MANAGEMENT OF SCHEDULE RISKS OF PREFABRICATION HOUSING PRODUCTION IN HONG KONG

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Management of Schedule Risks of Prefabrication Housing Production in Hong Kong

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CERTIFICATE OF ORIGINALITY

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Abstract

As a solution to a series of dilemmas and constraints witnessed in the construction industry in Hong Kong, prefabrication housing production (PHP) is envisaged to gain momentum owing to its potential benefits such as environment-friendly, better quality, cleaner and safer working environment. Potential benefits may not be fully exploited if its inherent weaknesses of fragmentation, discontinuity, and poor interoperability not being mitigated, which nurtures a variety of risks that impose significant adverse influence on the schedule performance of prefabrication housing production. This is further exacerbated by the fact that the whole prefabrication manufacture sector in Hong Kong has been moved to offshore areas in the pearl river delta (PRD) region for a reason of lower material and labor cost. As a result, delay frequently occurs in PHP project despite the promise of the government to meet the high housing demand.

To help address schedule delay problems encountered in the construction of prefabrication housing, many studies have investigated risk-related issues in the management of PHP. However, none of these studies developed an effective tool for managing schedule risks of PHP by envisaging the key characteristics of schedule risks and prefabrication housing production. Most of previous research regarding to the management of prefabrication construction tends to consider risks from static and isolated perspectives, despite that these risks are coherently interrelated with each other and their influence varies throughout the whole PHP process. This study applies social network analysis approach to analyze and identify critical schedule risks with consideration of various stakeholders involved in major production processes of PHP from a network perspective, then a hybrid dynamic model is developed to evaluate and simulate the impact of identified schedule risks on the schedule performance of PHP in view of underlying interrelationships and interactions, employing the hybrid system dynamics (SD) and discrete event simulation (DES) method. The resulting hybrid model is validated through a serial of model structure tests and model behavior tests, with the use of data

collected from a PHP project in Hong Kong. Based on the simulation results, corresponding managerial and technical solutions are proposed for dealing with critical schedule risks and enhancing the schedule performance of PHP project.

This study contributes to current knowledge of the management of prefabrication construction by having developed an effective model that offers an in-depth understanding of how schedule performance of PHP are dynamically influenced by interrelationships and interactions underlying various schedule risk variables. Through depicting interrelationships underlying various identified schedule variables, the processes and interrelationships of the activities of prefabrication housing production can be better understood by the involved stakeholders to gain insight on the complicated mechanism inherent in the PHP system. The developed model not only has the benefits of ease of modifying model structure to reflect real schedule situation of PHP project, performing various risk analyses and communicating with simulation results, but also is of value of providing an experiment platform for identifying and determining managerial and technical solutions proposed to minimize and mitigate the influence of corresponding schedule risks prior to implementation.

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CHAPTER 1 Introduction

1.1 Overview

The balance of housing supply and demand is one of crucial concerns in Hong Kong, which is one of the most densely populous areas in the world. Hong Kong has an area of 1,104 sq. km. and an average population density of 6,420 persons per sq. km (Jaillon and Poon 2008a). Limited availability of land and expensive land prices have resulted in the prevalence of high-rise building construction in Hong Kong. Only a small percentage of the people can afford the high prices of the dwellings of private housing, with about 50% population resides in public housing (Census Statistics Department 2012). More than 100,000 applicants are on the list of Housing Authority for waiting public rental housing (PRH) and with a possibility of having to wait for at least seven years to move into a rental place given the PRH demand and supply (Census Statistics Department 2012). Housing issues in Hong Kong have resulted in widespread discontent. What is more, a series of dilemmas and constraints have been witnessed in the construction industry of Hong Kong, including safety, labor shortages, time, and environmental protection. As a solution to these problems, prefabrication has been increasingly advocated owing to its potential benefits such as environment-friendly, better quality, cleaner and safer working environment.

Potential benefits may not be fully exploited if its inherent weaknesses of fragmentation, discontinuity, and poor interoperability not being mitigated, which nurtures a variety of risks that impose significant adverse influence on the schedule performance of prefabrication housing production. Nevertheless, a tool to help the industry and management team understand, assess, and handle those schedule risks to prevent frequent schedule delay in prefabrication housing production, is lacked. Without such a tool, it is difficult to manage schedule of prefabrication housing production and ensure timely project delivery in prefabrication housing production in Hong Kong. This thesis is the culmination of my three-year PhD study with the aim of developing effective models for identifying, analyzing, evaluating schedule risks in prefabrication housing production in Hong Kong. The introduction chapter reviews the research background, states the research problem to be solved, outlines the research aim and objectives, justifies the methodology to be applied, highlights the contributions, and outlines the structure of the thesis.

1.2 Research background

1.2.1 Prefabrication Housing Production in Hong Kong

Prefabrication is a manufacturing process that takes place in a specialized facility where various materials are joined together to form a component of the final installation procedure (Association 1999). In the construction field, prefabrication is regarded as the first level of industrialization, which is followed by mechanization, automation, robotics, and reproduction (Richard 2005). Previous studies had used various terms and acronyms that are associated with prefabricated construction, including off-site prefabrication, precast concrete building (Kale and Arditi 2006), off-site construction (Pan et al. 2008), industrialized building (Jonsson and Rudberg 2013; Meiling et al. 2013), and modern methods of construction (Goodier and Gibb 2007), to name a few. Prefabricated construction can generally be categorized into the following four levels based on the degree of prefabrication implemented on the product: (1) component manufacturing and sub-assembly that are always done in a factory and not considered for on-site production, (2) non-volumetric pre-assembly that refers to pre-assembled units not enclosing usable space such as timber roof trusses, (3) volumetric pre-assembly that refers to pre-assembled units enclosing usable space and usually being manufactured inside factories but do not form a part of the building's structure such as the toilet and bathroom, and (4) whole buildings that refer to pre-assembled volumetric units forming the actual structure and fabric of the building such as motel rooms (Gibb 1999; Goodier and Gibb 2007).

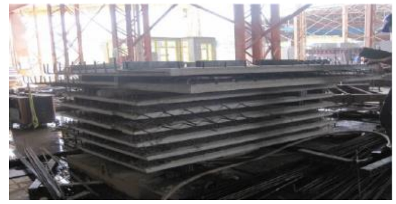
Prefabricated construction, as a modern construction technology replacing conventional cast-in-situ concrete construction, has attracted immense attention from many countries over the past two decades. This widespread interest can be largely explained by the inherent superiority of the technology, including, but not limited to, construction waste reduction (Baldwin et al. 2009; Tam et al. 2007), improved quality control (Jaillon and Poon 2008), noise and dust reduction (Pons and Wadel 2011), higher standards for health and safety (López-Mesa et al. 2009; Pons and Wadel 2011), cost saving (Chiang et al. 2006; Gibb and Isack 2003), reduced labor demand (Nadim and Goulding 2010), and low resource depletion (Aye et al. 2012; Won et al. 2013). These advantages significantly contributed to the increased performance of the entire construction industry. In the 1950s and the 1960s, for example, after World War II, a number of prefabricated building systems, such as prefabricated beams, slabs, facade units, and vertical structural components, were extensively developed in eastern and western Europe to satisfy the massive demand for housing reconstruction (Warszawski 2004). In Denmark, the highest precast level of 40% was recorded in 1996, after the implementation of the law on precast standardization, which aims to promote the adoption of prefabricated components (Jaillon and Poon 2009). In the mid-1980s, Hong Kong began to introduce prefabrication along with standard modular designs in public housing projects (Mak 1998). By 2002, prefabricated components accounted for approximately 17% of the volume of concrete products adopted in housing projects (Chiang et al. 2006).

Previously, housing production in Hong Kong mainly adopts conventional construction technologies characterized by fixed jobsites, labor intensive, formwork and falsework, cast-in-situ, wet trades, and bamboo scaffolding. While cast in-situ construction technology has its own strengths (e.g., high flexibility to design changes), it has received widespread criticisms. The Construction Industry Review Committee (CIRC) systematically reviews current development in the construction industry in Hong Kong and recommends improvement measures to uplift its quality and performance. The report, named Construct for Excellence, critically pointed out the problems surrounding the industry, including but not limited to: poor site safety record, inadequately trained workforce, and unsatisfactory environmental performance (CIRC, 2001). As a result, the wider use of prefabrication was proposed as a primary strategy to enhance the Hong Kong construction industry. In comparison with traditional housing production technologies, prefabrication housing production (PHP) in Hong Kong has the following benefits: (1) Better on-site construction environment as a result of reductions dust and noise, construction waste (Tam et al. 2015), water and air pollution (Hong et al. 2016); (2) Compressed project schedules that result from changing the sequencing of work flow (e.g., allowing for the assembly of components offsite while foundations are being poured on-site; allowing for the assembly of components offsite while permits are being processed) (Tam and Hao 2014); (3) Easier for quality control, labor supervision and fewer material deliveries (Li et al. 2016); (4) Fewer losses as a result of misplacement of materials and less requirements for on-site material storage (Lu et al. 2011); and (5) Safer working environment for worker through reducing dangerous operations, e.g., components traditionally constructed on-site at heights or in confined spaces can be fabricated offsite and then hoisted into place using cranes (Ingrao et al. 2014).

Precast Tie Beam

Precast Facade

Precast Volumetric Bathroom



Precast Slab

Precast Staircase

Precast Partition Wall

Precast Landing

Precast Refuse Chute

Figure 1.1 Typical precast elements in Hong Kong

In recent years, prefabricated components in Hong Kong have evolved from simple partition walls (dry walls) to highly pre-installed components. Typical prefabricated components in Hong Kong housing sector can be shown in Figure 1.1. The whole prefabrication manufacturer sector of Hong Kong has been moved to offshore locations in the PRD (Pearl River Delta) region in China, such as Shenzhen, Dongguan, Huizhou, Zhongshan, and Shunde, as results of the advantages of lower labor cost and abundant material resources in Mainland China. The offshore prefabrication housing production processes in Hong Kong are summarized in Figure 1.2: (a) design, (b) manufacture, (c) (d) storage, (e) cross-border logistics, (f) buffer and (g) on-site assembly. Normally, a client, which is normally Hong Kong Housing Authority in Hong Kong, hires designers for architectural and engineering design, with special consideration given to the adoption of modules and their structural safety, buildability, and transportation convenience. The design information is then transmitted to the manufacturer for the production of precast components. After the precast elements are produced at the PRD, companies with better coordination can transport the components through Shenzhen–Hong Kong customs and directly reaching construction sites in Hong Kong. Others most of companies have to store their components in a temporary storage in Lok Ma Chau, which is a large area close to the customs facility, for conveyance buffer purpose. Lastly, these precast components are installed by the assembly company to replace the traditional cast in-situ work. Despite the potential merits of adopting prefabrication, the problems in prefabrication construction such as fragmentation, discontinuity, and lack of interoperability, are still obvious and exacerbated by the offshore prefabrication processes. For example, it was noticed that a few of companies with better coordination could transport the components from the PRD, pass through Shenzhen-Hong Kong customs and reach construction sites in Hong Kong directly, while most of companies had to place their components in temporary storage in Lok Ma Chau, a large area close to the Customs facility, leading to low efficiency.

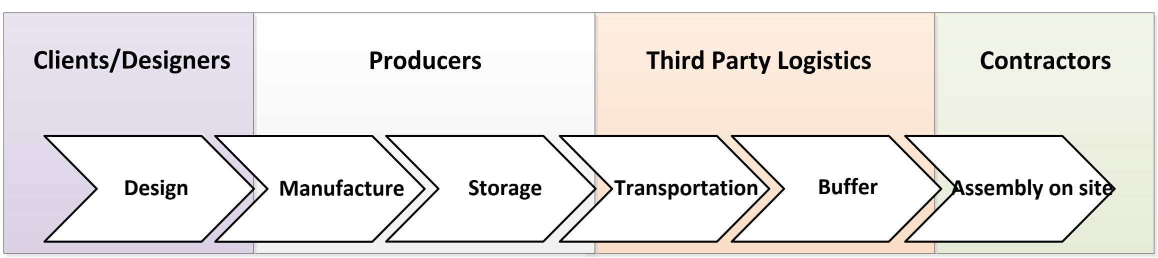


Figure 1.2 The offshore prefabrication housing processes

1.2.2 Schedule Delay and Management of Schedule Risks

The stakeholders in housing production may include clients (e.g., private developers and public developers such as Hong Kong Housing Authority), designers, consultants, contractors, suppliers, sub-contractors, end users, and facility managers. Various stakeholders involved in PHP have a hub-and-spoke representation, where the project occupies a central position and has direct connections with the related stakeholders. So the key stakeholders, such as designers and contractors, are not necessarily involved in the whole project life cycle, witnessing the discontinuity of different parties and different stakeholders that are designated to perform different tasks throughout the main processes of design, manufacturing, storage, transportation, and assembly on site. As such, they are not being able to work together and communicate with each other efficiently and, in fact, can have competing interests. This problem is often referred to as the fragmentation and discontinuity that exists in PHP, which can be further exacerbated by the fact that the whole prefabrication manufacture sector has been moved to offshore areas in the PRD region for a reason of lower material and labor cost, as new stakeholders, such as the offshore manufacturers, transporters, and host local authorities, are involved, resulting a more complex organization structure. The processes of design, manufacturing, storage, transportation, and on-site assembly thus are fundamentally fragmented, nurturing a variety of risks that impose major pressure on the time management of prefabrication housing production (PHP). These schedule risks might serve as trigger that generate new type risks or expand the impact to existing risks. As a result, delay frequently occurs in PHP project despite the promise of the government to meet the high housing demand. How to effectively manage those schedule risks by envisaging the key characteristics of schedule risks and prefabrication housing production will be critical for ensuring timely project delivery in prefabrication housing production in Hong Kong.

To help address these problems encountered in the construction of prefabrication housing, many studies have investigated the risk-related issues in the management of PHP. However, these studies tend to treat processes of prefabrication housing production separately and do not consider risks from the perspective of stakeholders, despite these risks being subject to different stakeholders designated to perform different tasks under different construction scenarios. Previous studies also do not sufficiently consider the interrelationships underlying the risk factors and their actual influence on dynamic basis. Nevertheless, it is stated by recent research that PHP is complex as a whole with various stakeholders involved, while activities in different PHP processes and variables within the specific process are largely interdependent. Also, schedule risks management of PHP is dynamic with the schedule performance of PHP varies all the time when the PHP project proceeds forward. In order to better understand a complex risk management system of PHP from more comprehensive perspective, taking dynamic interrelationships underlying various schedule risks in the PHP system for consideration from a dynamic point of view is necessary. To better identify, analyze, evaluate and handle schedule risks in PHP, this research pioneers to propose a systematic method that can be able to deal with the complexities of PHP by envisaging key system characteristics.

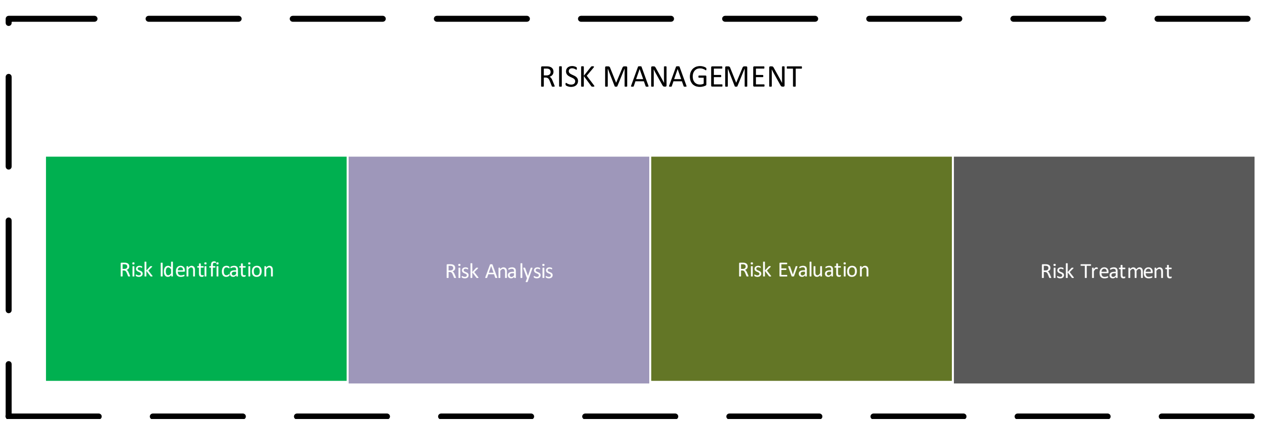


Figure 1.3 Framework of risk management

As shown in the Figure 1.3, risk management can be divided into 4 steps, risk identification, risk analysis, risk evaluation, and risk treatment (ISO 2009). The first step is to identify risks based on the processes, corresponding stakeholders, and objectives of the project. The second step is to analyze identified risks, which might include possibility analysis, causal analysis and interaction analysis, while the third step is to evaluate the potential impact of risks and finally propose countermeasures to handle the risks. In this study, the relationships among various PHP activities were considered from a dynamic perspective with consideration of interactions underlying various schedule risk variables. Thanks to the functions provided by SD and DES, interrelationships underlying various risk variables and the behaviors of the PHP system can be perfectly portrayed. Through the identification of critical schedule risks that have significant influence on the schedule performance of PHP through social network theory, a conceptual causal loop diagram is drawn to describe their causes-and-effect relationships in schedule management system of PHP, while stock-flow diagram is further developed to build calculation capacity into the model. Then a hybrid dynamic model will be further developed to evaluate and simulate identified critical schedule risks, employing the system dynamics (SD) and discrete event simulation (DES) method. The resulting hybrid dynamic model is validated to build up confidence by applying data collected from a PHP project in Hong Kong prior to in depth simulation analysis. Based on the simulation results, corresponding managerial and technical solutions are proposed for dealing with critical schedule risks and enhancing the schedule performance of PHP project.

1.3 Research Problem Statement

Established approaches by previous studies do not manage to gain comprehensive understanding of the schedule management of prefabrication housing production and prevent frequent schedule delay problems in public prefabrication housing delivery in Hong Kong. This might be accounted for the fact that previous studies have not comprehensively understand the key characteristics of prefabrication housing production when conducting research on schedule risk management in PHP practices. These key characteristics of prefabrication housing production include:

(1) PHP is complex with various stakeholders involved: The complicated nature of PHP can be demonstrated by the variety of stakeholders involved. Design, production, logistic and on-site assembly are all activities involved in PHP with each of the activities involves different stakeholders. Schedule risks are subject to different stakeholders designated to perform different tasks under different construction scenarios. Therefore, a social network analysis approach that can deal with schedule risks with consideration of the interrelationships underlying the risk factors and their actual influence on a network basis is desirable.

(2) Activities within PHP are largely interdependent: In conventional research of PHP, design, production, logistics, and on-site assembly are treated as independent activities, while all of them are actually closely interlinked and each activity has influence on the others. Therefore, effective schedule risks management of PHP should envisage the interdependent nature of activities and maintain a balance between them.

(3) Schedule risks management of PHP is dynamic: Conventional research on the management of PHP tends to take PHP management from static perspective while the management process

in reality is dynamic, which means that those analytic results will not be able change across with time to reflect actual management effect from a real-time manner.

In order to better understand a complex risk management system of PHP from more comprehensive perspective, taking dynamic interrelationships underlying various schedule risks in the PHP system for consideration from a dynamic point of view is necessary. The situation of frequent schedule delay in prefabrication housing production in Hong Kong and lack of research envisaging the key characteristics of prefabrication housing production lead to the fundamental research problem to be solved: how to effectively manage schedule risks by envisaging key characteristics of prefabrication housing production to ensure timely project delivery in prefabrication housing production in Hong Kong. To better identify, analyze, evaluate and handle the schedule risks in PHP, a systematic method that can be able to deal with the complexities of PHP by envisaging key system characteristics is required.

1.4 Research Aim and Objectives

The aim of this research is to develop a model to manage schedule risks in prefabrication housing production in Hong Kong. The research investigates major processes within prefabrication housing production, reveals the coordination structural of various stakeholders and influencing mechanism of interactions underlying various schedule risks, and provides a systematic method for assessing and simulating possible impact of schedule risks on the schedule of prefabrication housing production, such that potential schedule risks can be identified, analyzed, assessed and handled prior to implementation to ensure timely project delivery in prefabrication housing production in Hong Kong.

The specific objectives of this research are presented as below:

(1) To identify and analyze critical schedule risks that affect the schedule of prefabrication housing production with consideration of involved stakeholders;

(2) To develop a hybrid dynamic model for assessing and simulating potential impacts of the identified major risks on the schedule performance of prefabrication housing production;

(3) To propose corresponding solutions for dealing with major schedule risks in prefabrication housing production.

1.5 Research Design

A research path diagram is drawn as shown in the Figure 1.4 to facilitate the progress management of this research. As mentioned before, a total of three specific objectives are raised in this research, and the corresponding methodologies and expected outcomes are also illustrated.

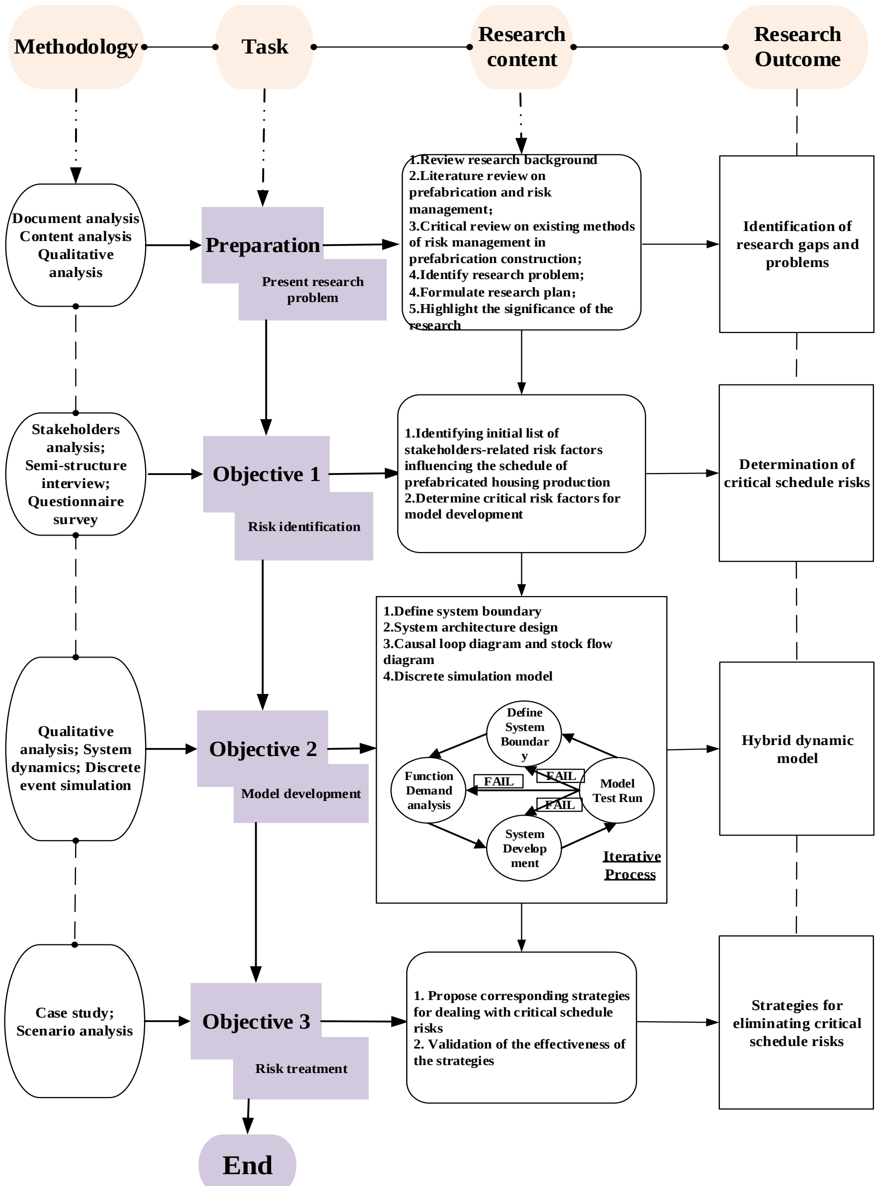


Figure 1.4 Research flow

Preparation: To identify the problem of this research.

Research content: (1) review research background; (2) review of research on prefabrication and risk management; (3) review existing methods of risk management in prefabrication construction; (4) present research problem; (5) make research plan; (6) highlight the significance of the research.

