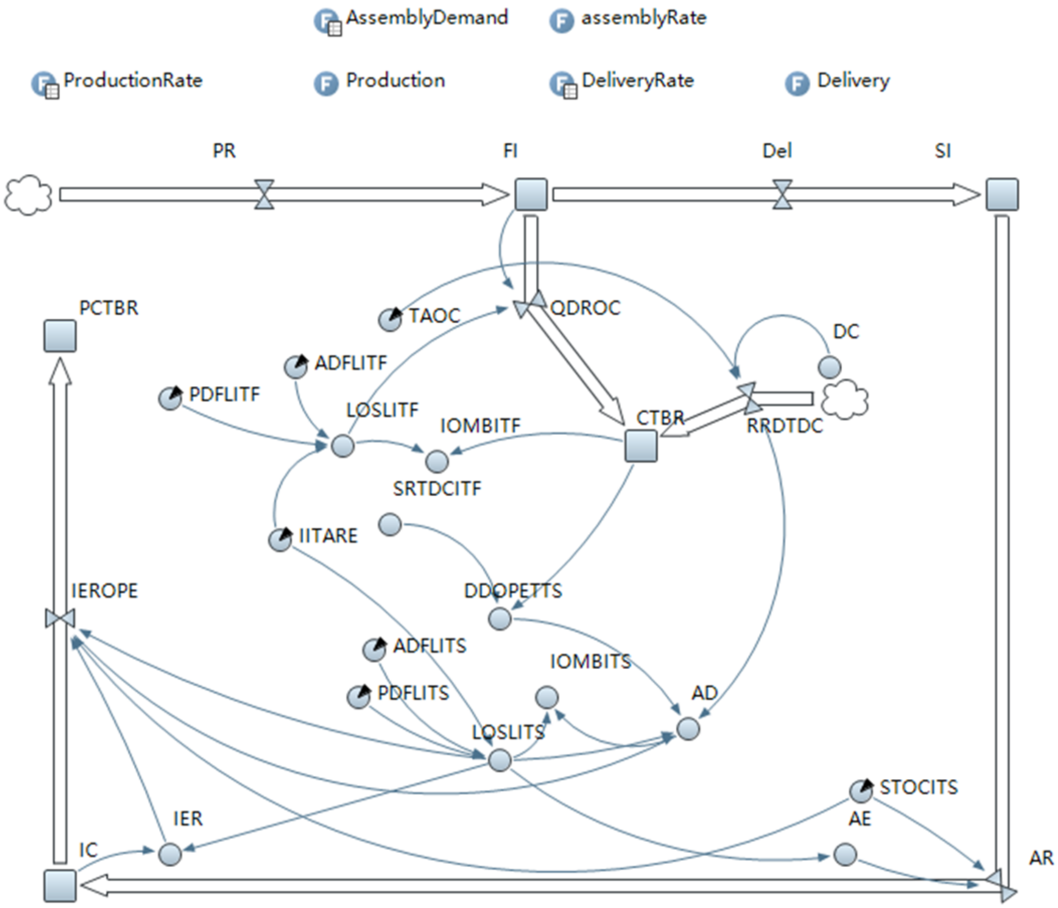


Figure 6.2 Stock-flow diagram of the model

Table 6.1 The variables in the model

Abbreviation	Variables	Variable type
PR	Production rate	Flow
CTBP	Components to be produced	Stock
TAOC	Total amount of components	Constant
STOCITF	Stock time of components in the factory	Constant
FI	Factory inventory	Stock
Del	Delivery	Flow
BI	Buffer inventory	Stock
SI	Site inventory	Stock
STOCITS	Stock time of components in the site	Constant
AR	Assembly rate	Flow
RRDTDC	Reproduction rate due to design change	Flow
DC	Design change	Auxiliary variable
CTBR	Components to be reproduced	Stock
DDOPETTS	Delayed delivery of precast elements to the site	Auxiliary variable
IITARE	Inaccurate initial time and resources estimation	Auxiliary variable

SRTDCITF	Slow response to design change in the factory	Auxiliary variable
LOSLITF	Lack of skilled labor in the factory	Auxiliary variable
LOSLITS	Lack of skilled labor in the site	Auxiliary variable
PDFLITF	Planned demand for labor in the factory	Constant
ADFLITF	Actual demand for labor in the factory	Constant
PDFLITS	Planned demand for labor in the site	Constant
ADFLITS	Actual demand for labor in the site	Constant
IOMLITF	Input of more labor in the factory	Auxiliary variable
IOMLITS	Input of more labor in the site	Auxiliary variable
QDROC	Quality defective rate of components	Flow
IEROPE	Installation error rate of precast elements	Flow
IER	Installation error rate	Auxiliary variable
IC	Installed components	Stock
PCTBR	Precast components to be reinstalled	Stock
AE	Assembly efficiency	Auxiliary variable
AD	Assembly delay	Auxiliary variable

The client recruits a designer directly and provides the design drawings for the manufacturer and the main contractor. Design change is a significant risk originated from the client. Since the stakeholders convey the latest information to each other using the traditional paper-based ways, their communication is inefficient. Therefore, the factory and the main contractor usually need several days to respond to the variations.

The main contractor is the major coordinator and planner of the supply chain. The master program from the main contractor reveals the milestones of the project. Therefore, the factory and the assembly sub-contractor arrange production and on-site construction schedule and resource deployment based on the master program. Revisions, however, often take place in the master program, which significantly disrupts the manufacturing and the on-site construction processes. In addition, such poor planning of resources often results in a large gap between the planned and actual demand for labor. The assembly sub-contractor is expected to complete the installation of each typical floor within six cycle days. However, the frequent revisions and errors in the assembly processes generate schedule delay, resulting in an assembly cycle of up to nine days for each typical floor. The delay leads to lack of skilled labor in the factory and the site.