Methodology: Qualitative content analysis; Literature review

The most important purpose of this phase is to identify the research topic. There are many studies covering a variety of perspectives of research on prefabrication and risk management in construction field. How to identify a research problem with theoretical and practical significance is critical for the research. Through serval times site visit and review on the previous research on prefabrication and risk management, the research problem, stated as how to effectively manage schedule risks by envisaging key characteristics of prefabrication housing production to ensure timely project delivery in prefabrication housing production in Hong Kong, is put forwarded. Along with the research problem, specific research plan is formulated. Critical literature reviews on both prefabrication and risk management are conducted to determine current research gaps and better understand of the background of this research. Various approaches established by previous research for managing risks in PHP are examined during the literature review. The rationale for using SNA approach for schedule risk identification and the use of the hybrid SD and DES approach for schedule risks evaluation in PHP is justified.

Objective 1: To identify major risks that affect the schedule of prefabrication housing production with consideration of involved stakeholders.

Research content: (1) formulate the initial list of schedule risks of PHP; (2) identify and analyze major risks that affect the schedule of prefabrication housing production with consideration of involved stakeholders.

Methodology: Literature review; content analysis; social network analysis; semi-structured interviews.

The major task of Objective 1 was to identify and analyze major risks that affect the schedule of prefabrication housing production with consideration of involved stakeholders. These major schedule risks lay the foundation for subsequent model development. Social network theory views the PHP as a complex system containing various stakeholders and relationships. The purpose of network analysis is to analyze stakeholder-associated schedule risks in PHP and their cause-and-effect relationships. The first step identifies the stakeholders and schedule risk factors that directly influence the PHP. The second step determines the interrelations between the identified schedule risk factors. In the third step, the adjacency matrix, together with the node and link lists, was imported into NetMiner 4 as the major input data for network visualization and analysis. The outcome of the network analysis was a list of critical stakeholder-associated risks and the critical interactions underlying those risk factors based on node level and link level metrics of SNA.

Objective 2: To develop hybrid dynamic model for evaluating and simulating potential impact of the identified critical schedule risks on the schedule performance of prefabrication housing production.

Research content: (1) define system boundary; (2) present causal loop diagram and stock flow for depicting interrelationships underlying the identified variables; (3) integration of system dynamics and discrete event simulation; (4) model varication and validation; (5) conduct scenario analysis on critical schedule risks.

Methodology: Qualitative analysis; system dynamics; discrete event simulation

This part of the study develops hybrid dynamic model for evaluating and simulating the potential impact of the identified major risks on the schedule of prefabrication housing production. A six-step procedure could be adopted to develop a system dynamics model, including: (1) system description, in which researchers are required to determine the scope of a proposed system, and identifying the major variables associated with the research questions is emphasized; (2) causal-loop diagram and (3) stock-flow diagram, where qualitative analysis is conducted to depict the interrelationships underlying the identified variables before mapping them into causal-loop diagrams, and stock-flow diagrams are subsequently constructed based on the causal-loop diagram and visualized by the Vensim software package for quantitative analysis; (4) integration of system dynamics and discrete event simulation, system dynamics model and its associated attributes are encapsulated into the discrete event module to form the hybrid dynamic model to simulate the variation of schedule behavior of PHP. In the system model, data can be exchanged between system dynamics and discrete event simulation. (5) model verification and validation, which serves as an essential process for increasing confidence in the proposed model, in which, a series of tests would be run prior to the model implementation; (6) simulation scenario analysis which mainly comprises base run simulation and scenario simulation would be finally conducted to analyze the possible impacts of schedule risks scenarios after the model have been proven reliable through verification and validation.

Objective 3: To propose corresponding strategies for dealing with major schedule risks in prefabrication housing production

Research content: (1) propose corresponding strategies for dealing with critical schedule risks; (2) evaluation of the effectiveness of the strategies through hybrid dynamic model.

Methodology: Case study; scenario analysis

The final objective involves understanding the actual meanings of the identified critical risk factors and interactions and categorizing these key relationships based on their meanings. In consolidating the SNA results and simulation results by the hybrid dynamic model with the interview findings previously collected before network analysis, these major stakeholder-associated risks are further discussed. Corresponding BIM-centered strategies for mitigating the identified critical schedule risks and interactions are proposed and discussed to address real-world problems in PHP, and these strategies are validated through the established social network model and hybrid dynamic model.

1.6 Significance of the Research

The significance of this research is reflected in the following three aspects:

(1) This research contributes to the body of knowledge of construction management, especially in the research filed of prefabrication construction. This study develops a SNA model to recognize and investigate the underlying network of schedule risks with consideration of involved stakeholders in prefabrication housing construction, such that critical risks and relationships that have important roles in structuring the entire network of schedule risks management in PHP can be identified and analyzed. The SNA model can assist project managers from different parties to identify and analyze schedule risks that may lead to schedule delay in PHP projects, also filling the research gap of absence of a systematic analysis method for analyzing schedule risks and their interrelations from a network perspective with consideration of involved stakeholders.

(2) This research is meaningful for its contribution in the understanding of the interaction mechanism and the dynamic features of schedule risks in prefabrication housing production. The schedule risks are not static through the processes of prefabrication housing production, and their impact may vary throughout the timeline of the whole process of PHP, which is a large and complex system. Schedule risks in the PHP system are interrelated, generating a variety of positive and negative feedbacks. Through portrayal and quantification of interrelationships between various schedule risks, the interaction mechanism and the dynamic features can be better understood.

(3) From a practical perspective, this research provides managers of prefabrication housing production with a tool through which to identify, analyze, evaluate and simulate potential impact of risks on the schedule of prefabrication housing production, such that major schedule risks can

be handled prior to implementation to ensure timely project delivery in prefabrication housing production in Hong Kong. The hybrid dynamic model allows numerous attempts at discovering approaches through various simulation analysis to improve the schedule performance of prefabrication housing production in Hong Kong.

1.7 Structure of the Thesis

This thesis comprises nine chapters.

Chapter 1 is an overall introduction highlighting the essential information of the whole research, including the research background, research problem statement, research aim and objectives, the design of the research, research methods, and the structure of the whole thesis.

Chapter 2 presents a comprehensive review of the literature regarding risks management in prefabrication housing production. Two categories of literature were reviewed: management of prefabrication construction and risk management in construction industry. The knowledge gaps and research trend in this particular research filed were identified to justify the significance of the study.

Chapter 3 describes the methodologies adopted throughout the research. This chapter firstly discusses the research framework, followed by the illustration of detailed methods employed such as literature review, content analysis, semi-structure interview, and case study. In addition, three major analysis methods, namely social network analysis (SNA), system dynamics (SD) analysis, and discrete event simulation (DES) were described in detail.

Chapter 4 presents the content regrading to identifying and analyzing critical schedule risks that affect the schedule of prefabrication housing production with consideration of involved stakeholders. The outcome of the network analysis was a list of critical stakeholder-associated risks and the critical interactions underlying those risk factors based on node level and link level metrics of SNA.

Chapter 5 describes the detailed development processes of a hybrid dynamic model for evaluating and simulating the potential impact of the identified major risks on the schedule of prefabrication housing production. A range of causal loop diagrams portraying the interrelationships underlying major schedule variables are portrayed and stock-flow diagrams are developed through the employment of Vensim. Through the integration of system dynamics and discrete event simulation method, system dynamics model and its associated attributes are encapsulated into the discrete event module to form the hybrid dynamic model to simulate the variation of schedule behavior of PHP with the help of Anylogic.

Chapter 6 introduces the content of data collection and quantification methods for building up confidence into the hybrid dynamic model and demonstrating its application. Model verification and validation testing includes model structure test and model behavior test.

Chapter 7 analyzes simulation results by the hybrid dynamic model. A range of analyses of devised schedule risk scenarios, including general analysis results of baseline scenario, analysis on single-risk scenario and analysis on multi-risk scenario are presented.

Chapter 8 presents managerial and technical solutions for mitigating schedule risks and enhancing schedule performance of PHP in the Hong Kong construction industry. The performance of managerial and technical solutions on schedule risks handling is theoretically simulated and validated. The best solutions are expected to be utilized by housing production related departments to counter potential schedule risks and improve schedule management level in the prefabrication housing production industry.

Chapter 9 summarizes the primary research findings and reviews the achievement of the research objectives proposed at the beginning of the study. The theoretical and practical contributions of the research and reviewed and highlighted. Finally, the limitations of this research and future research were discussed.

1.8 Chapter Summary

This chapter outline the overall pattern of the research, which include the research background, research problems to be solved, the principal aim and objectives of the research, research design, value and significance of the research.

CHAPTER 2 Literature Review

2.1 Introduction

This chapter presents an overall review of industry development situation of PHP in Hong Kong, and the literature review regarding to the management of prefabrication construction and risk management in construction industry. The chapter first investigate the external and internal situations of management practices of PHP in the Hong Kong construction industry through the SWOT analysis. It then reviews the current literature regarding to prefabrication construction and risk management in construction industry. Thus, the practical need from the industry and research limitations can be identified and form a solid justification for the significance of this research.

2.2 Industry Development Situation of PHP in Hong Kong

After critical literature review, it is evidently demonstrated by previous studies that the SWOT analysis approach is a better tool for investigating development status from a strategic perspective. Thus, strengths, weaknesses, opportunities, and threats (SWOT) analysis is conducted in this research to investigate the external and internal situations of management practices of PHP in the Hong Kong construction industry, enabling the identification of the main problems confronting the construction industry when adopting prefabrication technologies. The SWOT analysis can be conducted through three steps. In the first step, the current housing challenges confronted by the Hong Kong government are presented in detail through an analysis of collected materials. These materials are collected from two channels: through an investigation of the relevant government guidelines and reports and by consulting stakeholders involved in housing production, such as manufacturers, logistics personnel, and contractors. Second, research questions are designed to investigate the SWOT of prefabrication housing production in Hong Kong. Third, a comprehensive SWOT analysis is performed based on the developed research questions. The answers to the research questions are formulated based on the results of the analyses of information obtained from a series of semi-structured interviews with concerned major stakeholders, including HKHA (Hong Kong Housing Authority) staff members responsible for housing production in the region, managers from precast manufacturers and logistics companies and on-site managers of main contractors, as shown in the Table 2.1. Semi-structured interviews were conducted in 2014, with each semi-structured interview lasting between 50 and 60 minutes. The main cause for including these stakeholders in semi-structured interviews is their extensive experience in process of offshore prefabrication housing production in Hong Kong. These stakeholders are well informed on the current practices of prefabrication housing production in Hong Kong. The strategy to mitigate the effect of "bias" out is that the interviewees are from different major parties throughout the supply chain of PHP, besides, they all have extensive experience, such that their opinions to some extend reflect the situation of the whole supply chain of PHP.

Table 2.1 Information of interviewees involved in SWOT analysis

N.	Position	Organization	Stakeholder group	N.	Position	Organization	Stakeholder group
1	Structural Engineer	Hong Kong Housing Authority	Client	4	Supervising Supervisor	Chuen Kee Ltd	Assembly Company
2	Architect	Hong Kong Housing Authority	Client	5	General Manager	Wing Hong Shun Ltd	Production Company
3	Senior Project Engineer	Gammon Construction Ltd	Main Contractor	6	Business Manager	Yingyun Transportation Ltd	Logistics Company

(1) Questions formulation

The primary research questions developed for the semi-structured interviews are explained and presented as follows.

Question 1: What are the strengths of Hong Kong when implementing prefabricated construction management practices?

The first question aims to determine both internal and external strengths of Hong Kong in implementing prefabricated construction management practices. For example, this question may deal with the benefits that Hong Kong contractors may gain from the use of prefabricated components when the Buildings Department implemented the incentive schemes through JPNs 1 and 2. The interviewees may also be asked the following specific questions:

What policy advantages may Hong Kong have when promoting the application of prefabrication technology?

What factors caused Hong Kong to act as a pioneer in the use of prefabricated construction method in China?

Question 2: What are the weaknesses of implementing the management of prefabrication housing production (MPHP) in Hong Kong?

The second question examines the possible weaknesses of the Hong Kong construction industry when developing MPHP. For example, this question may explore the obstacles (e.g., relatively high construction cost and difficult vertical transportation) that contractors face in adopting prefabrication technology. During the interview, the professionals were asked to give their views on the following questions.

In what aspects should improvements be made to promote the use of precast units in housing production?

What are the disadvantages of implementing MPHP practices in Hong Kong?

What obstacles hinder the application of prefabrication technology in Hong Kong?

Upon which aspects does MPHP need to be enhanced?

Question 3: What opportunities can Hong Kong explore to develop MPHP?

The third question is designed to examine future possible opportunities of the Hong Kong construction industry when developing MPHP practices. This question requires information on the benefits that result from MPHP development, including improved quality, shorter construction period, and better construction environment. The third question can also be expounded further in the following questions.

What opportunities can the Hong Kong construction industry utilize to promote the use of prefabrication technologies?

What types of benefits will ensure the future improvement of MPHP in Hong Kong?

Question 4: What threats could the Hong Kong construction industry face when improving MPHP practices?

The last question intends to examine the threats that could prevent promotion of the use of precast units and improvement of MPHP in the Hong Kong construction industry. The interviewees were also asked the following questions.

What internal and external obstacles could the Hong Kong construction industry encounter in developing MPHP practices?

Is the environment of the Hong Kong construction industry suitable for a more extensive use of prefabrication technologies?

(2) SWOT analysis of MPHP in Hong Kong

SWOT analysis contributes to the formation of a better understanding of both the internal and external situation of MPHP practice in the construction industry in Hong Kong. The external conditions are related to the threats and opportunities, whereas the internal conditions refer to the weaknesses and strengths. A specific account of SWOTs as a result of a series of interviews is as shown as Table 2.2, and the discussion on strengths/weaknesses/opportunities/threats are based on both of interviewer results and literature review.

Table 2.2 SWOT analysis results

	Strengths	Weaknesses
Internal conditions	Extensive experience in prefabricated construction	Inefficient information transmission between the design and prefabrication stages
	Pioneer in promoting information technology (IT) in MPHP	Lack of real-time information visibility and traceability
	Consensus of building authorities regarding the promotion of prefabrication technology	Information gaps among stakeholders, technologies, and processes

	Leading role in promulgating MPHP-related regulations	Lack of interoperability between various stakeholders and their heterogeneous enterprise information systems (EIS)
External conditions	Opportunities	Threats
	Appeal to alleviate conflict between high housing demand and labor shortage	Inefficient installation management because of compact space
	Appeal to reduce construction waste	Inefficiency in transportation and high cost of cross-border logistics
	Appeal to alleviate construction safety hazards	Insufficient information storage method of precast elements

(1) Strengths

S1: Extensive experience in prefabricated construction

Prefabricated construction has long been adopted in Hong Kong. Along with public housing programs in Hong Kong, prefabricated buildings were first developed (e.g., home ownership scheme or HOS) in the mid-1980s; prefabrication and standard modular designs, were introduced in public housing projects (Jaillon and Poon 2009). The most frequently adopted precast elements include parapets, precast facades, partition walls, semi-precast slabs, staircases, and in more recent times, kitchens and volumetric precast bathrooms (Tam et al. 2007). Prefabricated components took up to approximately 17% of the total concrete volume consumed in projects of public housing in 2002 (Chiang et al. 2006), whereas a pilot project stretched the application of precast components to 65% in 2005, and included the use of structural walls and precast kitchen (Jaillon and Poon 2008b).

More recently, prefabricated components in Hong Kong have evolved from simple partition walls (dry walls) to highly complex pre-installed components. In general, the early adoption of prefabricated units in public housing projects and the HKHA's extensive experience in applying prefabrication technology have significant influence, and subsequently inspired prefabrication innovations in the private sector, including the use of precast staircases, façades, beams, slabs, and volumetric bathrooms. Innovations in the private sector have also affected those in the public sector with the use of precast structural walls and lost form panels (permanent formwork). Extensive experience has enabled innovations in the Hong Kong prefabrication sector to continue to thrive and be rewarding.

S2: Pioneer in promoting information technology in MPHP

HKHA pioneered the use of information technology (IT), such as the Housing Construction Management Enterprise System (HOMES) and radio-frequency identification (RFID), in housing production. HOMES was developed by HKHA to enhance the flow of information and project logistics management in housing production. This system is "a large-scale integrated platform for the entire development and construction cycle, from project planning and project management to site management, budgeting, contract, and payment settlement. It eases communication and collaboration with external contractors, and assists back-office, middle management and project teams in their daily work, as well as giving top management a consolidated up-to-date picture for future planning." HOMES provides remote access to assist professionals in different working locations to monitor current housing programs and in-time project progress in terms of schedule, budget, expenditures, and payment. This system also maintains the records of previous housing projects and serves as a collaboration and knowledge-sharing platform to facilitate information and experience sharing among internal and external working parties within public housing projects. HOMES also has a restricted module available to senior management, which provides up-to-date key performance indicators, business plans, public housing program reports, and overall financial status for strategic management purposes (Lam et al. 2009). In 2006, HOMES was recognized for its contribution to the housing sector by the Hong Kong Information and Communications Technology Awards.

Initially, RFID was introduced as an alternative technology to replace the barcode system for identifying items. Compared with both the barcode and magnetic strip systems, RFID can store a relatively larger amount of data. These data can be encrypted to increase data security. Using RFID enables simultaneous reading of data from multiple tags, thereby enhancing data processing efficiency. Unlike both barcode and magnetic strip systems, direct contact between an RFID reader and tagged items is no longer necessary because RFID uses radio waves for data transmission. Writing data back to the RFID tag is also possible, significantly increasing the interaction between items, system, and users. In recent years, RFID has been used extensively in the manufacturing, logistics, and retailing sectors because of the technology's automatic identification solution that can streamline identification and data acquisition. RFID has also been used in various applications, such as reading meters, preventing theft of store merchandise, tracking railroad cars and intermodal freight containers, collecting tolls, and conducting agricultural and animal research; this system also has potential in the construction industry. HKHA and Hong Kong MTR Corporation have explored RFID use to tag construction components manufactured offshore in the PRD region.

S3: Consensus of building authorities regarding the promotion of prefabrication technology

Housing production in Hong Kong mainly adopted conventional construction technologies characterized by fixed jobsites, labor intensive, formwork and falsework, cast in-situ, wet trades, and bamboo scaffolding. Although this cast in-situ construction technology has its own strengths (e.g., highly flexible to design change), the technology has also received widespread criticisms. In April 2000, Tung Chee Hwa, then Hong Kong Special Administrative Region (HKSAR) chief executive, appointed the Construction Industry Review Committee (CIRC) chaired by Henry Tang to conduct a comprehensive review of the state of the construction industry and recommend improvement measures to uplift its quality and performance. The report, entitled “Construct for Excellence,” critically identified the problems besetting the industry. Among the relevant ones are as follows:

- Poor site safety record;
- Inadequately trained workforce;
- Unsatisfactory environmental performance;
- Extensive use of traditional and labor-intensive construction methods; and
- Declining productivity growth and high building cost.

In the report, the extensive use of both prefabrication and standardized and modular components received consensus and was proposed as the primary strategy for improving the Hong Kong construction industry (Committee 2001).

S4: Leading role in promulgating MPHP-related regulations

Figure 2.1 shows that since 2000, the Hong Kong government has issued a series of policies to encourage sustainable construction to adopt prefabricated building components in construction projects. HKHA was also recommended to assume the lead role in promoting the extensive use of prefabrication in Hong Kong, while the private sector’s capacity for applying prefabrication should be enhanced through training, promulgation of related guidelines and codes, and research and development. Typically, following the government directive, the Hong Kong Buildings Department, Lands Department, and Planning Department jointly issued JPNs 1 and 2. The two JPNs stipulated that when green building technologies, including prefabrication, were adopted, building developers could receive GFA exemptions. A series of follow-up regulations have also been formulated to reinforce incentives of the use of prefabrication, including waste disposal charging scheme and waste disposal regulation notice that aims at reducing construction waste largely generated from conventional cast in-situ construction, forcing developers to shift from conventional construction method to more sustainable prefabrication method.

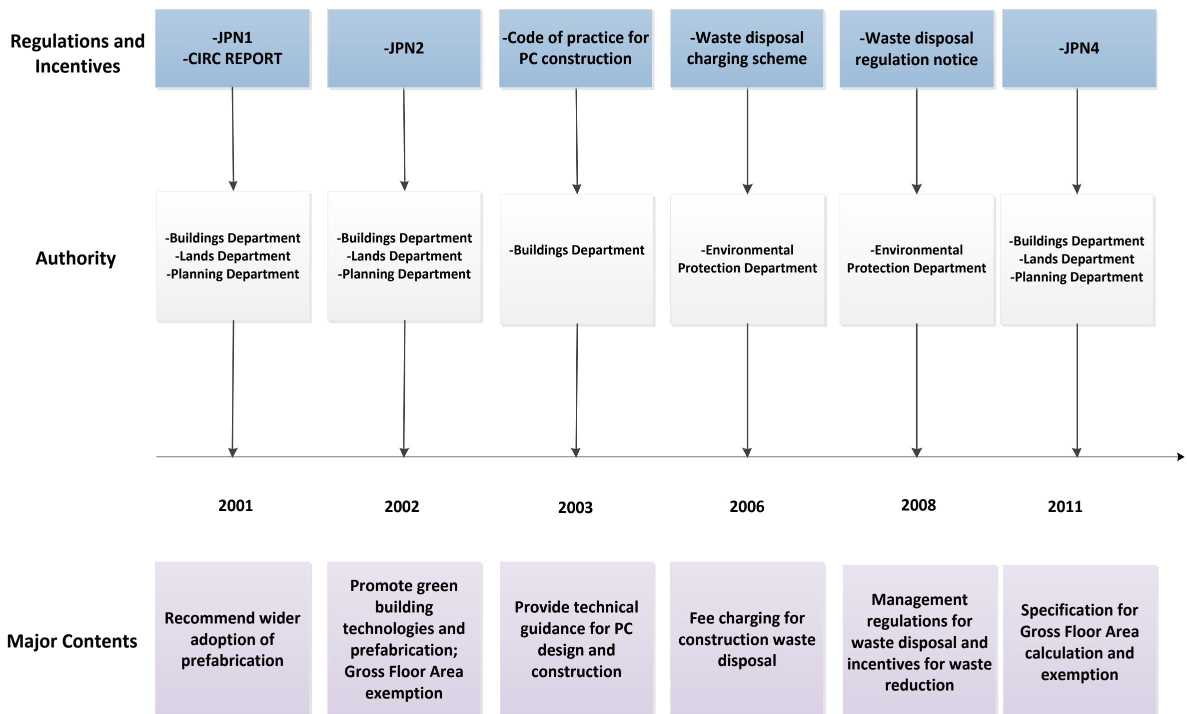


Figure 2.1 Regulations and policies development

(2) Weaknesses

W1: Inefficient information transmission between the design and prefabrication stages

Prefabricated housing enables manufacturers to prefabricate several construction components offsite in the offshore yards in the PRD region instead of managing all raw materials and installing them on site. However, this process has several weaknesses. First, both the method of considering the prefabrication features (e.g., suitability for mass production) in the building information modeling (BIM) process and transmission of the design information to the manufacturers are unclear. Ideally, technical drawings of the construction components (e.g., slabs, partitioning walls, staircases, etc.) should be generated directly from the BIM model to the manufacturers who will produce them accordingly. However, the idea of a “holistic BIM” has yet to be realized. Manual handling of ordering information is extremely difficult, if not completely impossible for both clients and suppliers/manufacturers. Similar to a garments or electronics company, a manufacturer commonly supplies various prefabrication components to different clients/contractors and their construction sites. Receiving orders and changes from the clients/contractors would cause the production to become prone to errors. Currently, companies have to allot extra labor costs on checking, counting, and sorting their raw materials, including semi-finished and finished prefabricated components, through a highly inefficient process. Information is also labeled using paper cards or painted labels without using new Auto-ID technologies (e.g., RFID). This approach results in difficulties in efficient retrieval of data for other purposes, such as production management, inventory management, and transportation. Consequently, components may be delivered by mistake to other construction sites, causing possible serious project delays. In general, the entire decision-making process in prefabrication manufacturing is based on outdated and inaccurate data, as well as the “rule of thumb.” Communication is also conducted through traditional and inefficient means, such as phone calls.

W2: Lack of real-time information visibility and traceability

Production, transportation, and assembly are the three major scenarios of off-shore prefabrication in Hong Kong. Thus, to enhance productivity, components will be stored and transported across the border to construction sites in Hong Kong for assembly. Ideally, the entire process should be traced and monitored closely to improve productivity and reduce problems through the logistic and supply chain. The prefabricated components are transported to Hong Kong mostly using lorries. Logistics companies are responsible for loading, fastening, and unloading the prefabricated building components, as well as for customs clearance. Consequently, these offshore prefabrication housing production processes lack real-time information visibility and traceability.

Logistics and supply chain management (LSCM) originated from the manufacturing industry, and is defined as a network of organizations involved through upstream and downstream linkages to minimize time spent on each activity and maximize value on each echelon (Cooper et al. 1997). LSCM plays a critical role in prefabrication logistics management in Hong Kong because most prefabricated components are generated in offshore sites in the PRD region. Prefabrication logistics management in construction can improve information flow, save costs, and support revenue-enhancing business strategies. One of the most significant approaches to LSCM is the just-in-time (JIT) delivery system that originated from the Toyota production management (Sugimori et al. 1977). In prefabricated construction projects, LSCM relies heavily on accurate and timely information sharing among different stakeholders. However, current logistics information is based mainly on paper, phone, and manual entry approaches, resulting in the prevalence of human error and data inconsistency.

W3: Information gaps among stakeholders, technologies, and processes

Stakeholder is a word increasingly used and abused in Hong Kong society and in the construction industry. Stakeholders are persons, groups, organizations, members, or systems that affect or can be affected by the actions of an organization. Stakeholders have different interests and would have different positive or negative influences on a system. Stakeholders in housing production may include clients (both public developers, such as HKHA and the Urban Renewal Authority and private developers), designers, consultants, contractors, suppliers, sub-contractors, end users, and facilities managers. Based on the current and typical design, bid, and build (DBB) housing delivery model, stakeholders have a hub-and-spokes representation. In the DBB model, the project occupies a central position and has direct connections with related stakeholders. These stakeholders are not necessarily involved in the entire project lifecycle and thus, may not always work together efficiently, and can also have competing interests. This situation is often referred to as the fragmentation and discontinuity that exist in the construction industry. With these structural problems, various issues are common, including risk aversion, short-termism, silo thinking, lost information, and ineffective communication.

Despite BIM being a common information platform where information and communication contributed and shared by stakeholders can be facilitated, addressing several weaknesses in this platform are necessary. First, the actual nature of the information is unclear. Uncertainties on how design information is received by production lines or how assembly information is embedded in prefabricated components and deciphered by workers on site still exist. Our observations indicated that workers were marking information, such as YL-HC/KT1B/8/39/PH, on prefabricated components using marking pens yet were unaware of the purpose of their actions. Product information is generally disconnected with the design information stored in a building information model. Although information is obtained using advanced RFID subsystems, making them “talk to” BIM remains a problem. Although ideally, BIM is a real-time information representation of an “as-built” project, this platform cannot synchronize with a project. Software vendors have developed several plug-ins for BIM to perform popular functionalities, such as clash dictation and bills of quantity (BQ) generation. However, the interface between a BIM system and an RFID subsystem or other peripheral devices (e.g., Webcam and laser scanner) has yet to be developed.

W4: Lack of interoperability between various stakeholders and their heterogeneous enterprise information systems

For the past several years, various stakeholders have developed their respective enterprise information systems (EIS), such as HOMES, based on their information requirements. Different companies have also customized their respective enterprise resource planning (ERP) systems or purchasing standard ERP packages. As stated by the interviewees, these systems have considerably facilitated the operations undertaken by different stakeholders by pushing precise information for decisions making. Nevertheless, these heterogeneous systems cannot "talk" to one another because of various reasons, including varying databases, functions, and operating systems. Another obstacle is the adversarial culture prevalent in the EIS sector. Stakeholders are self-guarded interest centers and thus, sharing information among them is not an industry-wide culture. This situation has been referred to as "information islands," which can be considered bodies of information that need to be shared but have no network connection. Therefore, information interoperability among EIS of various stakeholders is extensively recognized to be fairly low.

(3) Opportunities

O1: Appeal to alleviate conflict between high housing demand and labor shortage

Every country faces its own housing problems; however, no other housing problem is probably comparable to Hong Kong, where housing has been a major concern for the past several decades. At present, housing supply in Hong Kong is primarily through three channels, namely, private housing, PRH, and subsidized housing under HOS. HKHA records show that a total of 2,599,000 permanent residential apartments were in stock by the end of March 2012, among which, private apartments accounted for 56% (1,447,000), PRH accounted for 29% (761,000), with subsidized housing reaching 15% (391,000). These housing supplies are positioned in an increasingly decaying urban setting. The Housing, Planning, and Lands Bureau in 2005 reported that Hong Kong has approximately 39,000 private buildings, with approximately 13,000 of these buildings being over 30 years old. In ten years, this number will increase to 22,000. In terms of demand, 48,841 marriages were recorded in Hong Kong between the periods from 2004 to 2011; however, only 13,609 new private apartments were completed within the period, resulting in an average of 3.6 couples competing for one private apartment (Census Statistics Department 2012). The upsurge in prices of private housing has made this option affordable for only a very small percentage of people, with about 50% population having to reside in public houses (Census Statistics Department 2012). More than 100,000 applicants were on the wait list for vacant PRH (Census Statistics Department 2012). Given the PRH demand and supply, these applicants have to wait an average of seven years to move into PRH. Consequently, the housing issues have resulted in widespread discontent in Hong Kong. In July 2012, the new administration initiated a series of policies and regulations (e.g., “Ten measures by Leung,” “Hong Kong Land for Hong Kong Residents,” and the Special Stamp Duty) to address these issues. Producing more public apartments is one of the long-term strategies on the agenda of the government. Table 2.3 shows the public housing production forecasts, which was reiterated by HKSAR chief executive C.Y. Leung during the Policy Address where, through a large number of pages, an attempt to discuss the housing issues in Hong Kong was made.

Table 2.3 Public housing production forecasts

Year	Public Rental Housing	Subsidized Sale Apartments	Total
2012–2013	13,100	0	13,100
2013–2014	14,100	0	14,100
2014–2015	12,700	0	12,700
2015–2016	20,400	0	20,400
2016–2017	15,300	2,200	17,500

Grand Total		77,800

Source: Hong Kong Housing Authority

On the production sphere, even if the government can secure land supply, whether the existing industry capability is sufficient to deliver the ambitious housing plan within such a short period remains questionable. First, the construction industry has a severe labor shortage with only 294,400 employees, which takes up about 8% of the total Hong Kong labor force. From this total, approximately 50,000 are at the worker level. The construction industry is also losing its appeal because of various reasons, such as aging population (Census and Department 2012), the boom of the local construction market such as the 10 mega-infrastructure projects, and the poor image of the industry. Labor cost is also surging to increasing heights. The average daily wages of a bamboo scaffolder, mason, and bar bender and fixer reached HK$1,147.0, HK$1,247.5, and HK$1,295.5, respectively (Census and Department 2012). Despite the high wages, finding sufficient workers to produce houses remains a challenge.

O2: Appeal to reduce construction waste

The fulfillment of such an ambitious housing plan in Hong Kong have further environmental effects because of the dust, greenhouse gas emissions, noise pollution, consumption of non-renewable natural resources, and construction waste. The construction industry is generally regarded to be a significant contributor to the deprivation of natural resources and environment despite the significant contribution of this industry to build environment development. In 2011, solid waste transported to landfills reached a record high of 13,458 tons per day, of which construction waste accounted for 25% (Department 2012a). Waste dumping in landfills will cause extensive soil, water, and air pollution as the anaerobic degradation of the waste will generate CO_2 and methane. Construction waste also places enormous pressure on landfills as land resources are highly valuable in this compact city. Construction waste takes up landfill space at a rate of approximately 3,500m^3 per day and costs the Hong Kong government more than HK$200 million annually for landfill disposal (Poon et al. 2004). The Hong Kong Environmental Protection Department predicts that landfill facilities will reach their maximum capacity in the next 10 years, with an estimated 24% annual increase in construction waste for disposal (Department 2007).

O3: Appeal to alleviate construction safety hazards

Another problem faced by the housing plan of Hong Kong is safety, because the region is infamous for its high construction accident rates. According to the statistics from the Hong Kong Labor Department, the industrial accident rate in Hong Kong remains high at approximately 50% in 2011, although the number of industrial accidents has decreased steadily from 6,239 in 2002 to 3,112 in 2011 (Department 2012b). A high number of industrial fatalities were recorded in this sector, with fatalities totaling 23 and fatality rate at nearly 0.367 in 2011 (Department 2012b). The construction industry accounted for approximately 20% of all industrial accidents, a considerable percentage among all industrial fatalities in Hong Kong (Department 2012b). The accident and fatality rates in the construction industry are significantly higher than the average rate of all industries. Therefore, the implementation of such an ambitious housing plan will possibly result in more construction-related accidents if no action is taken. Among the various construction-related safety hazards, include falling from high places, motor vehicle crashes, excavation accidents, electrocution, and machines, asbestos, solvents, noise, and manual handling activities.

(4) Threats

T1: Inefficient installation management because of compact space

Construction sites in Hong Kong are often compacted, with limited spaces for storing large and heavy components. Therefore, site management is often on the critical path for the success or failure of a construction project. Under these circumstances, JIT delivery and assembly model would be desirable. However, a site manager in Hong Kong will normally have to reserve components/materials of 1.5 stores on site as buffer. The limited space results in more time for vertical transportation of precast units from the ground level to the designated floors. One interviewed manager stated that if an effective schedule for prefabrication assembly is lacked, then adoption of prefabrication may extend the floor construction cycle of cast in-situ floor from the usual five to seven days. Verification of the components is also inefficient primarily because of the extensive use of paper or paint labels. Workers have to pay attention to the verification process sequentially, leading to extra labor and time costs. Despite the focus of workers, accuracy of the verification process is not guaranteed because paper-based documents, or even the handwriting and modified labels, are frequently unclear. Current practice may also cause safety issues. Construction workers on the sites are often preoccupied with their responsibilities, several of which require space (e.g., for crane towers to hoist various components to proper positions). If the required spaces are occupied, then serious safety issues may occur.

T2: Inefficiency in transportation and high cost of cross-border logistics

As mentioned, the entire sector of the production of precast elements in Hong Kong has been transferred to the PRD region, such as Shunde, Dongguan, Huizhou, Zhongshan and Shenzhen. The transfer is a natural response to the changing socio-economic landscape in the region. Hong Kong imports all the construction materials from Mainland China, which is one of the major materials suppliers. China can offer a full spectrum of raw materials because of the availability of resources and strong manufacturing capability. Offshore prefabrication enables purchase of cheap materials from Mainland China, while enabling Hong Kong to take advantage of the cheap and abundant labor force in the PRD region. Once the precast elements are manufactured, only a few pieces of these typically large and heavy components can be delivered at a time using a heavy truck. Therefore, the progress, timing, and cost of the construction generally depend on the logistics of the prefabricated module delivery. Based on our pilot studies, the cost of cross-border logistics could take up to 15% to 20% of the total prefabrication production cost. The low efficiency of customs control also forces logistics companies to invest additional funds in leasing storage spaces near Lo Wu or Lok Ma Chau to store prefabricated components temporarily. This issue also has a negative effect on logistics efficiency and effectiveness.

T3: Insufficient information storage method of precast elements

One of the managers interviewed stated that it would be extremely difficult if not completely impossible for both clients and suppliers/manufacturers to handle ordering information manually. Similar to a garment or an electronics company, it is not uncommon for a manufacturer to supply various prefabrication components to different clients/contractors and their construction sites. Taking orders and changes from clients/contractors makes the process susceptible to errors. Currently, companies have to allot extra labor cost on checking, counting, and sorting their raw materials as well as semi and finished prefabricated components. However, efficiency to achieve this goal remains lacking. Another challenge is determining how to embed the design information in the prefabrication components for further use. Currently, information is labeled through paper cards or painted labels without using new auto-ID technologies. This approach causes difficulties in the efficient retrieval of data for other uses, such as production management, inventory management, and transportation. As such, components may be delivered to other construction sites by mistake, which may cause serious project delay.

2.3 Literature Review on the Management of Prefabrication Construction

2.3.1 Selecting Target Academic Journals

The review methods of previous research (Ke et al. 2009; Tang et al. 2010) offer valuable guidance in the selection of target academic journals in the MPC research domain. Ke et al. (2009) stated that a research team might contribute their research achievements to a renowned journal from their specific field or that which has a similar research topic (Ke et al. 2009). Accordingly, the authors of this study used the Scopus search engine to identify the journals that have published the most research on MPC from 2000 to 2015. The most-searched keywords in this search engine included prefabrication, prefabricated construction/building, precast concrete, off-site construction, modular construction/building and industrialized building/housing. Articles containing these terms in the title/abstract/keywords were considered for review in this research. The search is further narrowed based on the subject fields of engineering, decision sciences, social sciences, management, and environment, and based on the document type of the article or review. However, a certain number of unwanted articles still show in the search results despite the rigorous search criteria. The authors of this research subsequently scanned each article from the search results to filter and retrieve MPC-related papers.

It is found that nine journals, namely, Construction Management and Economics (CME), Automation in Construction (AIC), Journal of Construction Engineering and Management (JCEM), Journal of Architectural Engineering (JAE), Construction Innovation (CI), Building Research and Information (BRI), Habitat International (HI), Energy and Building (EB), and Building and Environment (BE) have published at least four MPC-related articles from 2000 to 2015. Besides, Engineering, Construction, and Architectural Management (ECAM), one of top 10 journals ranked by Chau (1997), was considered after consulting peer reviewers in the research community. Therefore, a total of 10 academic journals were used in the review analysis of MPC literature. The selection of journals was based on two criteria, namely, (1) the journals should be mainstream journals (with a certain number of publications according to the Scopus database search results) in the area of prefabrication and (2) the journals should either be ranked by Chau (1997) as one of the top 10 journals in the construction management field or acknowledged as a first-tier journal by peer reviewers who specialize in prefabrication (Wing 1997).

To gain an in-depth understanding of the main research stream in this domain, the contribution of each researcher, country, or institution is quantitatively assessed and analyzed by adopting the approach of Al-Sharif and Kaka (2004), in which the published articles of each researcher during a specific period and within a specific research field are counted (Al-Sharif 2004). This method identifies the top contributors to a particular research field, which enables researchers to trace the achievements of previous contributors and assists them in advancing the study from its findings.

The quantitative evaluation of an author's contribution in a multi-authored article is a conventional research topic that has attracted a large amount of interest from various research domains. At the beginning of a collaborative research, the contributions of each author are assumed to be even, which means that each author is regarded as an owner of a research regardless of how many authors have collaborated in a multi-authored article. This method has been improved by Howard et al. (1987) who suggested the discriminative assessment of an author's contribution by assuming that the former author has made a bigger contribution than succeeding authors. This assumption has been accepted in many studies that examine the research productivity of authors. Howard et al. (1987) also presented the following formula to explain their method in detail (Howard et al. 1987):

$$\text{Score} = \frac{1.5^{n-i}}{\sum_{i=1}^{n} 1.5^{n-i}}$$

where n is the total number of authors of the article and i is the ordinal position of the author of the article. Each paper is assumed to have a score of one point. A detailed score matrix that is obtained based on the formula is displayed in Table 2.4. Based on the matrix, in a paper with two authors, the first author is given a score of 0.60, while the second author is given 0.40. However, the ordinal position of the author may not invariably reflect the actual contribution difference because in exceptional circumstances, the chief author leaves the first ordinal position to the other authors. Therefore, to ensure the reliability of the evaluation, this research adopted another method that calculated the total number of citations in a particular article. This method is based on the assumption that the more citations a paper receives from other researchers, the higher contribution the authors provide to the research community. The results of both methods are discussed in the succeeding chapter.

Table 2.4 Score matrix for multi-author papers

Number of authors	**Order of specific author**				
	1	**2**	**3**	**4**	**5**
1	1.00				
2	0.60	0.40			
3	0.47	0.32	0.21		
4	0.42	0.28	0.18	0.12	
5	0.38	0.26	0.17	0.11	0.08

2.3.2 Result Analyses and Discussions

(1) Number of MPC related papers

Table 2.5 presents the number of prefabricated construction management related articles published across the period from 2000-2015. The total number of paper published in the 10 selected journals was 16463, among which 124 are found to dedicate in addressing MPC related issues. Even though papers in relation to prefabricated construction management only sign up a relatively low proportion of 0.75 percentage of the total publications, the number of annual published papers referring to the MPC research has been witnessed an impressive surging trend from just 1 at the beginning to 12 in 2015, which indicated that there appears an increasing attention from researchers to the MPC discipline.

Obviously, as Table 2.5 shows, the journals AC, CME, JCEM and JAE have published the highest number of MPC related articles over the study period, more specifically, AC has published 25 articles regarding to MPC from 2000 to 2015, followed by 23 in CME, 17 in JCEM and 13 in JAE. Obviously, the number and the ratio of MPC papers published in AC and CME is much higher than any other selected journals, indicating the two journals have made the most significant contribution to the research discipline of MPC. Moreover, from the statistics, it can be revealed that the average ratio of MPC related publications is 0.75% while the percentage in EB, BRI and BE is just 0.27%, 0.33%, 0.11%, much lower than the average level. Such an evident numerical difference might, to some extent, reflect the current research trend that relatively less efforts have been dedicated to the issues concerning energy and environment performance in the research of prefabrication, as these three journals mainly published articles which address construction management issues from energy and environment perspectives.

Table 2.5 MPC related articles published during the period from 2000 to 2015

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Target journals	Total	397	483	565	625	681	746	887	1075	964	977	1117	1297	1515	1667	1719	1748	16463
	MPC	1	2	3	4	4	4	8	10	11	9	10	13	13	8	12	12	124
	Ratio (%)	0.25	0.41	0.53	0.64	0.59	0.54	0.9	0.93	1.14	0.92	0.9	1	0.86	0.48	0.70	0.69	0.75
AC	Total	51	45	50	60	55	62	64	85	90	91	92	113	155	180	185	185	1563
	MPC	0	0	1	1	2	1	1	2	2	3	4	1	3	0	2	2	25
	Ratio (%)	0	0	2	1.67	3.64	1.61	1.56	2.35	2.22	3.3	4.35	0.88	1.94	0	1.08	1.08	1.6
CME	Total	38	48	61	73	92	99	122	118	105	100	103	96	85	85	88	96	1409
	MPC	0	1	0	0	0	2	1	2	4	1	2	2	0	4	1	3	42
	Ratio (%)	0	2.08	0	0	0	2.02	0.82	1.69	3.81	1	1.94	2.08	0	4.71	1.14	3.13	2.98
JCEM	Total	58	62	69	93	111	158	158	118	110	146	143	116	163	180	190	195	2070
	MPC	0	1	1	0	1	1	0	2	4	0	0	2	2	0	2	1	17
	Ratio (%)	0	1.61	1.45	0	0.9	0.63	0	1.69	3.64	0	0	1.72	1.23	0	1.05	0.51	0.82
JAE	Total	15	19	17	26	37	28	31	42	48	54	59	117	139	139	142	145	1058
	MPC	1	0	1	0	1	0	0	0	0	0	1	4	3	1	0	1	13
	Ratio (%)	6.67	0	5.88	0	2.7	0	0	0	0	0	1.69	3.42	2.16	0.72	0	0.69	1.23
ECAM	Total	37	37	38	36	39	35	36	37	34	36	36	36	36	36	36	38	583
	MPC	0	0	0	2	0	0	0	0	1	*0*	2	1	1	0	2	1	10
	Ratio (%)	0	0	0	5.56	0	0	0	0	2.94	0	5.56	2.78	2.78	0	5.56	2.63	1.72
CI	Total	0	17	16	16	16	16	16	21	18	28	25	27	27	27	28	28	326
	MPC	0	0	0	0	0	0	1	1	0	3	1	1	3	0	1	1	12
	Ratio (%)	0	0	0	0	0	0	6.25	4.76	0	10.71	4	3.7	11.11	0	3.57	3.57	3.68
HI	Total	32	31	34	34	34	37	68	31	39	58	55	66	56	130	134	136	975
	MPC	0	0	0	0	0	0	3	1	0	1	0	1	0	0	1	0	7
	Ratio (%)	0	0	0	0	0	0	4.41	3.23	0	1.72	0	1.52	0	0	0.75	0	0.72
EB	Total	73	81	105	110	129	130	158	134	249	159	280	419	503	526	542	545	4143
	MPC	0	0	0	0	0	0	2	0	0	0	0	1	1	3	1	3	11
	Ratio (%)	0	0	0	0	0	0	1.27	0	0	0	0	0.24	0.2	0.57	0.18	0.55	0.27
BRI	Total	31	39	31	35	22	14	31	49	52	41	42	44	41	42	42	44	600
	MPC	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2
	Ratio (%)	0	0	0	0	0	0	0	2.04	0	0	0	0	0	0	2.38	0	0.33
BE	Total	62	104	144	142	146	167	203	440	219	264	282	263	310	322	332	336	3736
	MPC	0	0	0	1	0	0	0	1	0	1	0	0	0	0	1	0	4
	Ratio (%)	0	0	0	0.7	0	0	0	0.23	0	0.38	0	0	0	0	0.30	0	0.11

(2) critical authors, institutions, papers of the MPC research

As shown in the Table 2.6, there appears an increasing trend in the number of writers from different regions showing interest in the research discipline of MPC. Table 2.6 and table 2.7 present more evidence to support this assertion. The statistics show that a total of 12 researchers contributed at least three MPC related articles, and 10 research centers were involved in more than three articles during the period from 2000 to 2015. Apparently, Wei Pan from The University of Hong Kong, Hong Kong has published the largest number of 9 articles in this domain, achieving the highest contribution score of 4.75, followed by Alistair G.F. Gibb, Ghang Lee and Charles M. Eastman who contributed 7, 7, and 7 papers respectively. In terms of the contribution of institution, Loughborough University, United Kingdom has contributed the largest number of publication of 15 papers, followed by 12 in the Hong Kong Polytechnic University, 8 in Georgia Institute of Technology, and 6 in Luleå University of Technology.

Table 2.6 Researchers involved in at least three papers

Researchers	Papers	Score	Affiliation
Wei Pan	9	4.75	Loughborough University； The University of Hong Kong
Alistair G.F. Gibb	7	2.29	Loughborough University
Rafael Sacks	7	2.47	Technion–Israel Institute of Technology； Georgia Institute of Technology
Charles M. Eastman	7	2.33	Georgia Institute of Technology
Nashwan Dawood	5	2.04	The University of Teesside
Chi-Sun Poon	5	1.84	The Hong Kong Polytechnic University
Andrew R. J. Dainty	4	0.95	Loughborough University
Helena Johnsson	4	1.23	Luleå University of Technology
Esin Ergen	3	1.28	Istanbul Technical University
John Henrik Meiling	3	1.34	Luleå University of Technology
Lara Jaillon	3	1.80	The Hong Kong Polytechnic University
Ramesh Marasini	3	1.47	University of Teesside

Table 2.7 Research centers contributing to more than four papers

Institution/University	Country	Researchers	Papers	Score
Loughborough University	UK	9	15	9.43
Hong Kong Polytechnic University	Hong Kong	24	12	11.15
Georgia Institute of Technology	USA	5	8	4.52
Luleå University of Technology	Sweden	10	6	5.53
University of Teesside	UK	4	5	4.40
Technion-Israel Institute of Technology	Israel	2	5	2.25
University of Plymouth	UK	2	5	3.14
National University of Singapore	Singapore	5	4	2.60
Istanbul Technical University	Turkey	4	4	3.07
The Pennsylvania State University	USA	4	3	1.85

The authors are suggested to cite a reference to its source when the unoriginal perspective is referred, and a reasonable reference is viewed as an evidence of the findings. Thus, the citation index analysis, as another effective way for evaluating the contribution of specific paper, is conducted in this study. The most frequently cited articles are tabulated in Table 2.8. Note that given the search service of Scopus is limited in terms of the coverage on the prefabrication related publications, Google Scholar is adopted to extract citation information of selected articles for ensuring consistent and reliable source. It can be found from the results that the article of Ergen et al. (2007) from Istanbul Technical University has been recorded as the most frequently cited paper of 174 times, and the researchers of Sacks, Tam, Pan, and also contribute significant efforts while the three articles (Sacks et al. 2004; Pan et al. 2007a; Tam et al. 2007) were also comprised in the most four frequently cited articles.