The manufacturer produces precast components according to the on-site assembly schedule. The main contractor usually sends the expected schedule to the factory four months in advance. Ideally, the manufacturer keeps two floors of components in inventory in the factory. However, the project is often rescheduled, resulting in a significant gap between the expected and actual demand for precast components. Once the on-site assembly is interrupted, the manufacturer has to store more components than expected. Excessive inventory means higher costs invested in production.

6.3 Model validation

Before any analysis could be carried out, it is important to build confidence in the model via structure test and behavior test (Forrester and Senge 1980). Qudrat-Ullah and Seong (2010) propose a series of tests for model validation, including (1) boundary adequacy test, which examines whether all the important concepts and structures are considered in the model, (2) structure verification, which tests the consistency of the model structure with related descriptive knowledge simulated in the system, (3) dimensional consistency test, which evaluates whether the equations of the variables are dimensionally in line with the real world, (4) parameter verification, which reveals whether all the parameters correspond to descriptive knowledge of the system, and (5) extreme conditions test, which examines whether the model behaves logically when subjected to extreme conditions. These tests constitute the core of SD model tests (Qudrat-Ullah and Seong 2010) and are used in this study to validate the robustness and reliability of the model.

Test 1 concerns whether all the important variables are computed in the model and are consistent with the research aim. This study conducts an on-site survey of the case project and invite the stakeholders to assess whether all the essential factors that constitute the system are contained in the model. By fully reviewing the stock-flow diagram, the study assures that all the essential variables are considered in the model and are in line with the research goal while those are irrelevant are excluded.

Test 2 examines the logicality of the model structure and could be particularly supported by practical data or the literature. This test is performed through examining the causal-loop diagram and the stock flow diagram to see whether the relationship structure involved matches the practice and professional knowledge. As the cause-and-effect relationships and the feedback loops are identified either from the literature (Li et al. 2017a) or based on the knowledge/experience of SCM for PBP, the model is believed to reasonably reflect the real world.

Test 3 checks the unit conformity of the variables in the model. It is required to ensure dimension consistency of the model by inspecting the measurement units of the variables and equations involved. This test has been done manually, and the model has been validated to be dimensionally consistent.

Test 4 verifies whether the parameters settings fit the real situations of practical projects. Since the values of all the parameters are based on the project documents (i.e., production records, master program) and the stakeholders' knowledge and experience of the case project, the model in this study could pass Test 4 as it reflects the real situation of a typical PBP.

Test 5 is performed under extreme conditions to inspect the model behaviors. According to Li et al. (2017a), design change and installation errors have extremely high probability to occur with considerable impacts on the supply chain performance of PBP. This study therefore assigns extreme values to these two variables. Specifically, design change is set to 0 and 100% respectively, revealing two scenarios in which this risk will not occur or will occur with 100% probability respectively. Similarly, installation errors are also set to 0 and 100% respectively to generate two scenarios in which the installation problems will be taken into account in two extreme environments. As a result, component inventory, schedule delay and quality problems remain at a reasonable level, indicating that the model behaviors comply with real situations based on the stakeholders' knowledge and experience.

The above analysis shows that the model has passed all the major tests and is therefore suitable for further analysis and simulation.

6.4 Results and discussions

6.4.1 Base run simulation

The base run simulation is modelled over 540 days, corresponding to the construction time of the case project. The simulation results have been illustrated in Figure 6.3 to Figure 6.6. The simulation results reveal the impacts of the SCR on the performance of the project supply chain by showing how the schedule, inventory, and quality problems vary dynamically over the project duration.

Figure 6.3 shows that the inventory in both the factory and the site are kept at a very high level, indicating huge wastes generated by the SCR. As can be seen, the greatest factory inventory reaches as large as 430 precast components, amounting to almost 10 floors of facades. The factory inventory decreases quickly in the second half of project duration; by contrast, the site inventory observes rapid increase in the later stage of the supply chain. This situation reflects that the downstream demands components at a fast space, but they cannot complete the assembly work soon due to the lack of skilled labor in the site. At the end of the simulation time, the site has up to 535 precast components in stock, indicating long schedule delay caused by the installation of those components and excessive storage area and costs.

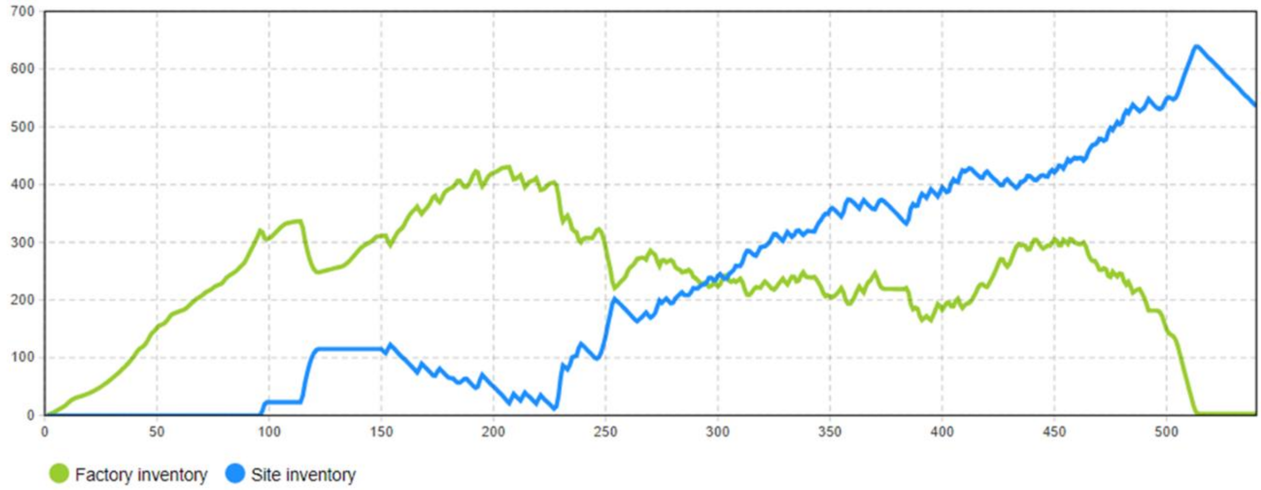


Figure 6.3 Inventory analysis

Figure 6.4 illustrates the number of precast components to be reproduced due to quality problems and design change and to be reinstalled due to the installation errors. Precast components to be reproduced shows an upward trend over the project duration, reaching a total of 130 components, revealing the significant impacts of the quality problems in the factory. Precast components to be reinstalled remains very few in the initial stage of the supply chain, but later increases quickly to 228 components, showing that the downstream is much more sensitive to the risk of skilled labor shortage.

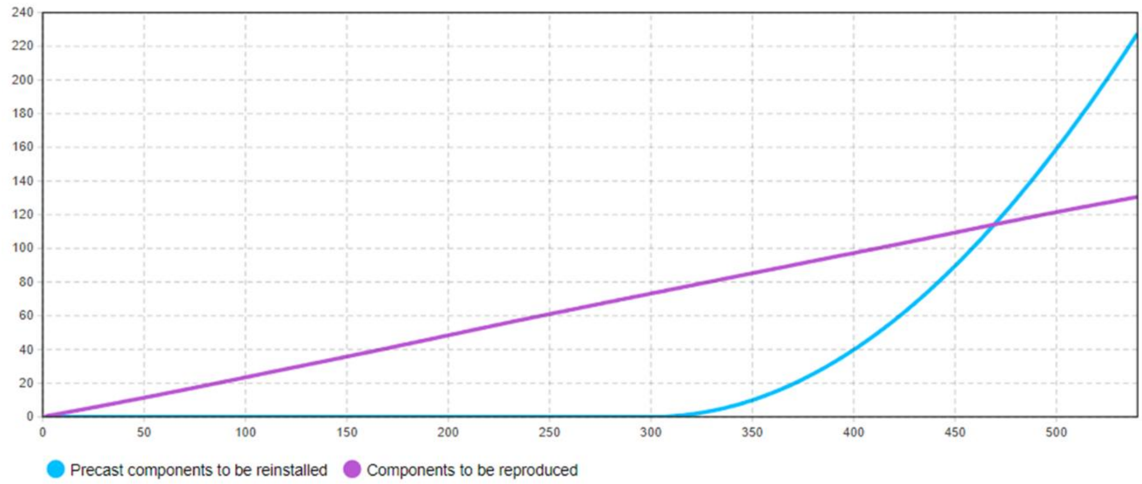


Figure 6.4 Reinstallation and reproduction analysis

Figure 6.5 demonstrates the assembly delay and delayed delivery of precast components to the site. Delayed delivery of components to the site, which is caused by quality problems in the factory and design change, slowly increases during the project duration and finally has a total of 31 days of delay. This delay has a direct impact on the assembly schedule. The trend of assembly delay is more complex than that of the factory's delivery delay, rising slowly in the first 250 days and then observing a rapid increase to 78 days. This is because assembly schedule is affected by multiple risk factors, including installation errors, lack of skilled labor in the site, component reproduction due to design change, and delayed delivery to the site. Therefore, assembly schedule is sensitive the variations in both the upstream and the downstream supply chain, resulting in considerable schedule delay.

Figure 6.6 illustrates the demand for more labor in the factory and the site. The factory and the site are in demand of extra 17 and 10 labor respectively to deal with problems caused by the SCR.