Table 2.8 Most frequently cited papers of MPC

Document title	Times
Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS (Ergen et al. 2007)	174
Parametric 3D modeling in building construction with examples from precast concrete (Sacks et al. 2004)	169
Towards adoption of prefabrication in construction (Tam et al. 2007)	135
Perspectives of UK housebuilders on the use of offsite modern methods of construction (Pan et al. 2007a)	107
Sustainable performance criteria for construction method selection in concrete buildings (Chen et al. 2010)	106
Benchmark tests for BIM data exchanges of precast concrete (Jeong et al. 2009)	104
Differentiation of rural development driven by industrialization and urbanization in eastern coastal China (Long et al. 2009)	103
Just-in-Time management of precast concrete components (Pheng and Chuan 2001)	99
Future opportunities for offsite in the UK (Goodier and Gibb 2007)	97
Developing a precast production management system using RFID technology (Yin et al. 2009)	87
Numerical and experimental analyses of MPC containing sandwich panels for prefabricated walls (Carbonari et al. 2006)	76
Leading UK housebuilders' utilization of offsite construction methods (Pan et al. 2007b)	74
Learning to see work flow: an application of lean concepts to precast concrete fabrication (Ballard et al. 2003)	65
Process model perspectives on management and engineering procedures in the precast/prestressed concrete industry (Sacks et al. 2004)	61
Constraint programming approach to precast production scheduling (Chan and Hu 2002)	52

2.3.3 State of the Art and Future Research Trend

For the purpose of gaining comprehensive understanding into the discipline of MPC, the collected academic articles were examined and further classified through two steps. The first step is to sort the literatures by answering the question of what data collection and analysis methods have been adopted, while the second step is to determine the number of papers published each year on prefabricated construction management topics during the period from 2000 to 2015. Future research directions on this discipline will be finally explored on the basis of the classification results derived from the two steps mentioned before.

(1) Research and analytical methods used

It is found from the classification result that the data collection methods, adopted in previous studies on MPC domain, vary to a great extent. A common data collection methodology carried out by researchers could be divided into four types, namely, (1) literature review, which is normally conducted by researchers to extract valuable data or conclusion drew by previous research; (2) survey, one of main data collection methods in construction management field, is generally carried out via conducting face-to-face interviews with or distributing questionnaires to industry practitioners; (3) case study, characterized in providing a great amount of description and detail about a particular case, is conducted by researcher to gain in-sight understanding of one or more real-world building projects; (4) experiment, convenient for precisely controlling and manipulating variables, is primarily adopted to research the physical properties of prefabricated element. The number of articles, which is counted according to the classification of data collection method, is shown in the Table 2.9. It is obvious that case study and survey are the primary methods for gathering data (together account for 71.78%) in the prefabrication research. This might be attributed to the fact that prefabricated construction management is, by nature, immediately related to the specified context of construction industry practice, which requires researchers to conduct in-depth surveying of the industry practice prior to putting forward valuable measures and recommendations.

Table 2.9 Data collection and analysis methods in publications of MPC

Data collection method	Number of papers	Percentage
Literature review	20	16.13%
Survey	38	30.65%
Case study	51	41.13%
Experiment	15	12.10%
Data analysis method	Number of papers	Percentage
Descriptive statistics	31	25.00%
Statistical analysis	35	28.23%
Simulation/modeling	58	46.77%

After the data collection, three types of data processing method are normally adopted for analyzing the information, including: (1) statistical analysis; (2) descriptive analysis; and (3) simulation/modeling. The classification results of the data processing method are tabulated in Table 2.9. It is revealed that half of selected articles adopt the simulation method for data analysis, 35 papers use statistical analysis, and a number of 31 papers focused on prefabrication research through applying the descriptive statistics method. Interestingly, it is found from the examination that, at the beginning of the studied period, researchers are inclined to adopt relatively ordinary method, such as statistical and scenario analysis, to conduct information processing, while more complex methods, such as Georgia Tech Process (Lee et al. 2007), Radio Frequency Identification Technology and GPS (Ergen et al. 2007; Yin et al. 2009), Building information modeling (Jeong et al. 2009; Sacks et al. 2010), and dynamic simulation (Pan et al. 2008), have started to sever as an increasing important role in the course of data processing in prefabricated construction management research domain. It is expected that through the employment of these innovated systematic information technologies, the complexity and dynamics of the process of prefabricated construction can be better simulated to reflect the real-world industry practice.

(2) Research interests and future research directions

Over the last decades, construction management related journals have testified a sustainable growth in the research of prefabricated construction management, the themes of which are diverse in content, writing over from industry analysis to prefabricated construction strategy research. This paper identified five categories for the research interests of MPC articles, including (1) industry prospect analysis; (2) review of development and application; (3) performance evaluation; (4) technique promotion environment; and (5) Design, Production, transport and assembly strategies. The Figure 2.2 presents the structure of research interests in the discipline of MPC.

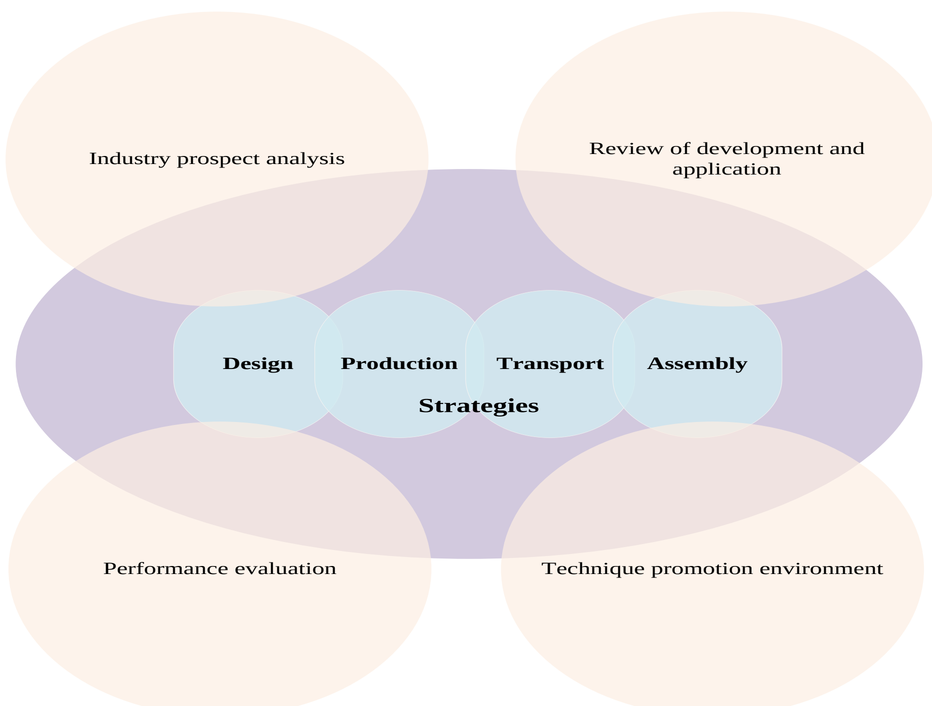


Figure 2.2 The framework of research interests in the discipline of MPC

The sub-topics of these categories within the research interests are listed as follow:

(1) Industry prospect analysis (1. benefits, incentives of prefabrication adoption (Tam et al. 2007); 2. defects, barriers to apply precast technique (Blismas and Wakefield 2007; Mao et al. 2015); 3. future opportunities of precast industry (Nadim and Goulding 2010)

(2) Review of development and application (1. case experiences analysis (Meiling et al. 2013); 2. evolution of prefabricated building systems (Jaillon and Poon 2009; Uttam and Le Lann Roos 2015)

(3) Performance evaluation (1. environmental performance (Aye et al. 2012; Pons and Wadel 2011; Hong et al. 2015); 2. economic performance (Pan et al. 2008); 3. social performance (Johnson 2007)

(4) Marketing environment for technique promotion (1. guideline and policy (Kale and Arditi 2006); 2. attitude of various stakeholders (Pan et al. 2007a); 3. public perspectives (Engström and Hedgren 2012); 4. stakeholder relationships (Jeong et al. 2009)

(5) Design, Production, transportation and assembly strategies (1. production control (Yin et al. 2009); 2. transportation and stockyard layout planning (Marasini et al. 2001); 3.Architectural design measures (Leskovar and Premrov 2011); 4. precast assembly techniques (Dawood 2006); 5. construction information flow processing (Ergen and Akinci 2008; Tam et al. 2015).

In keeping with the identified six research interests, future research directions can be further derived on the basis of the discussions of what have been done and what remain to be done in the domain of prefabricated construction management, as presented in Figure 2.3.

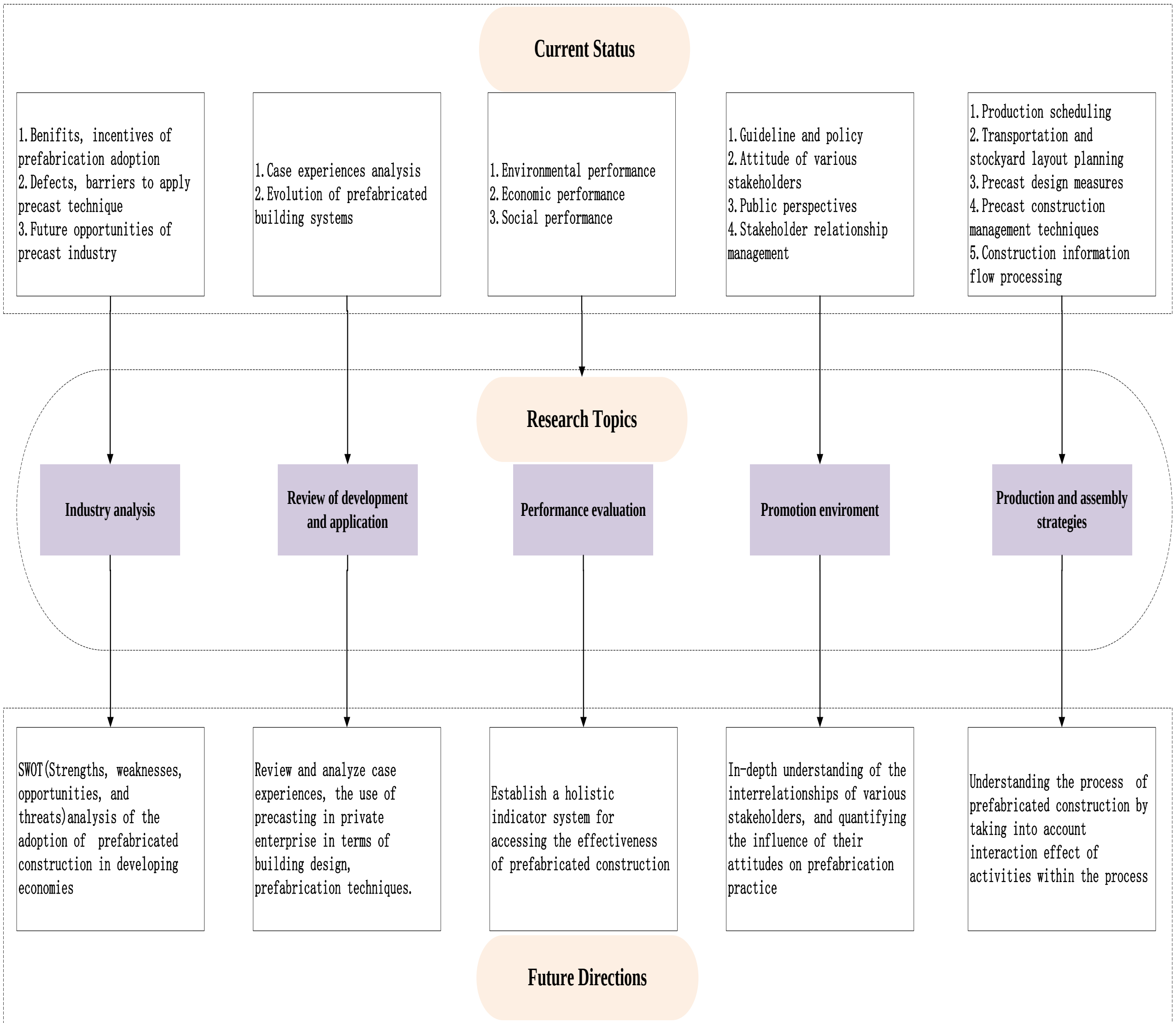


Figure 2.3 Future research directions in the discipline of MPC

Existing literature regarding to the first topic of "industry prospect analysis" has mainly focused on examining what factors facilitate or inhibit the adoption of prefabrication techniques. For instance, Tam et al. (2007), when conducting an industry-wide survey study, found that "better supervision", "reduce overall construction costs", and "shorten construction time" were the most critical advantages for adopting prefabrication. Through interviews and workshops, Blismas and Wakefield (2007), discerned that "a low level of knowledge", "negative sentiments from past failures" and "immense changes to existing processes" are the major constrains to the success of off-site manufacture. However, it is found from the selected papers that most of the research efforts within this topic have been devoted in developed economics, such as USA (Ballard et al. 2003), Australia (Blismas et al. 2010), HK (Poon et al. 2003) and UK (Arif and Egbu 2010). While SWOT (strengths, weakness, opportunities, and threats) related analyses on the adoption of prefabricated construction are lagged far behind in some developing countries, where have a great demand for sustainable buildings due to rapid urbanization.

Within the second topic "review of development and application", it is found that existing prefabricated construction practices are mainly confined to public sector, while conventional construction method including the use of bamboo scaffolding in-situ concreting, timber formwork and wet trades are still widely adopted by private enterprises. Maas and van Eekelen (2004) investigated an office building which was constructed and transported over water for identifying the difference compared to the conventional building. By employing a dynamic simulation software, Pan et al. (2008) examined a High-Speed Railway project in terms of the overall production procedures involved in the planning of pre-cast yard, equipment capacity, production, transportation and launching. Jaillon and Poon (2009) pointed out that as lack of comprehensive database on high-rise buildings that leaded to the failure of providing any data on the use of prefabrication in private enterprises. A sole study found in the collected articles, examined the adoption of volumetric and modular prefabricated component in a conceptual residential building which was never built (Girmscheid and Rinas 2012). These indicate a lack of research reviews the adoption of precast technologies in the private enterprise. Therefore, with the expectation of bridging the research gap within this topic, future research should be conducted to gain understanding of the evolution and application of prefabrication technology in residential buildings in private enterprise.

It is found that recent studies in relation to the topic “performance evaluation” have transferred from “a conventional focus on cost-benefit analysis” to “a more extensive perspective of sustainability, covering not only economic benefit, but also environmental and social effectiveness”. For example, in order to determine to what extend precast techniques could improve the quality and reduce the environmental impact, Pons and Wadel (2011) carry out a life cycle analysis to compare three main industrialized technologies that have been extensively applied in building school centers in Catalonia and a non-prefabricated one, from a technical and environmental point of view. López-Mesa et al. (2009) conducted a contrastive analysis toward residential buildings in Spain to verify if the environmental impact of a precast concrete floor is lower than that of an in situ cast floor. A multi-residential building was investigated by Aye et al. (2012), to assess the potential environmental and social benefits brought by precast techniques in terms of reusability of materials, reducing the space required for landfill and need for additional resource requirements. The review of the identified literature revealed that although the separate evaluation of environmental or social impact of the prefabrication begins to appear in this domain recently, existing research should be further extended to establish a more holistic indicator system which covers all economic, social and environmental perspectives, when accessing the effectiveness of prefabricated construction.

When it comes to the topic ‘marketing environment for technique promotion’, after the report by Egan (1998), plenty of studies have attempted to investigate the attitudes of various stakeholders towards the application of prefabricated construction. It is suggested that the attitudes of architects, contractors/producers, developers, maintenance and implementers had vital influence on the success of innovative modern construction schemes due to their contribution to the development process and their role in the decision making process (Palmer et al. 2003; Pan et al. 2007a). A study by Edge et al. (2002) revealed that owing to the strong negative influence of the post-war 'precast', house purchasers will resist any innovations in housing industry that tend to influence what a conventional house look like, while these similar perspective obstacles, directly or indirectly leading to the historical failure of prefabrication practices, also exists among others stakeholders (Pan et al. 2004). A few of studies backed by government have explored drivers and obstacles of prefabrication application from a more extensive range of stakeholders' attitudes. A housing forum in UK examined the obstacles to innovative construction methods that architects, contractors, consultants, developers and clients are confronting on a daily basis in their organizations' working relationships (Brown 2002). The study provided recommendations around aspects of culture, design and construction, and the regulatory environmental and called for efforts from the whole supply chain. While acknowledging the contribution of preceding studies, it should be also noted that litter attention has been draw on the investigation of the interrelationships among different attitudes of various stakeholders and gaining understanding of to what extend can the attitudes of industry practitioners influence the decision on the use of precast techniques. Therefore, developing approaches that can quantify the effect of stakeholders' attitudes on decision-making of the prefabrication adoption is probably a promising research direction.

As for the fifth topic, it is widely acknowledged that the monitoring and control of the processes of prefabricated construction and their variables have strategic importance in order to respond to the dynamics of the building industry. Many monitoring processes are focused on controlling time and cost and the overall performance is evaluated through a standard set of key performance indicators (Fang and Ng 2011; Shamsai et al. 2007; Vukovic and Trivunic 1994). These passive approaches do not take into account a holistic/system view and therefore ignore the interrelationship between various external and internal variables impacting a construction process (Dawood 2006). The whole management process of prefabricated construction is of high complexity, within which the activities are interrelated and deserved systematic analysis and organization. Such complexity cannot be better understood without considering the interrelationships underlying these activities. A number of researchers have been aware of this significant feature grounded in the process of prefabricated construction and conducted relevant studies from a systematic point of view. Pan et al. (2008) investigates the overall production procedures involved in the planning of pre-cast yard, equipment capacity, production, transportation and launching by adopting a dynamic simulation software called SIMPROCESS. To provide the optimal or near-optimal combination of interactional production sequences, resource utilization, and minimum makespan, a genetic algorithm-based searching technique is adopted by Leu and Hwang (2002) in consideration of resource constraints and systematic mixed precast production. While acknowledging their contributions, further research following similar path is in pressing need.

2.4 Research gaps and Industry Needs

Through the critical review of the literature for the last decade, a wide range of research themes in the discipline of PHP from worldwide have been investigated and summarized. Their research outcomes have greatly contributed to the knowledge body of the management of PHP, providing valuable and constructive information for managers in PHP. While acknowledging their contribution, one major research gap of previous literature should be addressed: a lack of research on devising an effective method to manage schedule risks in PHP by considering involved stakeholders and interrelationships underlying various activities and variables from dynamic perspective. The research gap is evidenced as follow:

(1) Processes of prefabrication housing production have been treated separately. Current research on PHP is conducted according to the hierarchy of PHP, ranging from design, production, logistics, storage and on-site assembly in a series. Along the lines of the hierarchy, most of the research has considered related problems of PHP that arise from single specific process rather than viewing the processes as a whole.

(2) Few research has been dedicated to risk management of PHP with consideration of involved stakeholders. Previous research on the risks in prefabrication construction projects has been confined to issues of completeness and accuracy without consideration of stakeholder-associated risks and their cause-and-effect relationships. the majority of previous research were limited to the use of linear impact analysis when assessing the impact of risks or stakeholders on PHP without consideration of the associated risks and stakeholders, and the interrelationship between risks and stakeholders. The reality is that most schedule-related risks are interrelated and associated with various stakeholders in PHP projects and risk source analysis is an indispensable component in

risk management planning/registers to facilitate the risk response and mitigation actions. The stakeholder-associated risks could be far more unpredictable and difficult to manage than first thought. Schedule risks are subject to different stakeholders designated to perform different tasks under different construction scenarios. How to identify critical schedule risks and corresponding stakeholders and quantify their impact from a network perspective has been a major concern in the research field of PHP.

(3) Activities in different PHP processes and variables within the specific process are generally viewed as independent rather than interdependent. In conventional research on prefabrication, processes including design, production, logistics, storage and on-site assembly are generally viewed as independent operations and even activities within a single process are isolated, neglecting the fact that the variation of one variable might have immediate influence on the other. However, as argued by (Li et al. 2014b), most of the variables within PHP are interdependent. For example, the increase in the number of quality problems of precast elements will cause design variations; and subsequently project scope variation will expand, which leads to increase in the number of precast elements to be installed and cause schedule delay. Failing to take such interrelationships into account might be the reason why there is a lack of sufficient understanding of risk management of PHP.

(4) Most research on the risk management of PHP has been conducted from a static point of view. Most research on risk management of PHP has by and large been based on empirical analysis obtained from surveys. And that kind of analysis fails to track the varied risk condition throughout the timeline to reflect actual management effect from a dynamics manner.

Apart from the research gaps, the industry need is highlighted as lack of a tool to handle schedule delay problems that mostly caused by various risks embedded in the fragmented processes of prefabrication housing production, while this problem has been seriously besetting managers of prefabrication housing production in Hong Kong. In consideration of the research gaps of existing research and industry development situation summarized above, the following issues are in need for future research:

(1) PHP is complex as a whole with various stakeholders involved: PHP is an inseparable process as precast components should be manufactured and transported to sites to fit in with the schedule of on-site assembly in seamless connection manner, and most risks are interrelated and associated with various stakeholders. A social network analysis approach that should be applied to deal with schedule risk with consideration of the interrelationships underlying the risk factors and their actual influence on a network basis.

(2) Activities in different PHP processes and variables within the specific process are largely interdependent: In conventional research of PHP, design, production, logistics, and on-site assembly are treated as independent activities, while in reality, the supply chain is inseparable as precast components should be manufactured and transported to sites to fit in with the schedule of on-site assembly in seamless connection manner. Effective schedule risks management of PHP should envisage the key characteristics of interdependent nature of activities in prefabrication housing production, taking interrelationships underlying various schedule risks in the PHP system for consideration.

(3) The management of Schedule risks of PHP is dynamic: Conventional research on the management of PHP tends to view PHP management as a static process, while the management

process in reality is dynamic, which means that those analytic results will not be able change across with time to reflect actual management effect from a real-time manner.

The research question is put forwarded based on above three points: Is it possible to effectively manage schedule risks in PHP by considering involved stakeholders and interrelationships underlying various activities and variables from dynamic perspective?

2.5 A Path Forward

To deal with the four research limitations highlighted above, social network analysis and the Hybrid system dynamics and discrete event simulation approach are adopted in this research for the following reasons:

(1) SNA is used for dealing with complex system with various stakeholders involved. The social network theory views PHP from the angle of system perspective, under which are various relationships of involved stakeholders and related concerns. The aim of applying network analysis is to investigate the influence of the variation of relationship structures on system behavior. The SNA theory is about examining the structure and patterning of relationships in a system and try to find out the rationale behind and potential influences. SNA is widely regarded as an excellent way to deal with system problems of high complexity with various stakeholders involved (Pryke 2012; Wasserman and Faust 1994; Yang and Zou 2014).

(2) With hybrid system dynamics and discrete event simulation approach, interrelationships underlying activities and variables within the PHP can be better depicted, modeled and simulated.

During the past decades, many research has adopted the hybrid SD and DES approach to model and simulate manufacture and construction systems (Lee et al. 2006; Alzraiee et al. 2015; Venkateswaran and Son 2005; Penoa-Mora et al. 2008). These studies not only justify the superiority of the hybrid system dynamics and discrete event simulation approach in depicting, modelling and simulating interrelationships underlying activities and variables within target systems, but also show that the hybrid system dynamic and discrete event simulation approach can gain a better understanding of the relationship between the behavior of a system over time and its underlying structure and decision rules.

(3) Hybrid SD and DES approach facilitates the examination of how the behavior of PHP system vary over time along with the change of various schedule variables from a dynamic perspective.

Hybrid SD and DES approach has the superiority of depicting, modeling and simulating dynamic system behavior. Venkateswaran et.al concluded that hybrid SD and DES is an excellent systematic approach to understand the dynamics of manufacturing systems and integrated enterprise (Venkateswaran and Son 2004). DES specializes in modeling a complex system from detailed procedure to simulate behavior of individual components in dynamic manner, while SD approach focuses on developing model to handle stated characteristics because it can simplify a complex system into operable units through its special analytical tools. The hybrid DES and SD method provides effective tool for considering from both perspectives of detailed procedure and stated characteristics, enabling project managers to gain a deeper insight into schedule management and acquire a multidimensional understanding of schedule delay with consideration of both the short-term operational procedures and long term risk effect.