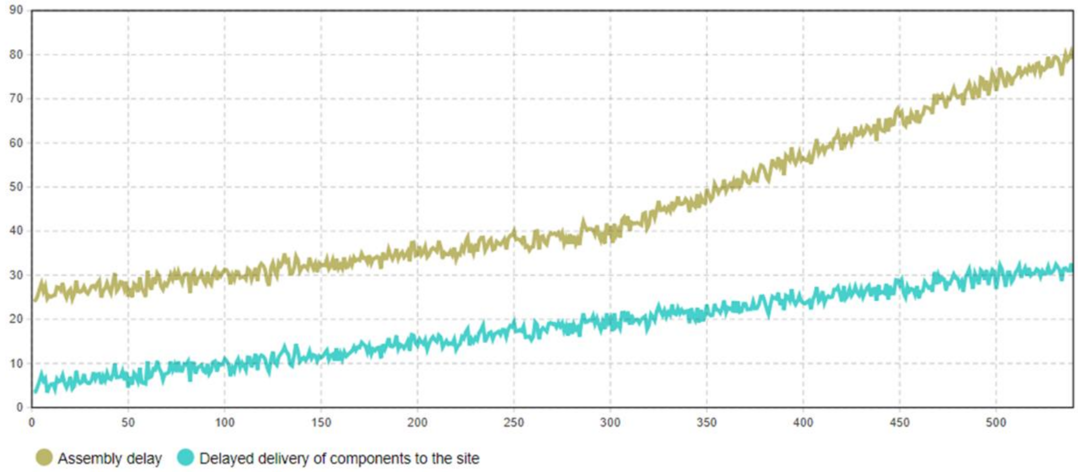


Figure 6.5 Delay analysis

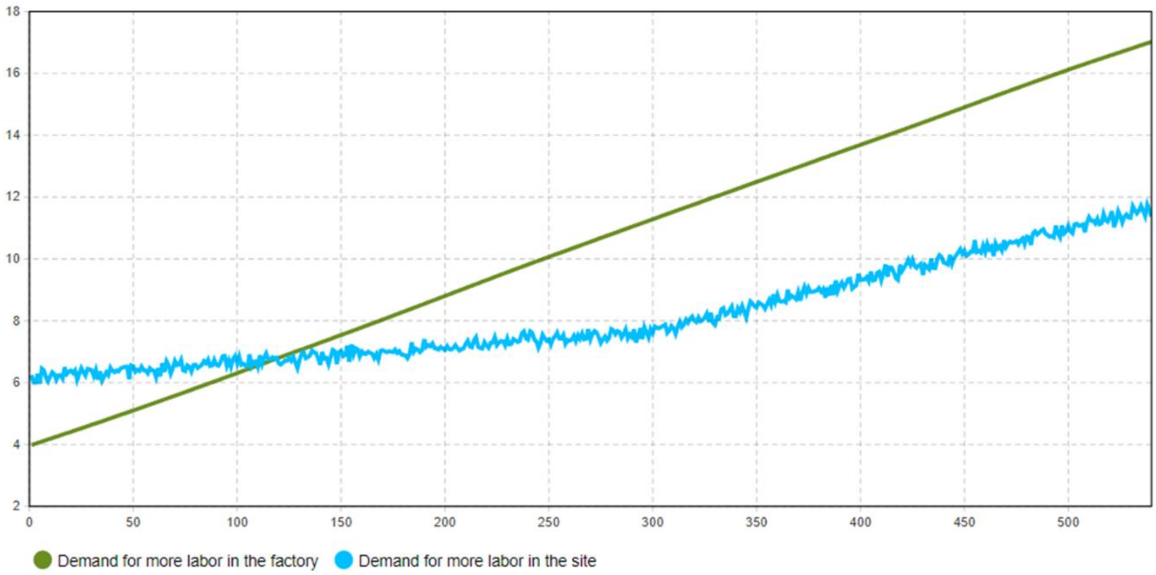


Figure 6.6 Labor analysis

6.4.2 Scenario analysis

The base run simulation shows that SCR have significant impacts on the inventory, schedule and quality performance of the PBP in Hong Kong. These SCR are individually evaluated using scenarios to see their impacts on the project supply chain.

Seven scenarios are then developed to assess the SCR, including QDROC, DC, LOSLITF, LOSLITS, IITARE, SRTDCITF, and IEROPE, by increasing and decreasing their values by 50% respectively. **Table 6.2** shows the simulation results.

The results show that three SCR, including QDROC, LOSLITF, IITARE have critical impacts on the upstream production process with 450% variation range in factory inventory. DC is also an important risk due to its high influence on multiple aspects of the supply chain with 63.35%, 30.43%, 60.47%, and 52.17% variation ranges in precast components to be reproduced, assembly delay, delayed delivery of precast components to the site, and demand for more labor in the factory respectively. LOSLITS illustrates huge impacts on the downstream work with up to 196.77% and 199.34% variations in site inventory and precast components to be reinstalled respectively, while IITARE shows similar but relatively less impacts with 136.78% and 113.77% variation ranges in those two aspects respectively. The major influence of IEROPE is observed on precast components to be reinstalled and assembly delay with 66.47% and 30.43% variation ranges respectively.

It can be seen that DC, LOSLITS, IITARE, IEROPE, and DDOPETTS are the five SCR that have considerable impacts on multiple aspects of the supply chain with over 30% variation ranges in them. They are therefore considered to be the top SCR in PBP and useful strategies to address these risks are in need of further development.

Table 6.2 Simulation results

SCR		Factory inventory	Site inventory	Precast components to be reproduced	Precast components to be reinstalled	Assembly delay	Delayed delivery of precast components to the site	Demand for more labor in the factory	Demand for more labor in the site
QDROC	+50%	-2.338	535	135	228	79	32	18	12
	-50%	7.445	536	126	228	80	31	17	12
	Variation	-418.43%	0.19%	-6.67%	0.00%	1.27%	-3.13%	-5.56%	0.00%
DC	+50%	2.5	536	191	228	92	43	23	13
	-50%	2.5	536	70	228	64	17	11	10
	Variation	0.00%	0.00%	-63.35%	0.00%	-30.43%	-60.47%	-52.17%	-23.08%
LOSLITF	+50%	-2.338	536	135	228	80	32	20	12
	-50%	7.445	536	126	228	77	30	15	11
	Variation	-418.43%	0.00%	-6.67%	0.00%	-3.75%	-6.25%	-25.00%	-8.33%
LOSLITS	+50%	2.5	1053	131	152	80	31	17	13
	-50%	2.5	-1019	131	455	98	31	17	12
	Variation	0.00%	-196.77%	0.00%	199.34%	22.50%	0.00%	0.00%	-7.69%