To conclude, the SNA and the hybrid SD and DES approaches are appropriate methods to identify, analyze and evaluate schedule risks in PHP by considering involved stakeholders and interrelationships underlying various activities and variables from dynamic perspective.

2.6 Chapter Summary

The chapter investigate the external and internal situations of management practices of PHP in the Hong Kong construction industry. Current literature regarding to prefabrication construction and risk management in construction industry are reviewed for identifying research gaps and future research directions. The practical need from the PHP industry and research gaps forms a solid justification for the significance of this research.

CHAPTER 3 Methodology

3.1 Introduction

As mentioned in Chapter 1, the principal aim of this research is to develop an effective method to manage schedule risks in prefabrication housing production in Hong Kong. Social network analysis approach is applied to deal with schedule risks with consideration of the interrelationships underlying the risk factors and their actual influence on a network basis. And with hybrid system dynamics and discrete event simulation approach, interrelationships underlying activities and variables within the PHP can be better depicted, modeled and simulated. To gain a better understanding of why SNA and hybrid SD and DES approach is appropriate for achieving the research objectives, a review of SNA and hybrid SD and DES is conducted. The chapter ends by presenting modeling procedures adopted by previous research for developing SNA and hybrid SD and DES models.

3.2 Research Methods

3.2.1 Document analysis

In this research, document analysis is conducted to the external and internal situations of management practices of PHP in the Hong Kong construction industry. Then the current literature regarding to prefabrication construction and risk management in construction industry are also reviewed through content analysis, such that the practical need from the industry and research limitations can be identified and form a solid justification for the significance of this research. Moreover, document analysis is also conducted to form the initial list of involved stakeholders and associated schedule risks in prefabrication housing production and is used to analyze previous literature to identify variables to be built in the hybrid dynamic model.

3.2.2 Expert interview

Expert interviews are conducted throughout this research. In the preparation stage, expert interviews are conducted to look into the current industry development situation of PHP in Hong Kong, enabling the identification of the main problems confronting the construction industry when adopting prefabrication technologies. For the objective 1, the stakeholder-related schedule risks in PHP were identified along with stakeholder identification through a series of semi-structured interviews. For the objective 2, expert interviews are also carried out for data collection purpose for the verification and validation of hybrid dynamic model. Expert interviews are mainly conducted toward managers from four major involved parties in the PHP management, namely Wing Hong Shun Ltd., Yingyun Transportation Ltd., and Gammon Construction Ltd., and HKHA.

3.2.3 Case study

In this research, case study is conducted to validate and build up confidence into the developed hybrid dynamic model. The selected case for validating the model in this research is the Tuen Mun project and the materials of the case are mainly collected toward four major involved parties in the PHP management, namely Wing Hong Shun Ltd., Yingyun Transportation Ltd., and Gammon Construction Ltd., and HKHA.

3.2.4 Simulation

In this research, simulation is conducted to evaluate how and to what extend the hybrid dynamic model can function as an experiment platform to assess the impacts of different schedule risks on the schedule performance of PHP project. Simulation results that considerate mixtures of various risk scenarios under different timeline of the PHP project are generated, providing insights into how the schedule of the same PHP project will vary when different schedule risks occur under different timeline.

3.3 Analytical Tools

Before selecting the SNA and hybrid SD and DES approaches as the main analysis techniques, a variety of approaches have been summarized and compared to see which methods are suitable for dealing with the key characteristics of PHP, that are PHP is complex with various stakeholders involved, activities and variables within PHP are interdependent, management of schedule risk is dynamic. SNA is used for the identification of critical schedule risks with consideration of involved stakeholders in PHP. The social network theory views PHP from the angle of system perspective, under which are various relationships of involved stakeholders and related schedule risks. The aim of applying network analysis is to investigate the influence of the variation of relationship structures on system behavior. The SNA theory is about examining the structure and patterning of relationships in a system and try to find out the rationale behind and potential influences. As for the hybrid SD and DES together, hybrid dynamic model is a model that developed with hybrid system dynamic and discrete event simulation method, with an aim to evaluate and simulate impacts of schedule risks in PHP by considering interrelationships underlying various activities

and variables from dynamic perspective.

3.3.1 Social Network Analysis

Every construction project has its unique characteristics and its schedule duration is previously set and limited, as such extra efforts are required to construct and organize effective management team and build up trust between various involved project stakeholders and within the management team. Stakeholders are participants in the human process of joint value creation. PHP projects often comprise many organizational stakeholders, thus selecting suitable stakeholders for participatory processes such as schedule management s is not an easy task. It is necessary for various project teams to learn working more efficiency as one complete organization. Uncertainty is a problem for project managers due to reliant relationships among uncontrolled elements in its situation and the construction project. Stakeholders management requires the capacity of balancing various interests and claims on project resources. Nevertheless, an environment in high uncertainty and complexity makes achieving this balance more difficult. PHP projects are uncertain and complex in nature, such that stakeholder analysis is needed for the project managers of these projects.

As discussed in the chapter 1, with the fragmentation and discontinuity problems, various stakeholder-associated risks, are nurturing throughout the PHP, causing frequent schedule delay that beset the prefabrication industry in Hong Kong. To handle this problem, sources and causes of risks and corresponding stakeholders need to be identified and analyzed, potential impact should be assessed and measures should be taken by each stakeholder in PHP project to alleviate possible adverse influences. Stakeholder-associated risk analysis is vital not only for determining wide-ranging risk list and understanding sources and causes of risks, but also for its contribution to effective schedule management and enhancing the schedule performance in the management of PHP. The number of studies on the barriers, risks and critical success factors in delivering prefabricated housing projects has grown significantly in recent years. Both researchers and practitioners accept the fact that the whole process of prefabricated construction is more complex and problematic because the construction industry is "extremely conservative, and subject to slow rates of change due to regulatory, liability and limited technology transfer from other sectors of society". Therefore, an understanding of the risks in prefabricated construction is critical for industry players to analyze risks, thresholds and develop responding strategies proactively to help with the management of scheduling. To mitigate risks, it is important to identify the risk sources.

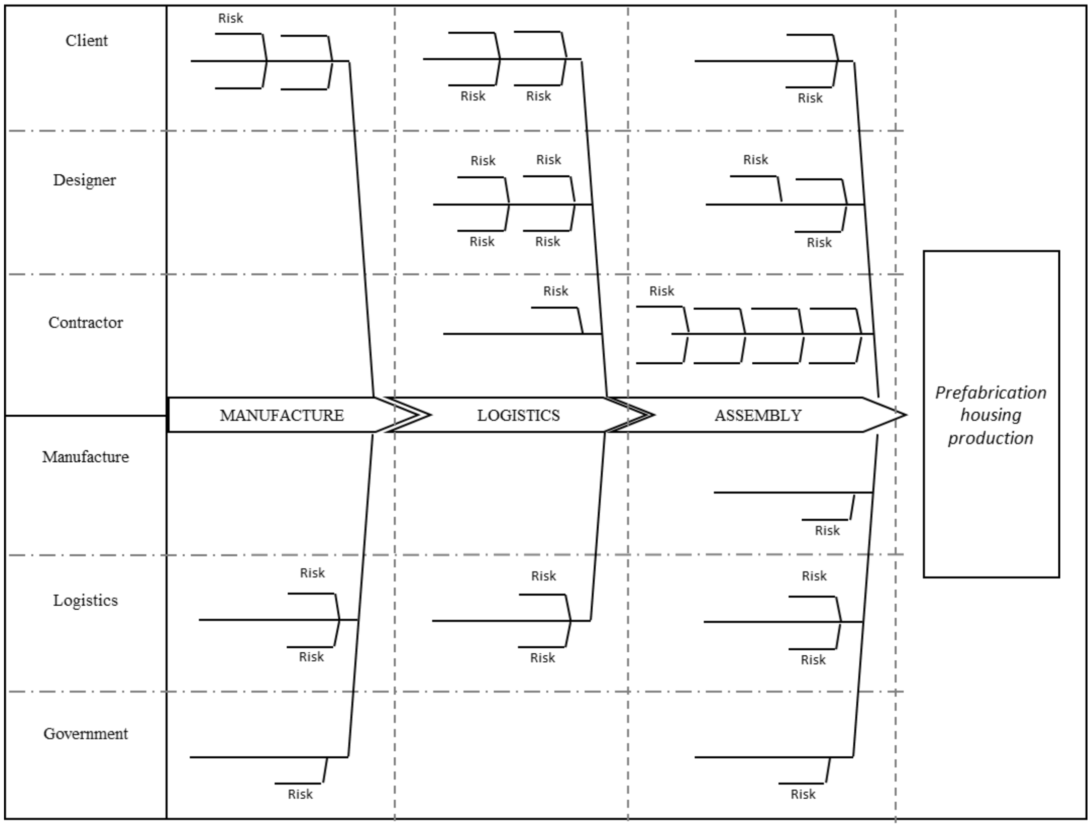


Figure 3.1 Risk network

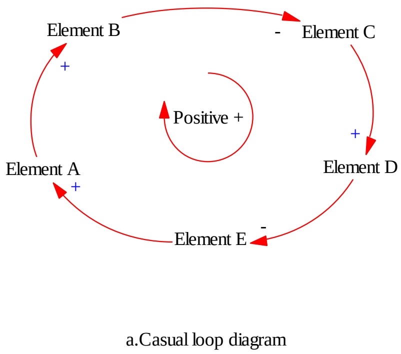
However, the difficulties of using the risks identified in the literature to track the risk sources are that: (1) many risks are too general and related to different stakeholders, thus increasing the difficulties for practitioners to develop risk response strategies; (2) the stakeholder groups used by previous studies were not comprehensive, so many risks associated with external project stakeholders were not identified.

Therefore, it is worthwhile to review the stakeholder groups in order to help practitioners to identify the possible risk sources, as shown in the Figure 3.1. The social network theory views PHP from the angle of system perspective, under which are various relationships of involved stakeholders and related schedule risks. The aim of applying network analysis is to investigate the influence of the variation of relationship structures on system behavior. The SNA theory is about examining the structure and patterning of relationships in a system and try to find out the rationale behind and potential influences.

3.3.2 Hybrid System Dynamics and Discrete Event Simulation Method

(1) System dynamics

System dynamics, introduced by Jay Forrester in the 1960s at the Massachusetts Institute of Technology, is defined as a computer-aided approach for understanding the behavior of a system with time (Forrester 1968). System dynamics is now widely applied in various fields, such as social science, agriculture, management, economics, and engineering. It is accepted as a conceptual modeling technique capable of understanding, studying, simulating, and analyzing large-scale complex systems. The conventional methodology applied to system issues tends to depict relationships underlying system variables and comprehend subsequent system behavior from a narrow or isolated perspective. By contrast, large-scale complex systems normally comprise numerous sub-systems. Among these sub-systems are causal relationships that are interactive and interactional: one value-changed variable would have a feedback-based impact on another, eventually influencing the behavior of the whole system. The system dynamics methodology specializes in handling stated characteristics because it can simplify a complex system into operable units through its special analytical tools. These analytical tools include causal-loop diagram and stock-flow diagram, which also contribute in analyzing feedback relationships from a multi-dimensional and dynamic perspective.



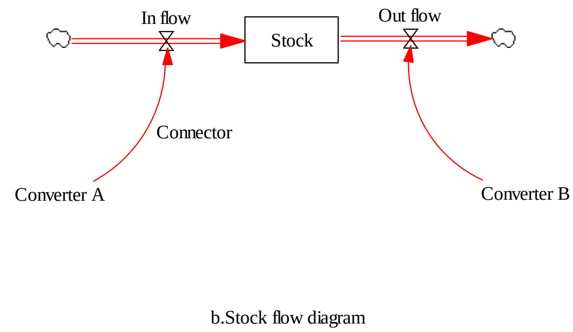


Figure 3.2 Typical example of casual loop and stock flow diagram

Causal-loop diagrams and stock-flow diagrams are two major tools for system dynamics modeling, as shown in the Figure 3.3. Causal-loop diagrams serve as the preliminary sketches of causal hypotheses during model formulation and simplified representation of the real-world behavior. Meanwhile, a stock-flow diagram is a computer-based tool visualized for quantitative simulation and analysis, which is built based on the causal-loop diagram. Feedback loops can be negative or positive based on the direction of influence that parameters have on each other. A negative loop is self-reinforcing; it amplifies disturbances in the system to create even higher variations in behavior. Stock-flow diagrams can be represented by four structural elements: stocks (represented by a rectangle) indicate major accumulation within a system; flows (values with block arrow symbol) serve as an instrument that hinder or prompt the flow of information from the stock; converters (symbolized by a lone circle) act as intermediate variables for miscellaneous calculation; and connectors (symbolized as simple arrows) serve as information links that represent the reasons and impacts within the model structure (Yuan 2012).

(2) Discrete event simulation

For its inherent merits of analyzing complex and interactive system from a dynamic perspective, discrete event simulation (DES) is taken as an effective tool for analyzing and simulating discrete events throughout construction life (Lu 2003; Martinez 2009). DES emphases on the analysis of discretely changed state variables, and specializes in simulating systems that are driven by discrete events (Law et al. 1991). Discrete event simulation has been widely adopting in project management filed. Zhang et al. proposed the application of discrete event system simulation method for the schedule simulation and control in the construction management, resulting in high prediction accuracy (Zhang 2015). Alvanchi et al. (2011) used discrete event simulation to analyze the assembly plan of prefabricated construction, and evaluated the robustness of different manufacturing processes in the steel-structure bridge, finally determining the optimized scheme. Zhang (2013) used discrete event simulation to analyze the pollutant emission during the construction process, effectively considered the uncertainty in the emission of pollutants in the process of construction.

The discrete event modules we used include “Source”, “Split”, “Combine”, “Sink”, and “System dynamic module”, as shown in Figure 3.4. “Source” is the place where work generates; “Split” is workflow shunt which will be used when a task has two following task. When a task has more than one previous task, “Combine” will be used. Only when all preparatory tasks have completed can the task flow spread to the next module. “Sink” is the place where task flow finish. The entire construction project is completed when task flow arrives at this module. “System dynamic module” is used to generate work object. According to the data from specific project, we can get all the data for each work module and simulate the schedule of the entire construction project. There are three relations between tasks in the construction project, namely one to one, one to many and many to one, as shown in Figure 3.4. In our system model, Anylogic can identify critical path automatically and export the delay in the critical path.

①One to one

Take “Task 4” and “Task 5” in Figure 3.4 for example. When the system dynamics model has finished in “Task 4”, the system dynamics model in “Task 5” will be triggered, at the meantime, the corresponding properties will be transferred to “Task 5”.

② One to many

Take “Task 1”, “Task 2” and “Task 3” in Figure 3.4 for example, “Task 1” is connected to “Task 2” and “Task 3” as previous task, when the work in “Task 1” has finished, work in “Task 2” and “Task 3” will be triggered automatically.

③ Many to one

As shown in Figure 3.4, “Task 2” and “Task 3” are connected to “Task 4” as previous task. The work flows of “Task 2” and “Task 3” are combined at “Combine”, only when all the tasks have finished in “Task 2” and “Task 3” can “Task 4” be triggered.

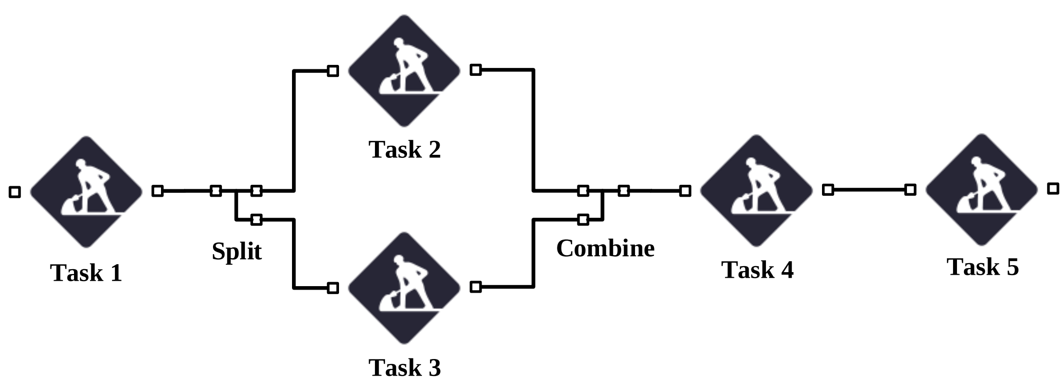


Figure 3.3 Example of working procedure

(3) Hybrid system dynamics and discrete event simulation approach

Although discrete event simulation is demonstrated as a powerful tool for the analysis of discrete events during running processes, there are obvious deficiencies in the analysis of system interaction (Alvanchi et al. 2009). Instead, the system dynamics analysis can effectively analyze the interactions underlying in the various factors in the system but it fails to analyze the running process of discrete events. In the light of this, there is promising prospect to conduct the analysis with the combination of system dynamics and discrete even simulation. It is widely acknowledged that construction project management mainly contains two levels: strategic project management (macro level) and operational project management (micro level) (Lee et al. 2006; Peña-Mora et al. 2008). Strategic project management focuses on scheduling, budgeting and resource allocation (Rodrigues and Bowers 1996), containing a multitude of feedbacks. For example, schedule delay tends to increase workers' pressure; when the pressure exceeds a certain level, it could reduce working efficiency; then the construction rate would decline with the decreasing of working efficiency, and finally increase schedule delay. Therefore, SD will give construction project management an edge in strategic project management.

With regard to operational project management, however, SD cannot reflect the physical specifications of construction process (Alvanchi et al. 2009). To be more specific, operational project management is mainly concerned about micro-level issues, such as the predecessor and successor relationship of network activity, detailed information for execution and etc., which are impossible for SD to analyze since it does not generally form a work breakdown structure (WBS) of discrete sub-activities (Peña-Mora et al. 2008). In contrast, discrete event simulation (DES), which analyzes construction process with an event-oriented view (Martin and Raffo 2001), could effectively address this issue. In addition, DES can combine with network planning technology (e.g. critical path method, and program evaluation and review technique) and make up the deficiencies of network planning technology that cannot consider multiple progress impact factors (Hyari and El-Rayes 2006; Georgy 2008). However, DES is unable to reflect the feedbacks in the process of construction which is the strength of SD.

Based on the above analysis, it is imaginable that if SD and DES were combined together, a comprehensive risk analysis containing both macro and micro levels would be conducted, which means that construction project management would be more in line with the actual situation. In this paper, we build a SD-DES model which encapsulates SD models into each event in the DES model. SD models mainly address feedbacks, containing resource allocation, rework and any other macro phenomenon while DES mainly focuses on the construction process in terms of the predecessor and successor relationship, resource usage and any other micro variables. There are three advantages of our SD-DES model. Firstly, it considers macro and micro levels simultaneously, enabling project managers to gain a deeper insight into schedule management and acquire a multidimensional understanding of schedule delay. Specifically, SD models analyze the project performance influenced by different kinds of schedule risks and exchange data with the DES model. In the meantime, the DES model analyzes detailed information (e.g. duration, start time and finish time of each task) to figure out critical path and real-time schedule. In addition, the data in the DES model would give feedbacks to SD models. Secondly, it is of high level of universality. As is known to all, any construction project is unique; therefore, a model that could only be applied to a special construction project is not successful. In our model, system dynamics model is encapsulated into an event (e.g. earthmoving, pipe installation and precast element installation) of the DES model to constitute a concrete “task module”. With such a “task module”, an activity on node network can be built according to the network planning of any project. Thirdly, it could calculate critical path automatically. The critical path of a project could change under all kinds of risks during the process of construction, so it is important to identify critical path automatically or the accuracy of schedule would be affected. In our model, the actual time in each "task module" will be compared with the latest time. Once the actual time exceeds the latest time, it suggests that this task will be postponed. Due to the fact that there are likely more than one route postpones, a bubble method is proposed to get the maximum delayed task from all the tasks in a certain time, so this task is on the critical path. Connecting all the identified tasks, the critical path can be attained.

3.3.3 Modeling Processes for Applying Hybrid SD and DES Approach

As discussed above, construction project management mainly includes two levels: strategic project management from macro level and operational project management from micro level (Lee et al. 2006; Peña-Mora et al. 2008). The hybrid SD and DES approach specializes in handling both strategic level and operational level relationships in a complex system because it can simplify these feedback relationships into operable units using causal loop diagrams, stock flow diagrams and DES working procedure from a multi-dimensional and dynamic perspective. Therefore, this study uses hybrid SD and DES approach to investigate the influence of risks on the schedule of prefabrication construction. Generally, five steps are needed for developing an SD model as shown in the Figure 3.5, which includes: (1) Determining the boundary of system; (2) Mapping casual loop and stock flow diagram to depict relationships underlying identified variables; (3) Encapsulating system dynamics model and its associated attributes into the discrete event module; (4) Implementing tests including direct structure test and structure-oriented behaviour test to build up confidence for the developed model prior to simulation analysis; (5) risk scenario analysis that comprises baseline simulation and scenario simulation will be performed to investigate possible impact on the schedule of PHP under various risk scenarios.

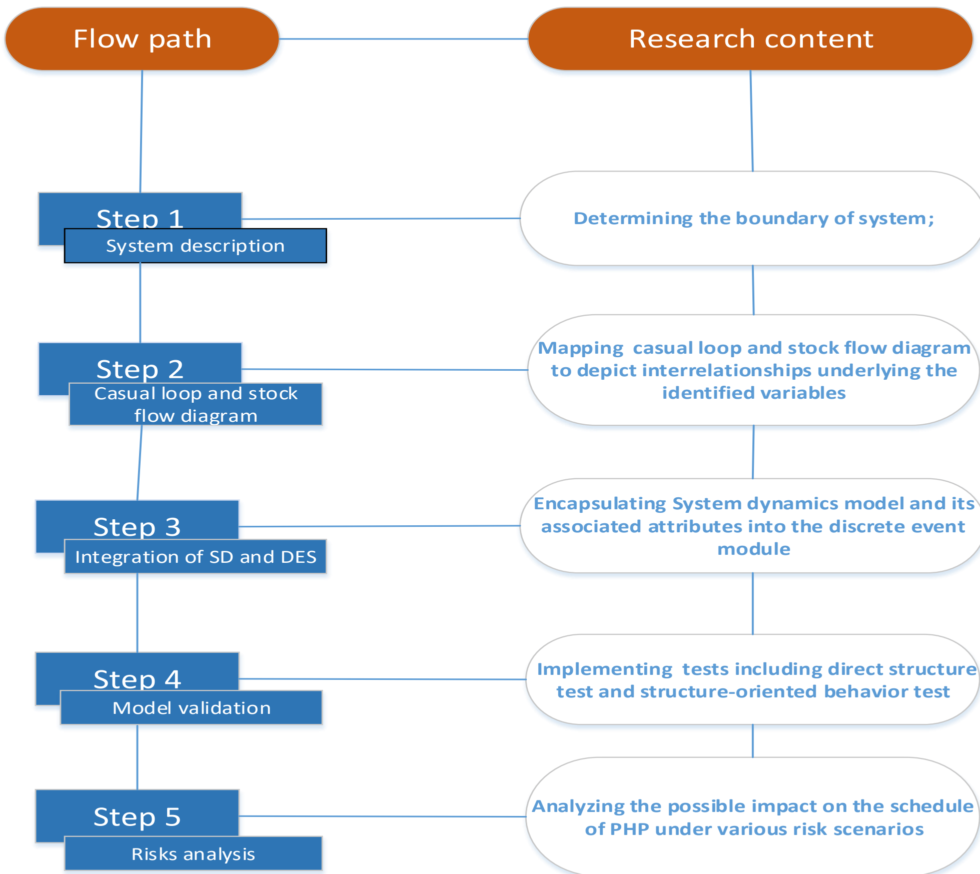


Figure 3.4 Flow of applying Hybrid SD and DES approach

Step 1: Determining the boundary of system

The purposes and goals for developing the model are stated in the first step, which will help to identify the boundary of a model and indicate what are needed to include in the model and what are not. Once the purposes and goals are determined, all related variables that have great influence on the behavior of the system should be first identified and inserted into the hybrid dynamic model for further analysis.

Step 2: Mapping casual loop and stock flow diagram to depict relationships underlying identified variables

After the identification of essential variables, qualitative analysis was conducted to identify the underlying interrelationships among these variables based on an extensive literature review and semi-structured interviews with practitioners and professionals. The casual diagram, which consists of a series of feedback loops that determine behaviors of the whole system by establishing connections among various factors, serves as a visualized conceptual model for presenting the results of the qualitative analysis. With the interrelationships underlying the identified variables qualitatively defined within the causal-loop diagram, a stock-flow diagram should be constructed to mathematically quantify their impacts by employing the Vensim software. The stock-flow diagram is a more detailed model compared with the causal-loop diagram. A number of auxiliary variables absent in the causal-loop diagram are added to the stock-flow diagram to ensure that the previously defined relationships can be smoothly converted to quantitative expressions.

Step 3: Encapsulating system dynamics model and its associated attributes into the discrete event module

Through the use of Anylogic software, data can be exchanged between system dynamics and discrete event simulation. The encapsulation technology adopted in the system model is one of the characteristics of object-oriented. Encapsulation refers to bind the properties and behavior of an object together and put them into a logical unit which hidden all the properties. All the access to the properties from outside can only be realized by user interface. This approach not only enables the protective effect of the object properties, but also improves the maintainability of software systems;

Step 4: Implementing a serial of verification and validation tests which include structure test and structure-oriented behavior test to establish confidence into the hybrid dynamic model prior to simulation analysis

Prior to simulation analysis, model structure test, including direct structure test and indirect structure test will be first conducted. Direct structure test which includes structure dimensional consistency test, boundary adequacy test, parameter confirmation test, and confirmation test, checks the validity of the model by comparing the model structure with real system structure to help calibrate the model to fit real world situations. The indirect structure test exploits the merits of direct structure test and quantitative test, aiming at making the model more convincing in term of system behavior. It includes integral error test, behavior sensitivity, and test extreme-condition test.

Step 5: Risk scenario analysis

After building up confidence for the developed model, simulation analysis can be conducted to analyze and evaluate the impact of risks on the schedule of PHP. Single-risk and multi-risk scenario simulation with pre-defined scenarios will be conducted to explore the impact of risks on the schedule across the timeline of PHP, while the sum of the combined impact of multiple risks is compared with the simple sum of the impact on each single risk to gain understanding on the iterative effect of the interrelationships underlying various risks.

3.4 Chapter Summary

This chapter presents the methodology of the research. The research methods adopt in the research, namely, document analysis, experimental study, simulation, expert interview, case study, are introduced. Data analysis tools, social network analysis and hybrid system dynamics and discrete event simulation method, are introduced for identifying, analyzing, evaluating schedule risks in PHP.

CHAPTER 4 Critical Risks Affecting the Schedule of Prefabrication Housing Production

4.1 Introduction

The purpose of this chapter is to identify and analyze critical schedule risks that have influence on the schedule performance of prefabrication housing production with consideration of involved stakeholders. First, the stakeholders and schedule risk factors that directly influence the schedule of PHP are identified. Then the interrelations between the identified schedule risk factors are determined for further network visualization and analysis. The outcome of the analysis of this chapter is a list of critical stakeholder-associated risks and the critical interactions underlying those risk factors based on node level and link level metrics of SNA.

4.2 Identification of Stakeholders and Schedule Risks

4.2.1 Research flow of SNA

Social network theory views the supply chain of PHP as a complex system containing various stakeholders and relationships. The purpose of network analysis is to analyze stakeholder-associated schedule risks in PHP and their cause-and-effect relationships. This methodology has been applied in various research areas, including but not limited to green building project (Yang and Zou 2014), waste management (Caniato et al. 2014), construction industry (Zou et al. 2006), information science (Otte and Rousseau 2002), and social science (Borgatti et al. 2009). With reference of previous research, the general process of SNA can be divided into four main parts: (1) identification of stakeholders and their schedule risks, (2) determination of risk interrelations, (3) determination of the risk network, and (4) identification and verification of risk mitigation strategies.

The first step identifies the stakeholders and schedule risk factors that directly influence the PHP. Chain referral sampling is applied for this purpose, that is, to completely identify stakeholders and their associated risks. Two representatives from the main contractor and manufacturer were approached to initiate the chain. They were asked to locate closely-related stakeholder groups. These referrals were then asked to locate any potentially affecting or affected stakeholder groups who were not yet included in the chain. A tentative stakeholder list previously compiled based on the document analysis of previous literature was provided as reference in the referral process. Along with stakeholder identification, the stakeholder-related schedule risks of PHP were identified through a series of semi-structured interviews. The interviews were conducted with representatives from different stakeholder groups. The participants all had direct involvement in the supply chain of PHP, and to ensure the representativeness and reliability of the collected data, the chosen participants were at or above the senior managerial level and had at least five years of experience in their expertise, as shown in the Table 4.1. Semi-structured interviews were conducted in 2015, with each semi-structured interview lasting between 40 and 50 minutes. Based on their empirical knowledge, the respondents were invited to express their views on the following three main questions: (1) What are the major risks that may influence the schedule of PHP? (2) To what extent can these risks lead to schedule delay? (3) How do these identified risks relate to the corresponding stakeholders? A reference list of stakeholder risks previously compiled based on document analysis and literature review was provided to facilitate the process. The interviews were transcribed, and the manuscripts were returned to the participants for feedback.

Table 4.1 Information of interviewees involved in SNA

N.	Position	Organization	Stakeholder group	N.	Position	Organization	Stakeholder group
1	Structural Engineer	Hong Kong Housing Authority	Client	7	Lifting Supervisor	Chuen Kee Ltd	Assembly Company
2	Architect	Hong Kong Housing Authority	Client	8	Supervising Supervisor	Chuen Kee Ltd	Assembly Company
3	Building Service Engineer	Meinhardt Ltd	Design Consultant	9	Factory Manager	Wing Hong Shun Ltd	Production Company
4	Senior Project Engineer	Gammon Construction Ltd	Main Contractor	10	General Manager	Wing Hong Shun Ltd	Production Company
5	Safety Manager	Gammon Construction Ltd	Main Contractor	11	Business Manager	Yingyun Transportation Ltd	Logistics Company
6	Site Agent	Gammon Construction Ltd	Main Contractor	12	Site Officer	Independent Checking Unit	Local Government

The second step determines the interrelations between the identified schedule risk factors. In this study, links are defined as the influence of stakeholder-related risk over another risk. For this purpose, a survey was designed to elicit responses from the representatives of the identified stakeholder groups. At the outset, the researchers provided verbal explanations/instructions (by telephone or face-to-face) for the survey structure and questions to the participants to minimize ambiguities in completing the survey. The survey questions required the participants to consider all possible interrelationships between various schedule risk factors based on their empirical knowledge. The respondents were asked to clearly define the direction of potential influence because the relationships can be reciprocal. For example, the influence exerted by SaRb on ScRd was distinguished from the influence of ScRd on SaRb, and they were treated as two different links. After listing the identified links, the respondents were asked to quantify each link in two aspects: the intensity of influence given by a risk over another and the likeliness of the occurrence of this influence, using a five-point scale where “1” and “5” denote the lowest and highest levels, respectively. The multiplication of the intensity of influence and likeliness provides a basis for assessing the influence level between two stakeholder-associated risks. When no influence exists between two nodes, the influence level is zero.

In the third step, the adjacency matrix, together with the node and link lists, was imported into NetMiner 4 as the major input data for network visualization and analysis. The step started with a visual inspection to gain initial insights into the main risk factors and their distribution in the influence network, and this sub-step was followed by a descriptive investigation based on network density and cohesion. These two metrics were chosen because they were good indicators of a network’s overall characteristics in terms of connectedness and complexity, reflecting the highly complicated relationships in the project. After descriptive analysis was performed, node-level metrics were calculated to explore the properties and roles of individual nodes and to determine the critical stakeholder-related risks. Along with node-level, link betweenness centrality was computed to measure the importance of interrelationships among risks. This investigation focused on relationships sourcing from or targeting the main stakeholder-associated risks identified in the node-level results to unlock the cause-and-effect relationships underlying these risk factors. The purpose was to recognize the main relationships in the network and to check any risks interactions with centrality scores greater than the cut-off point but not sourcing from or targeting the key nodes. Such links should be included as well to ensure the inclusiveness of the link-level analysis. The outcome of the network analysis was a list of critical stakeholder-related risks and the critical interactions underlying those risk factors.

The final stage involves understanding the actual meanings of the identified critical risk factors and interactions and categorizing these key relationships based on their meanings. In consolidating the SNA results with the interview findings previously collected before network analysis, these major stakeholder-related risks are further discussed. Corresponding solutions for mitigating the identified critical schedule risks and interactions are proposed and discussed to address real-world problems in PHP after assessment of the influence of critical schedule risks by the developed hybrid dynamic model developed in the following chapters, and these strategies are validated through the established social network model and hybrid dynamic model. Please be kindly noted that as the purpose of the fourth chapter is just to identify and rank critical schedule risks with consideration of involved stakeholders, while identified schedule risks are further analyzed and assessed in the hybrid model in the next three chapters, so the timing of risks and the projects' phase in which schedule risks are most likely to occur and impact the operation are not taken for consideration in this chapter. To another word, this chapter analyzes schedule risks from a static point of view while the hybrid dynamic model analyzes schedule risks from dynamic point of view with consideration of the timing of risks and the projects' phase.

4.2.2 Data collection results

After a series of interviews was conducted, a total of seven stakeholder groups directly involved in PHP were identified. They are coded numerically as S_a, where a = 1 to 7, namely, (1) client, (2) designer, (3) main contractor, (4) manufacturer, (5) logistics, (6) assembly company, and (7) local government. Along with the major stakeholders, a total of 35 stakeholder-associated schedule risks were also identified. The number of schedule risks and related stakeholders are summarized in Table 4.2. These nodes were coded numerically into S_aR_b for further analyze purpose in the software, in which a indicates a specific stakeholder group, and b represents the related schedule risk factor. Based on literature review and interviews, a total of 30 schedule risk factors are identified, with seven respective stakeholder's groups generating 52 nodes. After the risk nodes are identified and coded, the links in the risk network representing the influence between two nodes are further defined and numbered. Links represent relations and dependencies among objects. Three basic types of relationships between each pair of risks exist in the organizational structure: (1) An independent relationship refers to risks that are not related to each other. (2) A dependent relationship indicates that a direct influence exists between two risks. (3) An interdependent relationship refers to risks that are in a mutually dependent relationship directly or within a large loop. The classical risk assessment approach is used to evaluate the consequence and likelihood of each risk on project objectives. In our study, risk relationship instead of individual risk is defined by the influence of one risk on the other and the likelihood of the interaction between the risks.

Table 4.2 Identified schedule risks and associated stakeholders

Risk ID	S. Node	Stakeholders	R. Node	Risk name	Source	Category
S1R1	S1	Client	R1	Inadequate project funding	(Mojtahedi et al. 2010)	Cost
S3R1	S3	Main contractor				
S1R2	S1	Client	R2	Inefficiency of design approval	(Hossen et al. 2015)	Organizational

S1R3 S2R3 S3R3	S1 S2 S3	Client Designer Main contractor	R3	Low information interoperability between different enterprise resource planning systems	Interview	Information transfer
S1R4 S2R4 S3R4 S4R4 S5R4 S6R4	S1 S2 S3 S4 S5 S6	Client Designer Main contractor Manufacturer Logistics Assembly company	R4	Change in project scope	(Taylan et al. 2014)	Cost
S1R5 S2R5 S3R5 S6R5	S1 S2 S3 S6	Client Designer Main contractor Assembly company	R5	Tight project schedule	(Taylan et al. 2014)	Organizational
S2R6	S2	Designer	R6	Incomplete design drawing	(Mojtahedi et al. 2010)	Quality
S1R7 S2R7 S3R7	S1 S2 S3	Client Designer Main contractor	R7	Design change	(Hossen et al. 2015)	Quality
S3R8	S3	Main contractor	R8	Safety accident occurrence	Interview	Safety
S2R9	S2	Designer	R9	Redesign because of errors in design	(Hossen et al. 2015)	Quality
S2R10 S3R10	S2 S3	Designer Main contractor	R10	Inefficient design data transition	Interview	Information transfer
S3R11	S3	Main contractor	R11	Inefficient verification of precast components because of ambiguous labels	Interview	Information transfer
S3R12	S3	Main contractor	R12	Inefficient communication between project participants	(Taylan et al. 2014)	Information transfer

S3R13	S3	Main contractor	R13	Weak response to design change during construction	Interview	Organizational
S3R14	S3	Main contractor	R14	Inadequate planning and scheduling	(Hossen et al. 2015)	Organizational
S3R15	S3	Main contractor	R15	Delay of the delivery of precast elements to site	(Mojtahedi et al. 2010)	Organizational
S4R16	S4	Manufacturer	R16	Design information gap between designer and manufacturer	Interview	Information transfer
S4R17	S4	Manufacturer	R17	Serial number recording error	Interview	Information transfer
S4R18	S4	Manufacturer	R18	Precast components mistakenly delivered	(Aibinu and Odeyinka 2006)	Organizational
S4R19	S4	Manufacturer	R19	Remanufacturing because of quality control and damage during production	Interview	Quality
S4R20	S4	Manufacturer	R20	Misplacement on the storage site because of carelessness	Interview	Information transfer
S5R21	S5	Logistics	R21	Transportation vehicle damage	Interview	Quality
S5R22	S5	Logistics	R22	Transportation road surface damage	(Hossen et al. 2015)	Environment
S5R23	S5	Logistics	R23	Reapplication of custom declaration	Interview	Safety
S5R24	S5	Logistics	R24	Logistics information inconsistency because of human errors	Interview	Information transfer
S5R25	S5	Logistics	R25	Custom check	Interview	Safety
S6R26	S6	Assembly Company	R26	Difficult identification of proper precast components	Interview	Information transfer
S6R27	S6	Assembly Company	R27	Slow quality inspection procedures	(Aibinu and Odeyinka 2006)	Organizational
S6R28	S6	Assembly Company	R28	Tower crane breakdown and maintenance	Interview	Quality
S6R29	S6	Assembly Company	R29	Installation error of precast elements	Interview	Information transfer
S7R30	S7	Government	R30	Excessive approval procedures	(Taylan et al. 2014)	Organizational

S7R31	S7	Government	R31	Uncertain governmental policies	(Yang and Zou 2014)	Environment
S7R32	S7	Government	R32	Imperfect technological specifications on prefabrication	(Yang and Zou 2014)	Quality
S3R33 S6R33	S3 S6	Main contractor Assembly company	R33	Civil disturbances	(Aibinu and Odeyinka 2006)	Environment
S3R34 S6R34	S3 S6	Main contractor Assembly company	R34	Labour dispute and strikes	(Aibinu and Odeyinka 2006)	Environment
S3R35 S6R35	S3 S6	Main contractor Assembly company	R35	Inclement weather	(Hossen et al. 2015)	Environment

4.3 SNA Results of Schedule Risks

4.3.1 Network Level Results

The analysis results based on the above discussed indicators are presented. Figure 4.2 indicates the risk network which has 52 stakeholder risks with interrelationships of 597 links, with network density of 0.225, the mean distance between nodes of 1.928 walks, and network cohesion of 0.962, indicating that the network is dense and most of risks are interrelated. A large area of green nodes tends to be located in the center of the map, indicating that the risks related to information transfer are interrelated

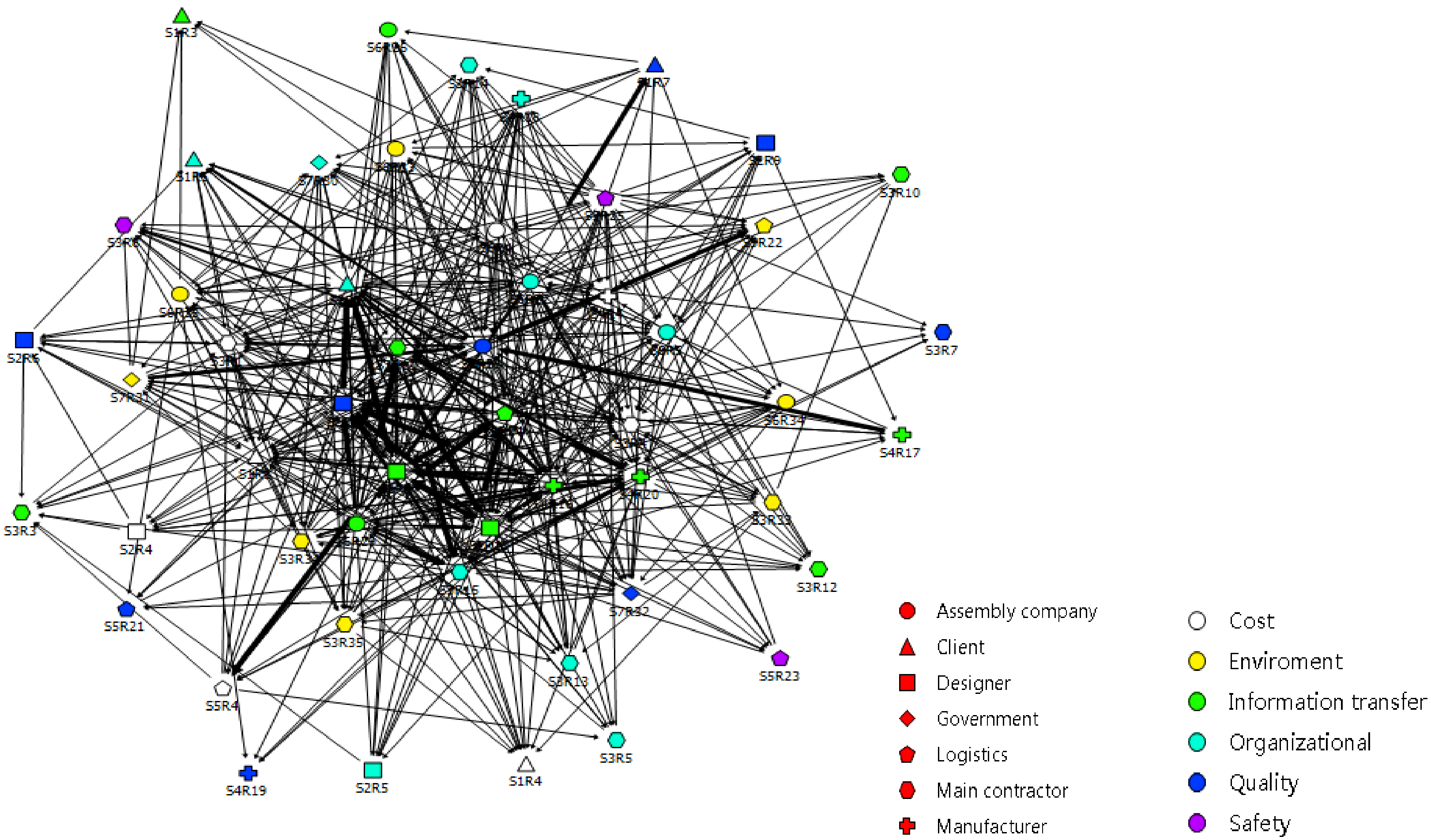


Figure 4.1 Stakeholder-associated schedule risk network

4.3.2 Node and Link Level Results

Node and link related analysis is also conducted to identify critical stakeholder-associated risks. The status centrality map that depicts the relative outgoing impact, including all risks, is shown in Figure 4.3. Some interesting findings are identified. The risks related to client, designer, main contractor, and manufacturer are located relatively centrally. This finding indicates the high influence of these stakeholders on the PHP process. Assembly company and logistics also have considerable roles in PHP. The information transfer and quality risks related to different stakeholder groups seem to be more significant than other risk categories. This finding is different from those of previous research, in which the cost-related risks are considered to be more important. The significance of information transfer-related risks in PHP highlights innovative Internet technology, which may increasingly have a more importation role in the construction industry. Along with status centrality, other metrics, including out-degree, degree difference, are initially computed for the nodes, relatively measuring the direct out-going influence, net influence level respectively.

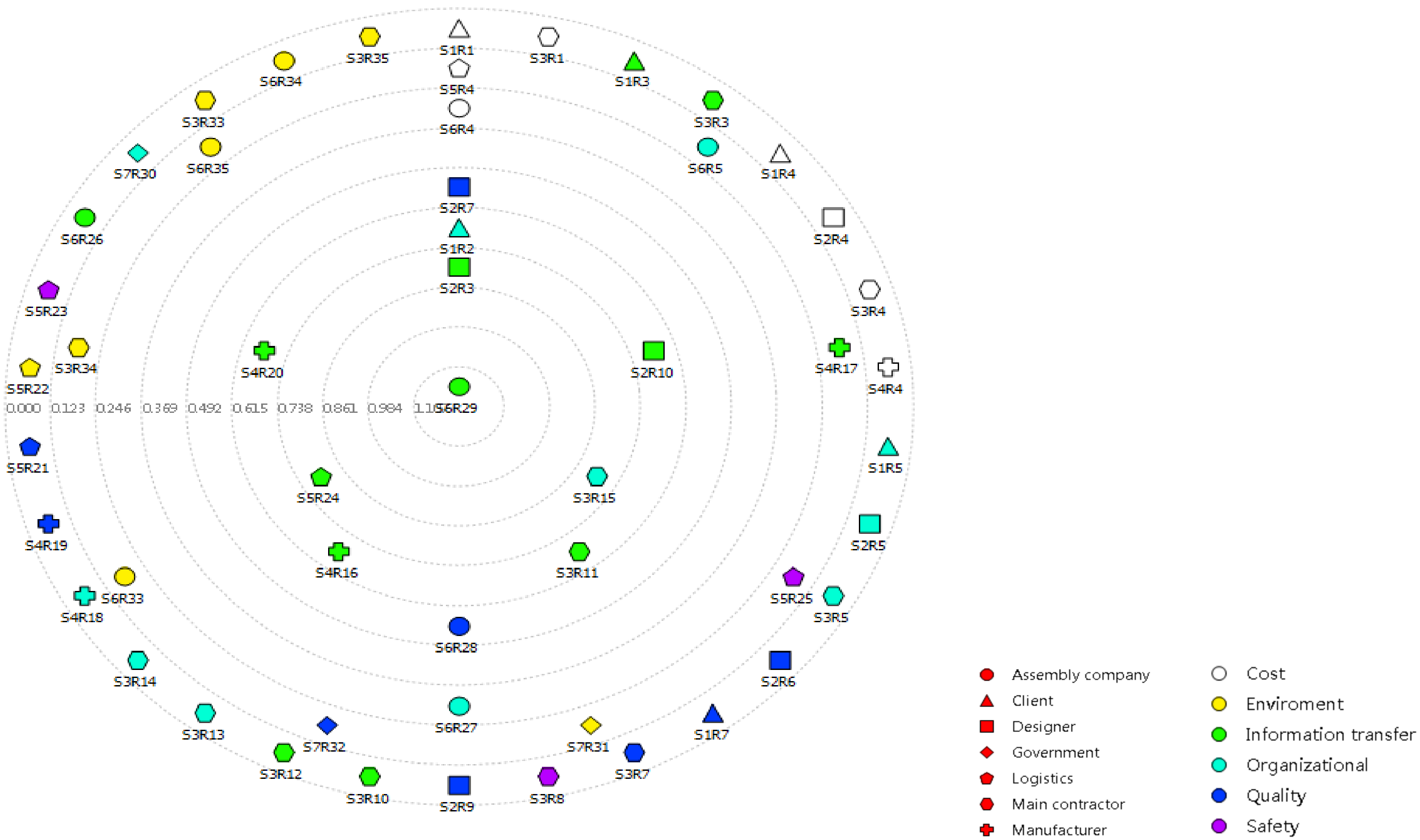


Figure 4.2 Status centrality ma

Table 4.3 presents the twelve rankings in each of the out-status centrality, out-degree, and degree difference magnitude results. As shown in Table 4.3, three stakeholder risks ranked in accordance to ego size are identified: S6R28 ("crane breakdown and maintenance problem" sourced from the assembly company), S2R3 ("low information interoperability between different enterprise resource planning systems" sourced from the designer), and S5R24 ("logistics information inconsistency because of human errors" sourced from logistics). With regard to out-degree indicator, S1R2 ("inefficiency of design approval" sourced from the client), S2R3 ("low information interoperability between different enterprise resource planning systems" sourced from the designer), and S6R27 ("slow quality inspection procedures" sourced from the assembly company) are considered to be the three most significant risk factors. In terms of the metric of the degree difference, S5R25 ("low information interoperability between different enterprise resource planning systems" sourced from the designer), S6R4 ("change in project scope" sourced from the assembly company), and S1R2 ("inefficiency of design approval" sourced from the client) are regarded as factors that have significant net influence level.