IITARE	+50%	-2.338	949	135	167	79	32	20	13
	-50%	7.445	-349	126	357	88	30	15	11
	Variation	-418.43%	-136.78%	-6.67%	113.77%	11.39%	-6.25%	-25.00%	-15.38%
SRTDCITF	+50%	2.5	536	131	228	81	34	17	12
	-50%	2.5	536	131	228	76	28	17	11
	Variation	0.00%	0.00%	0.00%	0.00%	-6.17%	-17.65%	0.00%	-8.33%
IEROPE	+50%	2.5	536	131	340	92	31	17	13
	-50%	2.5	536	131	114	64	29	17	10
	Variation	0.00%	0.00%	0.00%	-66.47%	-30.43%	-6.45%	0.00%	-23.08%
DDOPETTS	+50%	3	536	131	228	95	47	17	13
	-50%	3	536	131	228	63	15	17	9
	Variation	0.00%	0.00%	0.00%	0.00%	-33.68%	-	0.00%	-30.77%
AD	+50%	3	536	131	228	117	31	17	15
	-50%	3	536	131	228	39	30	17	8
	Variation	0.00%	0.00%	0.00%	0.00%	-	-3.23%	0.00%	-46.67%

6.5 Chapter summary

This chapter provides a dynamic model by the SD theory to simulate the supply chain of a prefabricated building project considering the critical SCR. By collecting information from a case project, data of the variables involved is input into the model. The impacts of the SCR on the inventory, schedule, and quality performance of the project are modelled.

Chapter 7 Conclusions

7.1 Introduction

This chapter summarizes major information of the study, including the major research findings, contributions to knowledge and the industry and limitations of the research. The research objectives are also reviewed to check whether they are fully achieved. Finally, future research directions are provided based on the limitations of the study.

7.2 Review of research objectives

This study primarily aims to examine the impacts of the dynamically interacting SCR on the performance of PBP in Hong Kong.

The specific objectives of this research are listed as follows.

(1) To investigate the real situation of SCM for PBP, identify the embedded problems and analyze their root causes;

(2) To identify stakeholder-associated SCR and analyze their interactions in the context of PBP in Hong Kong;

(3) To develop a dynamic model for assessing the impacts of the SCR on the performance of PBP.

Chapter 2 reviews the most relevant research published in peer-reviewed journals, which provides significant theoretical foundation for the identification of research problems and solutions to the problems. Chapter 3 explains the theories and application of the research methods and tools that are used to address the research objectives of the study. These two chapters lays the foundation of further analysis. To realize Objective 1, Chapter 4 investigates the production, transportation and assembly processes of a prefabricated building project in Hong Kong using a combination of case study, document analysis, and interviews. The real-time information of precast components collected by automated data collection technologies and document analysis in a representative case project accurately reveals how the supply chain is managed and operated. Statistical analysis of the real-time data is conducted to show the real situation of SCM for PBP and identify the embedded problems. Interviews with experts indicate the root causes of the problems in SCM for PBP. The findings of Chapter 4 reveal the existence of SCR in PBP. To achieve Objective 2, Chapter 5 applies SNA to examine the stakeholder-associated SCR and their interactions in PBP. By doing this, the critical risks that significantly affect the performance of the supply chains of PBP are identified and prioritized. To address Objective 3, Chapter 6 incorporates the critical SCR identified in Chapter 5 into a dynamic model employing the SD theory to assess their impacts on the performance of PBP. The base run simulation and scenario analysis reflects the influence of the SCR on the inventory, schedule and quality performance of PBP supply chains.

7.3 Summary of Research Findings

Major research findings of the study are summarized as follows.

First, overproduction, excessive inventory, long lead time, limited considerations of resource planning, and significant delay in assembly schedule are serious problems which add considerable non-value-adding wastes to the supply chain and lead to cost overruns and schedule delay of the prefabricated building project. The root cause of the problems includes poor supply chain planning, poor communication between stakeholders, and poor control of working flows.

Second, SCR in PBP are closely associated with the stakeholders involved and they dynamically interact with each other to influence the risk network of the projects. The study identifies nine risks as critical SCR that significantly affect the supply chains of PBP, including inaccurate initial time and resources estimation related to the main contractor, lack of labor resource related to the manufacturer, lack of labor resource related to the assembly sub-contractor, delayed delivery of precast elements to site associated with the manufacturer, delayed assembly schedule related to the assembly sub-contractor, poor communication sourced from the designer, manufacturer, and main contractor, and design change from the client. The downstream supply chain managed by the client and the main contractor is a significant risk source in the network, and plays an important role in the overall network interactions. The control risks that determine the transformation of the client's order into raw material requests are important source nodes that have great potential to generate more risks, thereby leading to the complexity of the entire risk network.

Third, the inventory, schedule and quality performance are considerably affected by the critical SCR. The most sensitive SCR include design change, lack of skilled labor in the site, inaccurate initial time and resources estimation, installation error rate of precast elements, and delayed delivery of precast elements to the site, which have considerable impacts on multiple aspects of the supply chain with over 30% variation ranges in inventory, schedule and quality performance of the project, and therefore useful measures are in urgent demand to deal with those SCR.

7.4 Research contributions

This research reveals the real situation of SCM for PBP and critical risks involved in Hong Kong by comprehensively investigating all the stages and main stakeholders. The findings of this research will enable housing development in the public sector to have better quality, shorted duration, and reduced cost of production by improved supply chain risk management, presenting significant benefits for the general public in Hong Kong, and create win-win-win situations for all stakeholders of the residential developments. Contributions to knowledge and the industry are explained as follows.

7.4.1 Contributions to Knowledge

First, this study investigates the production, transportation and assembly processes using a series of advanced technologies, which reveals the status of the supply chain of a prefabricated building project with a large amount of real-time data. By doing analysis using real project data, this research tackles the limitations of previous studies which analyze project supply chains with simulation data or modelling methods. Also, major processes of the supply chain are investigated, which provides more comprehensive implications compared with other studies which explore single process of a project. This research shows the real situation of multiple processes of a prefabrication supply chain, thereby contributing to the body of knowledge by providing an in-depth understanding of current SCM for PBP in a realistic way.