Table 4.3 Top stakeholder-associated risks based on status centrality and nodal degree analyses

		Out-status Centrality		Out-Degree		Degree difference
1	S6R29	1.230	S1R2	27	S2R3	19
2	S3R15	0.853	S2R3	27	S6R4	11
3	S2R3	0.834	S6R27	26	S1R2	10
4	S5R24	0.819	S2R7	25	S3R34	8
5	S3R11	0.730	S4R16	25	S5R4	7
6	S4R16	0.720	S2R10	24	S1R7	7
7	S4R20	0.720	S4R20	24	S5R25	6
8	S2R10	0.714	S3R15	23	S3R33	6
9	S1R2	0.656	S5R24	23	S3R15	4
10	S2R7	0.585	S5R25	23	S7R32	4
11	S6R28	0.557	S6R28	23	S6R35	4
12	S6R27	0.261	S3R11	22	S3R13	4

Table 4.4 shows the top ten critical risks in terms of brokerage analysis. The top three nodes are S6R27 ("slow quality inspection procedures" sourced from the assembly company), S6R28 ("crane breakdown and maintenance problem" sourced from the assembly company), and S2R7 ("design change" sourced from the designer), with values of 455, 401, and 375, respectively. Table 4.5 displays the top twelve risks and the interrelations with the highest betweenness centrality.

Table 4.4 Top stakeholder risks based on brokerage analysis

Rank	Risk ID	Coordinator	Gatekeeper	Representative	Itinerant	Liaison	Total
1	S6R27	23	96	74	47	215	455
2	S6R28	7	44	62	46	242	401
3	S2R7	7	36	50	55	228	376
4	S2R3	5	28	36	50	208	327
5	S5R24	0	17	30	51	222	320
6	S3R11	16	81	33	34	133	297
7	S4R20	3	19	25	44	204	295
8	S4R16	3	21	26	37	204	291
9	S2R10	5	31	29	43	176	284
10	S6R29	7	44	39	33	146	269
11	S3R15	7	70	20	27	135	259
12	S1R2	0	17	0	38	185	240

Table 4.5 Key risks and interactions according to the betweenness centrality

Rank	Risk ID	Node betweenness centrality	Link ID	Link betweenness centrality
1	S2R3	0.126648	S2R3→S4R16	51.5
2	S6R29	0.080381	S2R10→S6R29	51.2
3	S2R7	0.068639	S4R16→S5R24	51.1
4	S6R27	0.060862	S4R16→S2R7	38.5

5	S3R15	0.053522	S2R3→S6R27	36.4
6	S5R24	0.049473	S2R3→S3R15	34.8
7	S4R20	0.047281	S4R16→S6R29	34.6
8	S2R10	0.045992	S5R24→S3R15	32.4
9	S6R28	0.040858	S2R7→S1R2	32.1
10	S4R16	0.040789	S6R28→S3R15	29.5
11	S3R11	0.040654	S2R3→S4R20	28.3
12	S6R5	0.033829	S2R7→S1R2	28.1

4.4 Determination of Critical Schedule Risks

The identification process of critical schedule risks relies on the results of SNA indicators in the above section, including degree of nodes, betweenness centrality, status centrality, and brokerage. In short, the risk interrelationships with higher output degree, higher degree difference, higher betweenness centrality, higher status centrality, and higher brokerage values should be identified with more attention. Based on the above analyzed results in terms of different indicators, twelve critical stakeholder risks are determined as shown in Table 4.6.

Table 4.6 Critical stakeholder risks and interactions

Critical risks	Risk description	Associated stakeholder
S5R24	Logistics information inconsistency because of human errors (LIIBHE)	Logistics
S2R3	Low information interoperability between different enterprise resource planning systems (LIIBDERPS)	Designer
S3R15	Delay of the delivery of precast element to site (DDPES)	Main contractor
S6R29	Installation error of precast elements (IEPE)	Assembly company
S2R7	Design change (DC)	Designer
S6R27	Slow quality inspection procedures (SQIP)	Assembly company
S6R28	Tower crane breakdown and maintenance (TCBM)	Assembly company
S1R2	Inefficiency of design approval (IDA)	Client
S2R10	Inefficient design data transition (IDDT)	Designer
S4R16	Design information gap between designer and manufacturer (DIGBDM)	Manufacturer
S3R11	Inefficient verification of precast components because of ambiguous labels (IVPCBAL)	Main contractor

S4R20	Misplacement on the storage site because of carelessness (MSSBC)	Manufacturer

4.5 Chapter Summary

This chapter identifies critical schedule risks that have significant influence on the schedule performance of PHP with consideration of involved stakeholders. The stakeholders and initial list of schedule risks in PHP are identified. Then the interrelations between the identified schedule risk factors are determined for network visualization and analysis. A list of critical stakeholder-associated risks and the critical interactions underlying those risk factors is finally determined. The identification process of critical schedule risks relies on the results of SNA indicators, including degree of nodes, betweenness centrality, status centrality, and brokerage.

CHAPTER 5 Development of A Hybrid Dynamic Model for Assessing and Simulating Impacts of Critical Schedule Risks

5.1 Introduction

A hybrid dynamic model that developed on the basis of the integration of system dynamics and discrete event simulation facilitates the examination of how the behavior of PHP system vary over time along with the change of various schedule variables from a dynamic perspective. With hybrid system dynamics and discrete event simulation approach, interrelationships underlying activities and variables within the PHP can be better depicted, modeled and simulated. The development of the hybrid dynamic model is presented in this chapter. To better understand the development of hybrid dynamic model, this chapter begins with a graphic chart interpreting the model development procedure. The purpose and boundaries of the model are defined, and the overview description of the model's structure is provided. Then, system dynamics model is developed through the causal loop and stock flow diagram with the help of Vensim software. System dynamics model and its associated attributes are encapsulated into a discrete event module and consequently forming the final hybrid dynamic model.

5.2 Model Description

5.2.1 Purpose of Developing A Hybrid Dynamic Model

The hybrid dynamic model is a model that developed with hybrid system dynamic and discrete event simulation method, with an aim to evaluate and simulate impacts of schedule risks in PHP by considering interrelationships underlying various activities and variables from dynamic perspective. Three main purposes are to be fulfilled by the hybrid dynamic model to be developed. Firstly, the hybrid dynamic model allows researchers and managers involved in PHP to comprehend interrelationships underlying activities and variables within the PHP from a dynamic perspective. Serving as an experiment platform, the hybrid dynamic model examines the relationships between various system behaviors and its underlying structure, facilitating the understanding of the mechanism of the influence of schedule risks on the schedule performance of PHP.

Secondly, the model provides a solid basis for analyzing and discussing the possible impact of major risks on the schedule of PHP. The hybrid dynamic model enables the quantification of impact of major risks on the schedule of PHP, such that various risk portfolios that predefined by the researchers and managers can be analyzed and discussed prior to project implementation.

Thirdly, the model serves as a practical tool for explaining and validating the benefits and weaknesses of specific strategies proposed to deal with identified major schedule risks prior to implementing those strategies. Once strategies are proposed by the researchers and managers for hedging potential schedule risks, the potential effect of the strategies on the schedule performance can be evaluated and simulated through the model and the findings based on the model can be relayed to others through hands-on training to analyze the benefits and weaknesses of the strategies.

Take strategy “mitigating installation error of precast elements for example, through the model, the effect of the strategy can be simulated to check whether it will result in enhancement on the schedule performance of PHP.

5.2.2 Boundary of the Hybrid Dynamic Model

Different system boundaries will generate different system structures and behaviours. System boundaries should be defined clearly to facilitate the system modelling process as well as meet research objectives. This research divides the hybrid dynamic model into three subsystems: prefabrication supply chain subsystem, schedule risks subsystem, and schedule performance subsystem. The relationship between the three subsystems is shown in Figure 5.1. The hybrid dynamic model focuses on investigating interrelationships of various schedule risk factors affecting schedule performance throughout PHP activities.

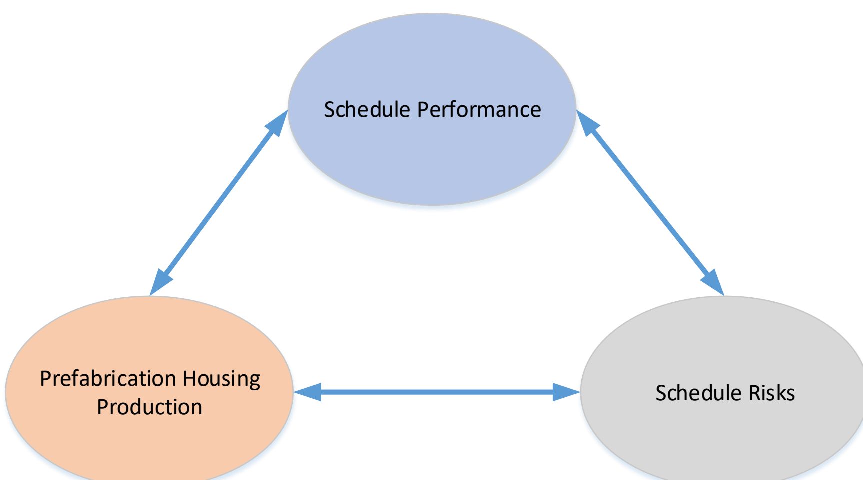


Figure 5.1 The relationships between the three subsystems

(1) Prefabrication housing production subsystem

The whole prefabrication manufacture sector in Hong Kong has been moved to offshore areas in the PRD region for a reason of lower material and labour cost. As so, prefabrication housing production is known as off-site prefabrication housing production. Prefabrication housing construction has a unique supply chain, which includes design, manufacture, storage, transportation, buffer, and assembly on site. Specifically, in the design process, the client will hire an architect, a structure engineer, and a services engineer to do the design work, with special considerations to structure safety, buildability, and even transportation convenience. Then, the design information will be transmitted to the manufacturing company to produce precast components and once the precast components are finished they will be placed on the storage site. Once the transportation order is received, the logistics company would transport the components from storage to the buffer near the border between Hong Kong and Mainland China. In the end, these components will be installed by an assembly company on the construction site. The PHP subsystem consists of a series of housing production activities. Prefabrication elements pass through all activities of the system.

(2) Schedule performance subsystem

The schedule performance subsystem includes two parts, namely, original schedule and actual schedule. Through comparing the values of the original schedule and actual schedule the schedule performance of PHP can be determined. If the original schedule is consistent with the original schedule, the project is indicated of having good schedule performance and the project is expected to be completed in time; otherwise, the project is said to have poor schedule performance and might be subject to project delay.

(3) Schedule risks subsystem

Based on literature review and expert interviews, schedule risks influence the schedule performance in terms of three ways, including project scale, resources, and management. Project scale, resources and management are three ways/channels that through which the influence of schedule risks flow in, ways/channels are not the schedule risks themselves. The identification process, and influence mechanism are different. The identification process is to identify critical schedule risks for further evaluation and simulation, while influence mechanism is designed as the ports through which the schedule risks flow and ultimately impact the schedule performance of PHP. Resources refer to labour, materials, and machinery, which are necessary elements for PHP project throughout the construction life. A housing construction can only be carried out smoothly with adequate resources, and shortage in resources has high influence on the schedule performance of PHP. Resources can be affected by the schedule performance subsystem and subsequently influence the prefabrication housing production subsystem. For example, the schedule performance subsystem encounters a schedule delay; it needs to increase the number of resources to finish the job faster. In return, increase in resources will accelerate construction rate and reduce schedule delay. Project scale indicates special quantities of housing construction. Project scale changes are common in the construction market. Owner's demand changes, design drawing changes, and changes in specific construction conditions would lead to project scale changes. Project scale changes would cause the change in resource demand, and may lead to schedule delay. Management is associated with operation efficiency and quality problems. Take one of quality problems, serious defect found in precast component for example, it will surely lead to rework and waste a large amount of time to get a new piece of precast element back to the construction site, causing schedule delay. It can be seen that management is interrelated with schedule performance subsystem. In addition, trying to speed up to catch up with schedule delay may increase the occurrence of project quality problems and installation error rate; hence, management can also be interrelated with prefabrication housing production subsystem.

5.3 Development of the Hybrid Dynamic Model

5.3.1 Development of System Dynamics Model

5.3.1.1 Causal loop diagram

Based on the analyses above, the causal-loop diagram, which depicts the interrelations underlying various variables, can be drawn, as shown in Figure 5.2. Four positive feedbacks and three negative feedbacks are defined within the diagram.

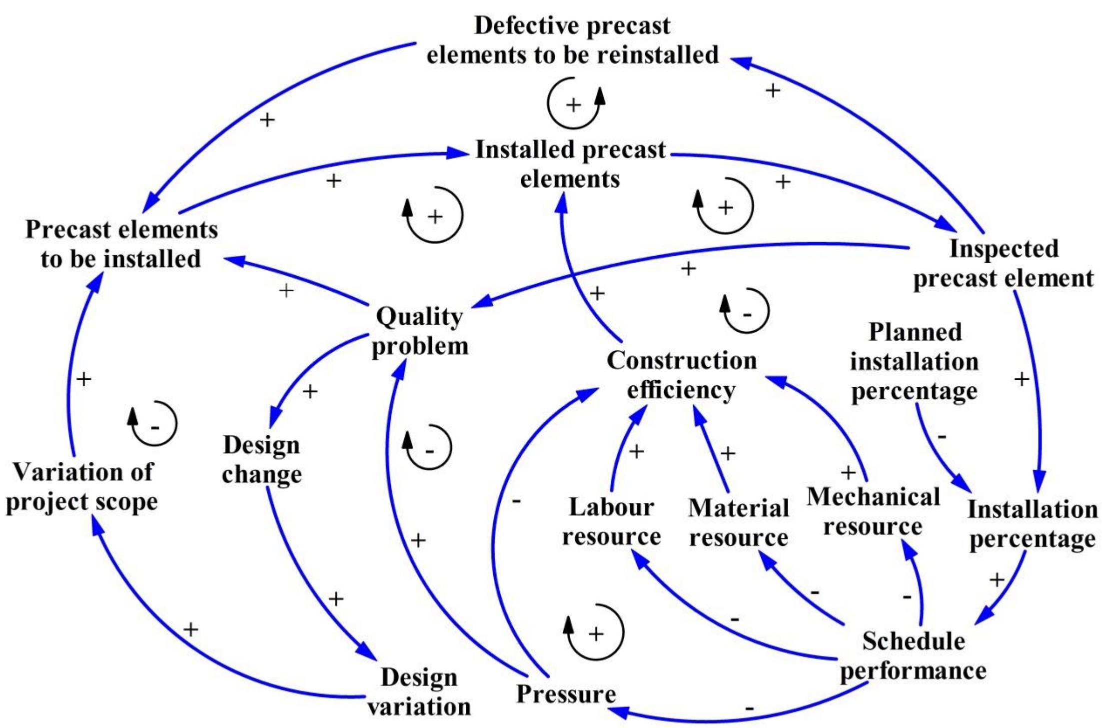


Figure 5.2 The causal-loop diagram of system dynamics

Feedback 1: An increase in the number of precast elements to be installed will raise the number of installed precast elements; and subsequently, the number of inspected precast elements increases, which leads to increase in the number of defective precast elements to be reinstalled, as there is a variable named defect rate that set according to practical experience of on-site assembly, which means that there is a portion of inspected precast elements will transferred into defective precast elements to be reinstalled if defect problems are found, that is, when the model is running, there is a portion of inspected precast elements will flow into the stock variable of defective precast elements to be reinstalled, causing the increase in “defective precast elements to be reinstalled”. Holding defect rate constant, the more work completed, the more mistakes will be found. More defective precast elements to be reinstalled will also lead to an increased number of precast elements to be installed. Feedback 1 has four positive correlations, and is considered as positive feedback loop. If feedback 1 is not controlled well, the stock of precast elements to be installed will continuously increase and remain at a relatively high level, which will cause serious schedule delay in PHP.

Feedback 2: Feedback 1 and Feedback 2 have almost the same framework apart from one variable, quality problem. The more precast elements inspected, the more quality problems are found while holding the defect rate constant, which will raise the number of precast elements to be installed. Feedback 2 also has four positive correlations, and is considered as positive feedback loop.

Feedback 3: The increase in the number of inspected precast elements will contribute to the installation percentage. If the installation percentage is in line with the planned installation percentage, schedule performance is said to be good. Otherwise, it will lead to schedule delay, which results in more project pressure. According to the related study, the relationship between pressure and efficiency could be described as an inverted U-shaped curve, which shows that proper pressure will increase work efficiency and having positive impact on the number of installed precast elements, which will finally increase the number of inspected precast elements. However, if pressure exceeds a certain level, construction efficiency will decrease and have opposite impact on both installed precast elements and inspected precast elements. Feedback 1 has four positive correlations and two negative correlations, which are considered positive feedback loop.

Feedback 4: Rework is not necessary having influence on pressure, as at the early stage there are many ways to deal with rework and hence have the probability to catch up with the delay. But if the delay could not be caught up due to limited resources and schedule performance of PHP is evaluated to be not meeting the plan, it will impose pressure to the management team. Apart from resulting in more pressure, bad schedule performance can also change the management strategies of project managers. As the schedule delay increases, the project manager will allocate more resources, including labour, material, and mechanical resources into the production, raising construction efficiency. The rest of feedback 4, from construction efficiency to schedule performance, is as the same as feedback 3, such that feedback 4 has five positive correlations and one negative correlation, and is considered as negative feedback loop.

Feedback 5： Supposing project pressure increases, the possibility of quality problem in construction will increase, which will also increase the number of precast elements to be installed and installed precast elements accordingly. The correlations from installed precast elements to pressure in feedback 5 are the same as feedback 3. Therefore, feedback 4 has six positive correlations and one negative correlation, and is considered as negative feedback loop.

Feedback 6： The increase in the number of quality problems will lead to more design variations; and subsequently project scope variation will expand, which leads to increase in the number of precast elements to be installed. The rest of feedback 6, from precast elements to be installed to quality problems, is the same as that in feedback 2. Feedback 6 has six positive correlations; thus, feedback 6 is a positive feedback loop.

Feedback 7: The correlations from installed precast elements to quality problems in feedback 7 are the same as feedback 5 and the correlations from quality problem to installed precast elements are the same as feedback 6. In general, feedback 6 has eight positive correlations and one negative correlation so that feedback 6 is a negative feedback loop.

5.3.1.2 Stock-flow diagram

Basically, compared with the casual loop diagram, stock-flow diagram is another form of model with more detailed information regarding system behaviors to be modelled. Previously defined relationships in the causal loop diagram will be converted in the stock-flow diagram for quantitative evaluation through adding back auxiliary variables. System dynamics model in this research can be viewed as a standardized model that is designed to depict and model the system behavior of specific construction process, and the SD model will eventually be packaged into the DES module while all DES modules that represent different activities of PHP will be eventually connected to form the final hybrid dynamic model. The SD model hence serves as the fundamental stone of the hybrid dynamic model. The logic of SD model is supported by different functional modules, including prefabrication installation module, resource allocation module, project quantity calculation module, and schedule performance module. All the models are interpreted as follow.

(1) Prefabrication installation module

As shown in Figure 5.3, The main structure of prefabrication installation module contains “precast elements to be installed”, “installed precast elements” and “inspected precast elements”.

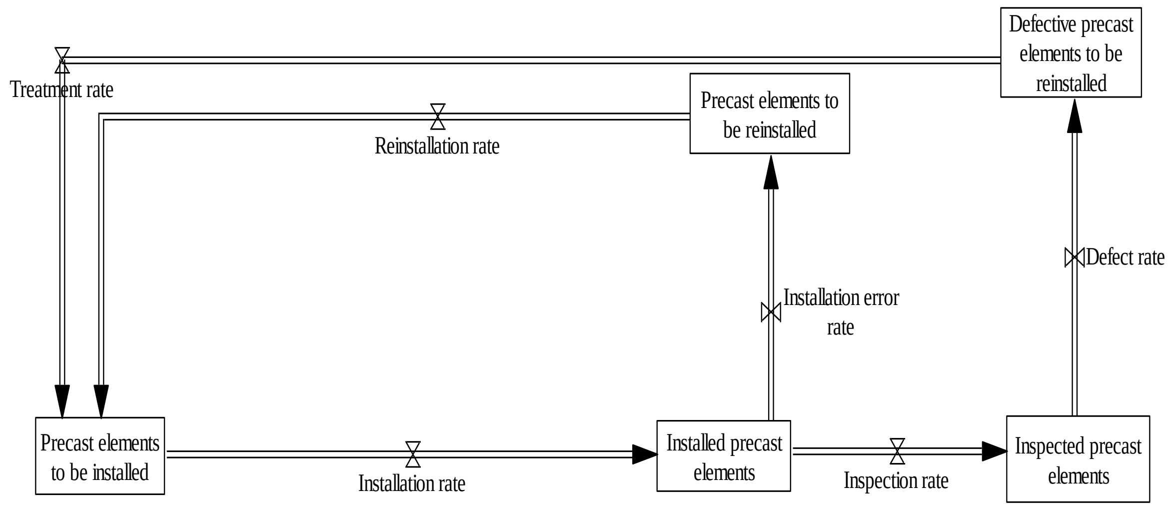


Figure 5.3 Prefabrication installation module

“Precast elements to be installed” refers to the total number of precast elements needed to be assembled in a specific activity. “Precast elements to be installed” is a stock and will be transferred to another stock “Installed precast elements” at a flow rate named “installation rate”. For example, to chase the single piece of precast façade, it will exist in “precast elements to be installed” at the first beginning, and once it is installed, it will be transferred to “installed precast elements” and after it is inspected by supervision engineers, and it will be placed in the stock “inspected precast elements” at a flow rate “inspection rate”. Other stock variables “defective precast elements to be reinstalled” and “precast elements to be reinstalled” and flow variables “installation error rate”, “reinstallation rate”, “defect rate” and “treatment rate” follow the similar work mechanism. Please be noted that the inspection which is done after installation is decided by the practical construction flow of the on-site assembly work. Because inspection before, during shipping the elements is done by the production and logistics company as there is no space for storage on construction site. The construction company implement just-in-time delivery, while the precast elements arrived at the site, they will be installed onto the building immediately and the on-site assembly company inspect the precast elements only after they are installed onto the building. The prefabrication installation module contains the major stock-flow variables, serving as the skeleton of the system dynamic model. Feedback loop will be constructed to connect prefabrication installation module with other modules in the following content.