Second, studies on SCR have mainly focused on the static perspective of risks while few of them have considered the dynamic interactions between SCR and their associated stakeholders. Since SCR are ascribed to stakeholders from design to the final assembly phase, it is important to examine SCR from their perspectives. This research fills a current knowledge gap by developing a dynamic social network to identify and prioritize stakeholder-associated SCR in the context of PBP in Hong Kong. The study provides an in-depth understanding of SCR in PBP by considering related stakeholders together with dynamic risk interactions when overcoming the limitations of traditional static risk analysis.

Third, this is the first study to comprehensively assess the impacts of SCR on the multiple performance of PBP. A dynamic model is developed considering the critical SCR and their interrelationships to evaluate how they interact to affect the supply chain performance of PBP. The inventory, schedule and quality are the major aspects that are highlighted when analyzing PBP's supply chain performance. By dynamically assessing the impacts of the critical SCR on those aspects, this study provides valuable implications about SCR management research in enhancing the performance PBP.

7.4.2 Practical contributions to the industry

First, this study provides a full picture of current situation of SCM for PBP using real data collected by advanced technologies, which enables the stakeholders to grasp the situation of the production, transportation and assembly processes of the supply chain. This research is of value in assisting the stakeholders deeply understanding the problems embedded in the supply chains of PBP and their root cause, thereby to deal with the problems with more efficient ways.

Second, this study assists the practitioners involved in PBP to understand the dynamic interactions between the SCR as well as their associated stakeholders. By providing a greater understanding of the risks embedded across the supply chains of PBP in Hong Kong, this study is of value in helping practitioners to deal with such risks more effectively and efficiently.

Third, the findings reveal the critical SCR that have considerable impacts on the inventory, schedule and quality performance of PBP. The practitioners could develop useful measures with a target at those critical SCR.

7.5 Research limitations

Although this study tackles the limitations of traditional SCM for PBP, there are still some limitations which are summarized as follows.

First, only one case project is employed for data collection of the major supply chain processes, social network analysis and variables of the modelling method. Although one case could provide useful information regarding the risks, it limits the generalization of SCR in PBP and therefore analysis of more cases is required to validate the findings of this study. Also, only facades are traced for real-time information, more types of components need to be investigated for tracking more detailed data of the supply chain.

Second, the interrelationships between SCR are assessed on the basis of the knowledge and experience of the selected stakeholders. Although they are representative of the project team, more stakeholders should be involved in the data collection process for the purpose of improving the accuracy of SCR interaction evaluation. In addition, the risk network developed for the case study is one-off, which needs to be improved by periodically reviewing and monitoring the dynamics of the network.

Third, the dynamic model simulates the supply chain using the SD method which adopts the up-bottom way to view the entire chain as a system but ignoring the entities involved in the system. As stakeholders play an important role in influencing the dynamic interactions between the SCR, the bottom-up way should also be involved to develop a hybrid model for more accurate findings of the SCR's impacts on the supply chain.

7.6 Future research directions

This study lays a solid foundation on future research regarding SCR management for

PBP, which could be summarized as follows.

First, overproduction, excessive inventory, long lead time and schedule delay are highly associated with a considerable amount of wastes which need to be further monitored and managed. Future research should survey more cases to review the generation of the wastes and develop a series of principles to control the operation of the production, transportation and assembly processes to reduce the wastes.

Second, future research could combine the real-time information of facades with the assembly sequence of all the precast components in the construction site to show the situation of supply chain operation in a more realistic way.

Third, since the SD model views the supply chain as a system and ignore the stakeholders involved, future studies could combine SD and agent-based modelling to simulate SCR in PBP. SD could be used to model the supply chain while the agent-based model be employed to model the stakeholders involved.

Fourth, PBP in Hong Kong involve a large number of units and the manufacturers and the general contractors are from different organizations. By contrast, an industrialized building system has reduced number of components with the same participant working for different processes, and therefore would conduct planning for the continuity at the outset of the supply chain. As a result, supply chain risks could be significantly less in an industrialized building system than those in a prefabricated building project. Future research therefore should pay more attention to the development of industrialized building systems in Hong Kong.

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Appendices

Appendix A: Survey on problems and their root causes in the supply chains of prefabricated building projects in Hong Kong

Dear Sirs/Madams,

This interview aims to investigate your **personal views** on problems and their root causes in the supply chains of prefabricated building projects (PBP) in Hong Kong. It would be extremely useful for us to learn about your expert experience and knowledge of supply chain management. Please note that any information kindly provided by you in the interview will be kept strictly **confidential** and used solely for academic purposes. Thank you very much for your cooperation!

LUO Lizi (PhD Candidate)
The Hong Kong Polytechnic University

1. Identified problems in the supply chains of PBP

This study have identified the following problems in the different stages of supply chains of PBP.

Production stage: highly fluctuating production schedule, production disorders, and unbalanced deployment of resources

Transportation stage: slow transportation schedule at the beginning of the supply chain

Assembly stage: assembly delay, poor consistency between upstream production and downstream demand, and inferior resource planning across the assembly stage

Inventory management: considerable overproduction and excessive inventory in the factory

Stock time of components: long stock time in the factory and the site

Lead time of components: long lead time over the supply chain

2. Please kindly provide answers with as many details as possible to the following questions.

(1) Does the described problem really occur in the supply chain management for the PBP?

(2) How does the problem occur in the supply chain?

(3) What is the root cause of the problem?

Thank you very much for your participation!

Appendix B: Survey on Supply Chain Risks in Prefabricated Building Projects in Hong Kong

Dear Sirs/Madams,

This interview aims to investigate your **personal views** on supply chain risks in prefabricated building projects in Hong Kong. It would be extremely useful for us to learn about your expert experience and knowledge of managing supply chain risks. Please note that any information kindly provided by you in the interview will be kept strictly **confidential** and used solely for academic purposes. Thank you very much for your cooperation!

LUO Lizi (PhD Candidate)
The Hong Kong Polytechnic University

1. Explanation of key terms

Prefabrication supply chain (PSC) consists of all construction processes, from the initial demands by the client/owner, through design, manufacturing, transportation and construction, to maintenance, replacement and eventual demolition of the projects. It also consists of organizations involved in the construction process, such as client, designer, manufacturer, transporter, main contractor, assembly sub-contractor. PSC is not only a chain of construction businesses with business-to-business relationships but also a network of multiple organizations and relationships, which includes the flow of information, the flow of materials, services or products and the flow of funds between client, designer, manufacturer, transporter, main contractor, assembly sub-contractor.

Supply chain risks (SCRs) refer to risks that can modify or prevent part of the movement and efficient flow of information, materials and products between the actors of a supply chain within an organization, or among actors in a supply chain.

2. Supply chain risks (SCRs) identification

SCRs are interrelated and associated with internal or external project stakeholders. A total of seven stakeholder groups directly involved in prefabricated housing projects (PHP) are identified. They are coded numerically as Sa, where a =7, namely, (1) client, (2) designer, (3) main contractor, (4) manufacturer, (5) transporter, (6) assembly sub-contractor, and (7) government.

A total of 30 SCRs have been identified based on literature review and interviews, and are summarized in the following table. All of the risks are numerically coded with S#R*, in which # indicates the number of associated stakeholder and * is the risk number related to this stakeholder. **For example, S2R3 is the third risk associated with the second stakeholder.**

1

Risk ID	Stakeholder node	Related Stakeholders	Risk node	Risks
S1R1	S1	Client	R1	Design change
S1R2	S1	Client	R2	Inefficiency of design approval
S1R3	S1	Client	R3	Delayed payment
S3R3	S3	Main contractor		
S2R4	S2	Designer	R4	Design errors
S2R5	S2	Designer	R5	Poor communication with other project participants
S3R5	S3	Main contractor		
S4R5	S4	Manufacturer		
S4R6	S4	Manufacturer	R6	Delayed delivery of precast elements to site
S4R7	S4	Manufacturer	R7	Component identification marking errors
S4R8	S4	Manufacturer	R8	Unclear component identification marks
S4R9	S4	Manufacturer	R9	Precast components mistakenly delivered
S4R10	S4	Manufacturer	R10	Poor factory layout management
S4R11	S4	Manufacturer	R11	Component damages
S5R11	S5	Transporter		
S4R12	S4	Manufacturer	R12	Poor quality of components
S4R13	S4	Manufacturer	R13	Long component lead time
S3R14	S3	Main contractor	R14	Inaccurate initial time and resources estimation
S4R15	S4	Manufacturer	R15	Slow response to design change
S3R15	S3	Main contractor		
S3R16	S3	Main contractor	R16	Lack of labor resource
S4R16	S4	Manufacturer		
S6R16	S6	Assembly sub-contractor		
S3R17	S3	Main contractor	R17	Safety accidents
S4R17	S4	Manufacturer		
S5R17	S5	Transporter		
S6R17	S6	Assembly sub-contractor		
S6R18	S6	Assembly sub-contractor	R18	Inefficient verification of precast components due to unclear labels
S3R19	S3	Main contractor	R19	Labor dispute
S6R19	S6	Assembly sub-contractor		
S3R20	S3	Main contractor	R20	Poor site layout management
S3R21	S3	Main contractor	R21	Tower crane breakdown
S6R22	S6	Assembly sub-contractor	R22	Installation error of precast elements
S6R23	S6	Assembly sub-contractor	R23	Delayed assembly schedule

S3R24	S3	Main contractor	R24	Inadequate professional pre-planning studies for project
S4R24	S4	Manufacturer		
S5R25	S5	Transporter	R25	Transportation vehicle damage
S5R26	S5	Transporter	R26	Traffic accidents
S5R27	S5	Transporter	R27	Prolonged custom declaration
S3R28	S3	Main contractor	R28	Bad weather
S6R28	S6	Assembly sub-contractor		
S7R29	S7	Government	R29	Excessive approval procedures
S7R30	S7	Government	R30	Governmental policy change

3. Supply chain risks (SCRs) assessment

SCRs do not exist individually, but interact with each other throughout the project lifecycle. Please assess the relationships between the SCRs referring to the following **EXAMPLE**.

	S1R1	S1R2	S2R1	S2R2
S1R1			**(3,2)**	
S1R2	(2,1)			(2,3)
S2R1				
S2R2	(4,5)			

The digital numbers inside the cells indicate **impact** and **likelihood**: the left element is the impact between the risks (5 scales with "5" meaning extremely high, and "1" meaning extremely low); the right element is the likelihood of the impact (5 scales with "5" meaning extremely high and "1" meaning extremely low). For example, in Table 3, **(3, 2)** indicates the first risk associated with Stakeholder 1 (S1R1) has a medium level (i.e., 3) of impact on the first risk associated with Stakeholder 2 (S2R1), and the likelihood of the impact is relatively low (i.e., 2).

Assessment criteria:

5-extremely high
4-high
3-medium
2-low
1-extremely low

Thank you very much for your participation!

Appendix C: Survey on the relationships between critical variables that interact with each other to influence the supply chain performance of prefabricated building projects

Dear Sirs/Madams,

This interview aims to investigate your **<u>personal views</u>** on the relationships between critical variables that interact with each other to influence the supply chain performance of prefabricated building projects in Hong Kong. It would be extremely useful for us to learn about your expert experience and knowledge of supply chain management. Please note that any information kindly provided by you in the interview will be kept strictly **<u>confidential</u>** and used solely for academic purposes. Thank you very much for your cooperation!

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No.	Target Variables	Source Variables	Relationships
1	Reproduction rate due to design change	Total amount of components	
		Design change	
2	Quality defective rate of components	Factory inventory	
		Lack of skilled labor in the factory	
3	Installation error rate of precast elements	Stock time of components in the site	
		Lack of skilled labor in the site	
		Installation error rate	
4	Assembly rate	Assembly efficiency	
		Stock time of components in the site	
5	Assembly delay	Reproduction rate due to design change	
		Delayed delivery of precast elements to the site	
		Lack of skilled labor in the site	
		Installation error rate of precast elements	
6	Input of more labor in the factory	Components to be reproduced	
		Lack of skilled labor in the factory	
7	Delayed delivery of precast elements to the site	Components to be reproduced	
		Slow response to design change in the factory	
8	Lack of skilled labor in the factory	Inaccurate initial time and resources estimation	
		Planned demand for labor in the factory	
		Actual demand for labor in the factory	
9	Lack of skilled labor in the site	Inaccurate initial time and resources estimation	
		Planned demand for labor in the site	
		Actual demand for labor in the site	

10	Input of more labor in the site	Lack of skilled labor in the site
		Assembly delay
11	Installation error rate	Lack of skilled labor in the site
		Installed components
12	Assembly efficiency	Input of more labor in the site

Thank you very much for your participation!

1 Appendix D: Abbreviations

Abbreviation	Term
Abstract	
PBP	Prefabricated building projects
SCM	Supply chain management
SCR	Supply chain risks
SD	System dynamics
SNA	Social network analysis
Chapter 2	
MTO	Make-to-order
ETO	Engineer-to-order
MTS	Make-to-stock
ATO	Assemble-to-order
Chapter 5	
S1R1	Client-associated design change
S1R2	Client-associated inefficient design approval
S1R3	Client-associated delayed payment
S3R3	Main contractor-associated delayed payment
S2R4	Designer-associated design errors
S2R5	Designer-associated poor communication with other project participants
S3R5	Main contractor-associated poor communication with other project participants
S4R5	Manufacturer-associated poor communication with other project participants
S4R6	Manufacturer-associated delayed delivery of precast elements to the site
S4R7	Manufacturer-associated component identification marking errors
S4R8	Manufacturer-associated unclear component identification marks
S4R9	Manufacturer-associated precast components mistakenly delivered
S4R10	Manufacturer-associated poor factory layout management
S4R11	Manufacturer-associated component damages
S5R11	Transporter-associated component damages
S4R12	Manufacturer-associated poor quality of components
S4R13	Manufacturer-associated long component lead time
S3R14	Main contractor-associated inaccurate initial time and resources estimation
S4R15	Manufacturer-associated slow response to design change
S3R15	Main contractor-associated slow response to design change
S3R16	Main contractor-associated lack of skilled labor
S4R16	Manufacturer-associated lack of skilled labor
S6R16	Assembly sub-contractor-associated lack of skilled labor
S3R17	Main contractor-associated safety accidents
S4R17	Manufacturer-associated safety accidents
S5R17	Transporter-associated safety accidents
S6R17	Assembly sub-contractor-associated safety accidents

S6R18	Assembly sub-contractor-associated inefficient verification of precast components due to unclear labels
S3R19	Main contractor-associated labor dispute
S6R19	Assembly sub-contractor-associated labor dispute
S3R20	Main contractor-associated poor site layout management
S3R21	Main contractor-associated tower crane breakdown
S6R22	Assembly sub-contractor-associated installation error of precast elements
S6R23	Assembly sub-contractor-associated delayed assembly schedule
S3R24	Main contractor-associated inadequate professional pre-planning studies for project
S4R24	Manufacturer-associated inadequate professional pre-planning studies for project
S5R25	Transporter-associated transportation vehicle damage
S5R26	Transporter-associated traffic accidents
S5R27	Transporter-associated prolonged custom declaration
S3R28	Main contractor-associated bad weather
S6R28	Assembly sub-contractor-associated bad weather
S7R29	Government-associated excessive approval procedures
S7R30	Government-associated governmental policy change
Chapter 6	
PR	Production rate
CTBP	Components to be produced
TAOC	Total amount of components
STOCITF	Stock time of components in the factory
FI	Factory inventory
Del	Delivery
BI	Buffer inventory
SI	Site inventory
STOCITS	Stock time of components in the site
AR	Assembly rate
RRDTDC	Reproduction rate due to design change
DC	Design change
CTBR	Components to be reproduced
DDOPETTS	Delayed delivery of precast elements to the site
IITARE	Inaccurate initial time and resources estimation
SRTDCITF	Slow response to design change in the factory
LOSLITF	Lack of skilled labor in the factory
LOSLITS	Lack of skilled labor in the site
PDFLITF	Planned demand for labor in the factory
ADFLITF	Actual demand for labor in the factory
PDFLITS	Planned demand for labor in the site
ADFLITS	Actual demand for labor in the site
IOMLITF	Input of more labor in the factory
IOMLITS	Input of more labor in the site
QDROC	Quality defective rate of components

IEROPE	Installation error rate of precast elements
IER	Installation error rate
IC	Installed components
PCTBR	Precast components to be reinstalled
AE	Assembly efficiency
AD	Assembly delay