(2) Resource allocation module

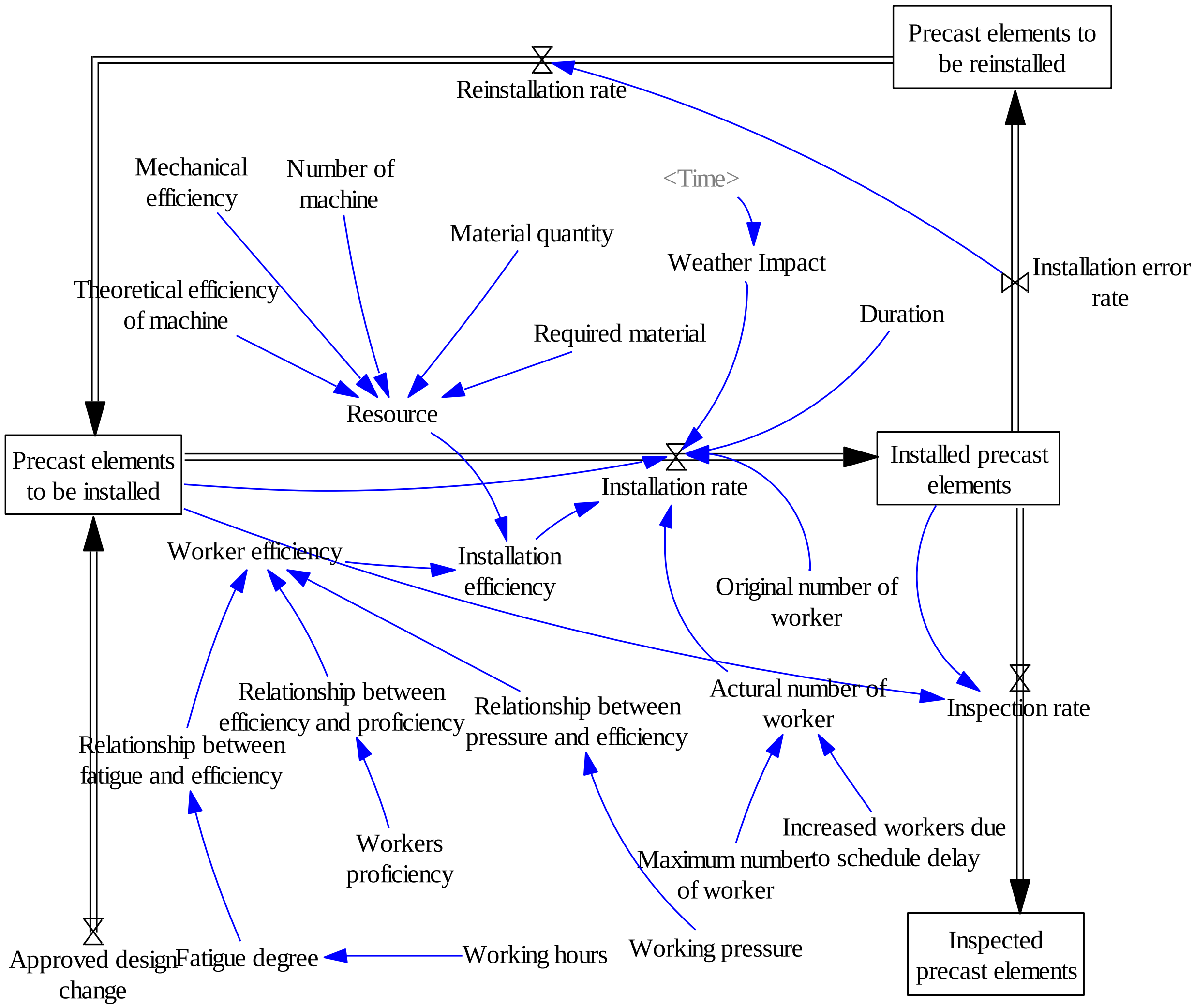


Figure 5.4 Resource allocation module

The resources mentioned in this research include three parts, namely labor, materials and machinery. The structure of resources subsystem is described in Figure 5.4. Labor variable can be affected by the number of workers and their working efficiency. The number of workers depends on maximum number of workers and original number of workers. The maximum number of workers refers to the maximum number of worker allowed for a specific construction task given limited construction space. The number of workers in each construction activity cannot exceed the theoretical maximum number of workers. The increased number of workers due to schedule delay is the additional number of construction workers arranged by project managers with consideration of the actual construction progress. The worker efficiency is determined by working pressure, working proficiency and the fatigue degree of worker. Many researchers have investigated and depicted the quantitative relationships between these four variables through table function and detailed function will be discussed in the next chapter. Apart from labor, material and machinery are another two parts of resource that will have high influence on installation efficiency. Material are determined by material quantity and required material variables, while machinery is determined by number of machine, mechanical efficiency and theoretical efficiency of machine. Moreover, weather and current duration of the project will affect the installation rate, as installation work is not allowed on stormy weather and under different construction stages the installation rate varies.

(3) Project quantity calculation module

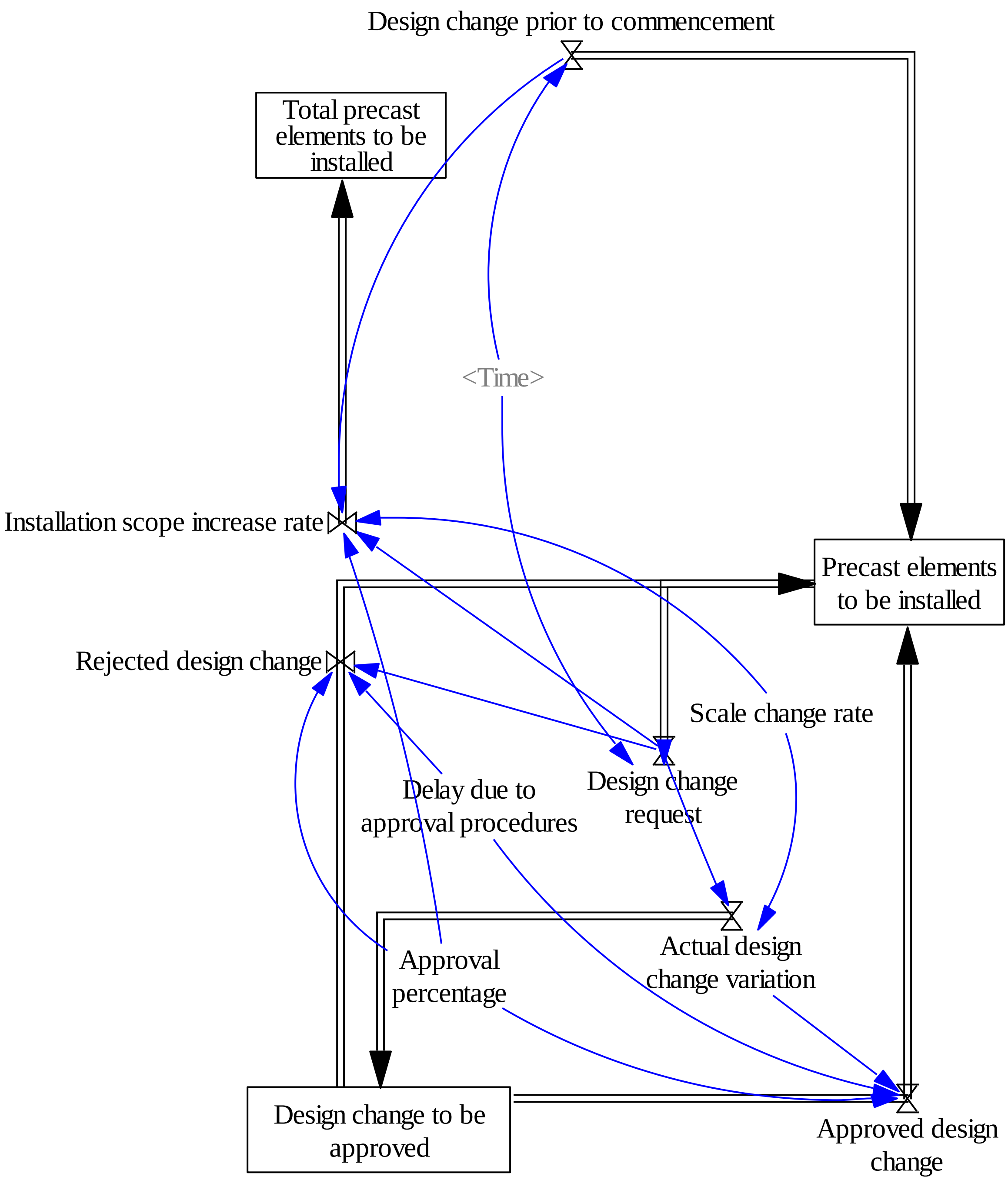


Figure 5.5 Project quantity calculation module

The variation of project quantity comes from two circumstances: one quantity variation is from design change prior to the commencement of the project. For this kind of change, as it occurs before the start of project construction, it would not be affected by sundry approval procedures required under the situation when the project already commences, and just simply increase or decrease project quantity; The other one is from the design change during construction which is mainly caused by quality problems, inappropriate design and the change of client demand. As this kind of design change occurs in process of construction, it needs additional approval from multiple authorities, which will directly lead to schedule delay. A percentage of request for design change is approved and will add up to the variable of precast elements to be installed, while the rest of design change rejected having no influence on the variable of precast elements to be installed. All relationships of the project quantity calculation module are depicted as shown in the Figure 5.5.

(4) Schedule performance module

In order to understand the cause of schedule delay, four scenarios are discussed as shown in Figure. A variety of risk factors, such as design errors, rework and variation in PHP will lead to schedule delay in PHP. With the intention of compensating low construction efficiency at the begin as a result of the occurrence of schedule risks, it would need an extended duration on the basis of the schedule initially planned to complete the original construction activity. If a construction activity in the original critical path is delayed due to schedule risks, its successor activities will be subsequently delayed and its start time will be postponed (Han et al. 2013). To avoid this situation, additional remedial actions, such as implementing overtime working plan, recruiting additional workers and procuring more resources (Park 2011), will be taken by the project managers to catch up with the delay (Williams 1997; Peña-Mora et al. 2008; Lee et al. 2009; Park 2011), as shown in the Figure 5.6. Remedial activities are normally implemented for the purpose of alleviating expected schedule delay. However, these activities will also raise the working pressure as a result of trying to ensure timely task delivery, which can be measured by dividing what we SHOULD with what we CAN do (Han et al. 2013). Though remedial action can, to some extent, speed up the production efficiency and shorten the delay, but if what we SHOULD do is much greater than what we CAN do as shown in the figure, the schedule delay could not be completely caught up (Newbold 1998).

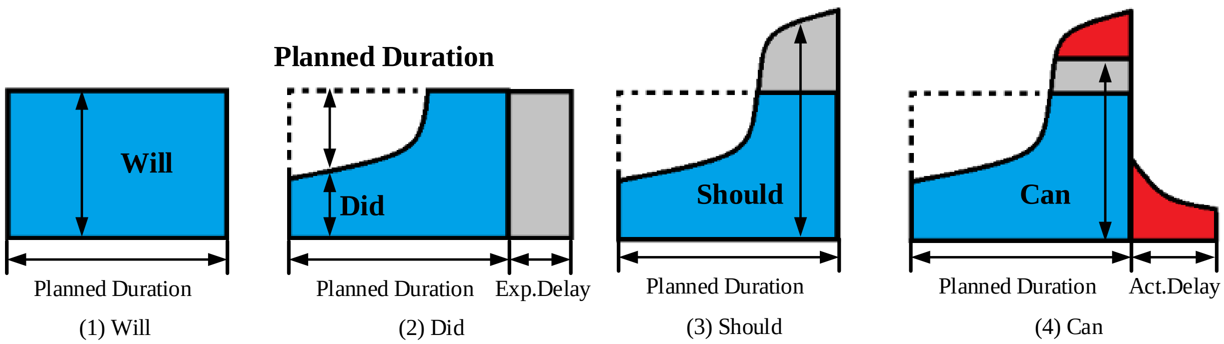


Figure 5.6 Interpretation of the cause of schedule delay (Han et al. 2013)

Two key variables, the actual percentage of completion and the planned percentage of completion, are defined in the research for the evaluation of schedule performance. The planned percentage of completion is a table function associated with duration based on the initial project schedule. The actual percentage of completion is defined as follows:

$$\mathrm{Ap} = \frac{Ipe}{Ipe + \mathrm{Iape}}$$

Where Ap refers to “the actual percentage of completion”, Ipe refers to “Inspected precast elements”, Ipe refers to “the increase of precast elements to be installed” and Iape stands for “the initial number of precast elements to be installed”. The structure of schedule performance module is shown in Figure 5.7.

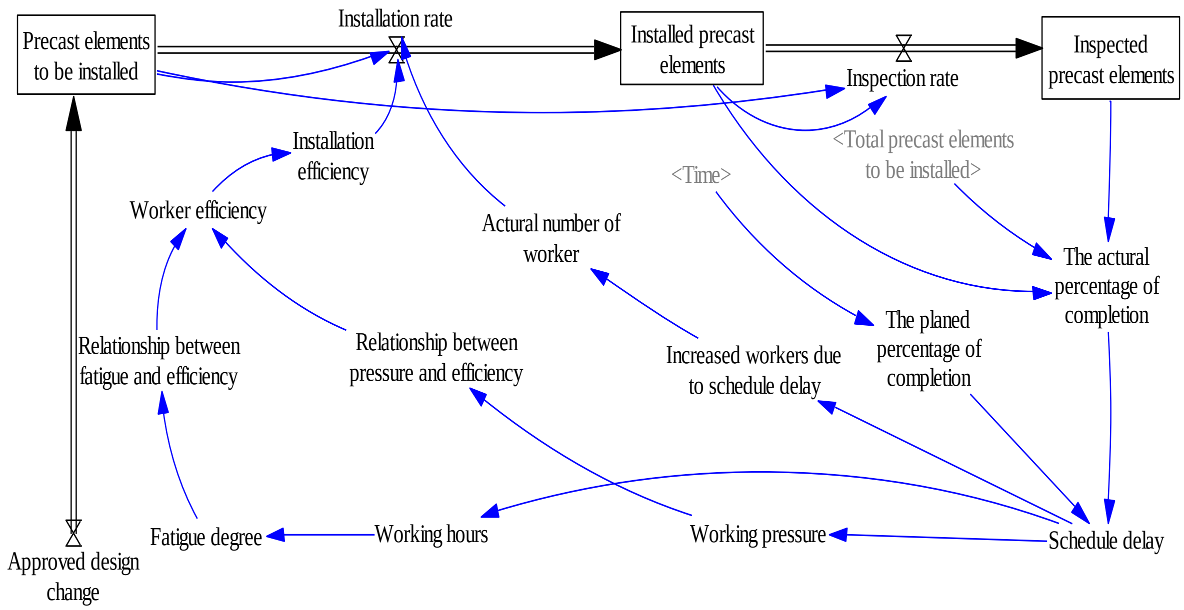


Figure 5.7 Schedule performance module

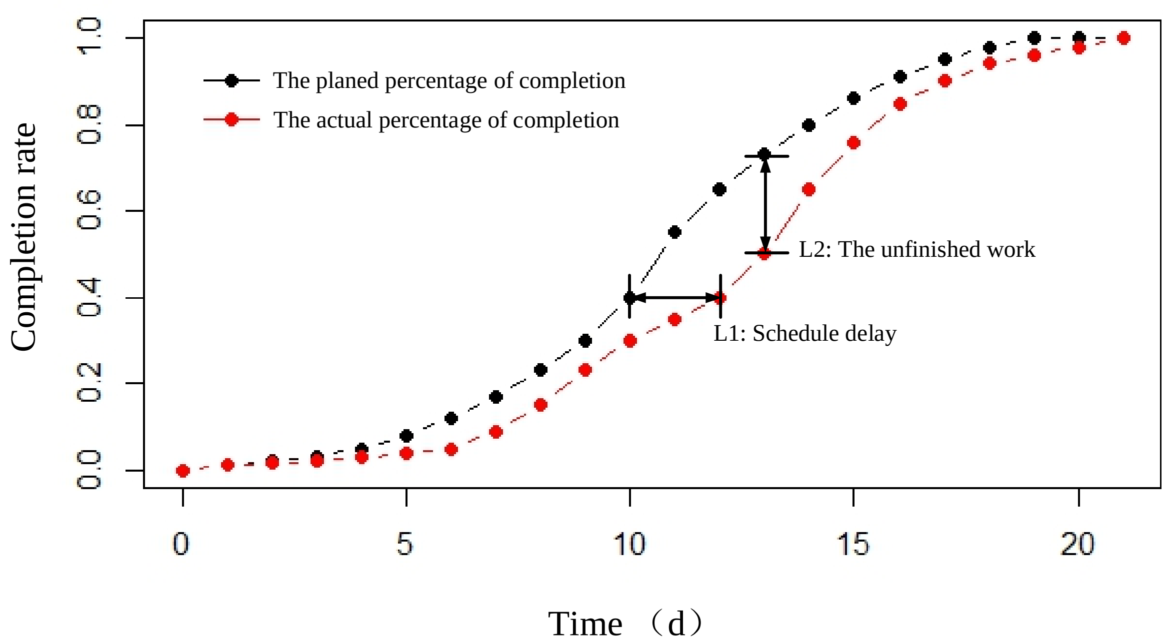


Figure 5.8 The planned percentage of completion and the actual percentage of completion

Based on the actual percentage of completion and the planned percentage of completion, schedule delay can be calculated. Figure 5.8 shows the curves of the planned percentage of completion and the actual percentage of completion. L1 in the figure indicates the time gap between real progress and original plan given the same completion percentage. L2 refers to the difference of completion percentage between real progress and original plan given the same timeline. Predicted schedule delay then can be calculated using the formula as follow:

$$\mathrm{Psd} = \frac{\mathrm{L2}}{Ir}$$

Where Psd stands for predicted schedule delay, Ir refers to installation rate that used to measure installation speed rate.

(5) Module integration

After interpreting interrelationships among variables through the causal loop diagram, and the development of four stock-flow modules, the final system dynamic model will be developed with the integration of four individual modules with the use Anylogic software to model and simulate schedule of PHP. The initial conditions for all state variable will be defined according to the data collected from the case study project. The integrated system dynamics model is presented along with brief definitions of variables in the model as shown in the Figure 5.9 and Table 5.1.

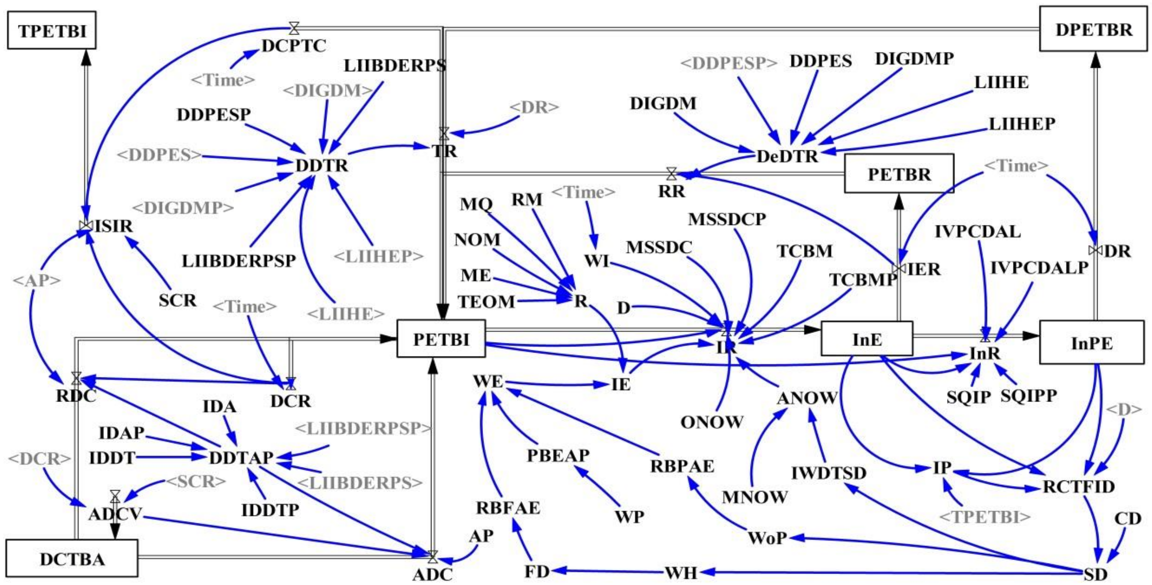


Figure 5.9 Integrated system dynamics model

Table 5.1 Variables in the model

No.	Abbrev.	Variable definition	Variable type
1	TPETBI	Total precast elements to be installed	Stock
2	DCPTC	Design change prior to commencement	Flow
3	ISIR	Installation scope increase rate	Flow
4	TR	Treatment rate	Flow
5	DDTR	Delay due to reproduction	Auxiliary variable
6	PETBI	Precast elements to be installed	Stock
7	RDC	Rejected design change	Flow
8	DDTAP	Delay due to approval procedures	Auxiliary variable
9	DCR	Design change request	Flow
10	SCR	Scale change rate	Auxiliary variable
11	AP	Approval percentage	Auxiliary variable
12	ADCV	Actual design change variation	Flow
13	DCTBA	Design change to be approved	Stock
14	ADC	Approved design change	Flow
15	WE	Worker efficiency	Auxiliary variable
16	TEOM	Theoretical efficiency of machine	Constant
17	ME	Mechanical efficiency	Auxiliary variable
18	NOM	Number of machine	Auxiliary variable
19	MQ	Material quality	Auxiliary variable
20	RR	Reinstallation rate	Flow
21	IR	Installation rate	Flow
22	RM	Required material	Constant
23	WI	Weather Impact	Auxiliary variable
24	D	Duration	Constant

25	InE	Installed elements	Stock
26	InR	Inspection rate	Flow
27	PETBR	Precast elements to be reinstalled	Stock
28	DPETBR	Defective precast elements to be reinstalled	Stock
29	DR	Defect rate	Flow
30	InPE	Inspected precast elements	Stock
31	IP	Installation percentage	Auxiliary variable
32	IER	Installation error rate	Flow
33	DeDTR	Delay due to reinstallation	Auxiliary variable
34	R	Resource	Auxiliary variable
35	IE	Installation efficiency	Auxiliary variable
36	PBEAP	Relationship between efficiency and proficiency	Auxiliary variable
37	RBFAE	Relationship between fatigue and efficiency	Auxiliary variable
38	FD	Fatigue degree	Auxiliary variable
39	WP	Workers proficiency	Auxiliary variable
40	WH	Working hours	Auxiliary variable
41	RBPAE	Relationship between pressure and efficiency	Auxiliary variable
42	WoP	Working pressure	Auxiliary variable
43	MNOW	Maximum number of workers	Constant
44	ONOW	Original number of workers	Constant
45	ANOW	Actual number of workers	Auxiliary variable
46	IWDTSD	Increased workers due to schedule delay	Auxiliary variable
47	SD	Schedule delay	Auxiliary variable
48	RCTFID	Required current time for initial duration	Auxiliary variable
49	CD	Current duration	Auxiliary variable
50	IDA	Inefficiency of design approval	Auxiliary variable
51	IDAP	Inefficiency of design approval probability	Auxiliary variable
52	IDDT	Inefficiency design data transition	Auxiliary variable
53	IDDTP	Inefficiency design data transition probability	Auxiliary variable
54	LIIHE	Logistics information inconsistency due to human errors	Auxiliary variable
55	LIIBHE	Logistics information inconsistency due to human errors probability	Auxiliary variable
56	LIIBDERPS	Low information interoperability between different enterprise resource planning systems	Auxiliary variable
57	LIIBDERPSP	Low information interoperability between different enterprise resource planning systems probability	Auxiliary variable
58	DIGDM	Design information gap between designer and manufacturer	Auxiliary variable
59	DIGDMP	Design information gap between designer and manufacturer probability	Auxiliary variable
60	DDPES	Delay of delivery of precast element to site	Auxiliary variable
61	DDPESP	Delay of delivery of precast element to site probability	Auxiliary variable
62	MSSBC	Misplacement on the storage site because of carelessness	Auxiliary variable
63	MSSBCP	Misplacement on the storage site because of carelessness probability	Auxiliary variable

64	TCBM	Tower crane breakdown and maintenance	Auxiliary variable
65	TCBMP	Tower crane breakdown and maintenance probability	Auxiliary variable
66	IVPCBAL	Inefficient verification of precast as a result of ambiguous labels	Auxiliary variable
67	IVPCBALP	Inefficient verification of precast as a result of ambiguous labels probability	Auxiliary variable
68	SQIP	Slow quality inspection procedures	Auxiliary variable
69	SQIPP	Slow quality inspection procedures probability	Auxiliary variable

5.3.2 Encapsulating System Dynamics Model into Discrete Event Simulation Module

As discussed before, construction project management mainly contains two levels: strategic project management from macro level and operational project management from micro level (Lee et al. 2006; Peña-Mora et al. 2008). Most traditional analysis focuses on strategic project management from macro level and fails to consider interactions among neighboring activities and build them into a model to better reflect the system behavior from a more realistic point of view, while actual PHP project is complex with various predecessor activities and successor activities connected with each other. To improve the traditional modeling method, this research encapsulates system dynamic model and its associated attributes into a discrete event simulation module, forming as a class to represent prefabrication activities with similar characteristics. Take the single installation activity for example, the process is depicted and simulated through system dynamics model, but its predecessor activities and successor activities could not be better depicted and modeled if discrete event simulation model are not built. When the system dynamics model is encapsulated into the discrete event simulation module, data can be transformed and exchanged within the module and cross other connected predecessor activities and successor activities that have been encapsulated as other modules. As shown in the Figure 5.10, the system dynamics model for cast-in-situ and prefabrication which is represented by red house and yellow box, will be wrapped into the discrete event module to form the cast-in-situ module and prefabrication module.

The “source” represents the entity generation port, and “sink” refers to entity aggregation port. Entity in this research is a fictitious concept, which can be viewed as an alarm that when the entity first flow into the “source”, the wrapped system dynamics model then will be triggered and begins to operate, and when the specific modelling process ends the entity will flow out to exit and continue to flow to the next “source” and trigger another system dynamics model. At the end, entity will reach “sink” and the whole simulation finishes. “queue” and “hold” are the function unit from the library of discrete event simulation software, which can be regarded as the controlling valve used to control the rhythm of entity flow and facilitate the coding process.

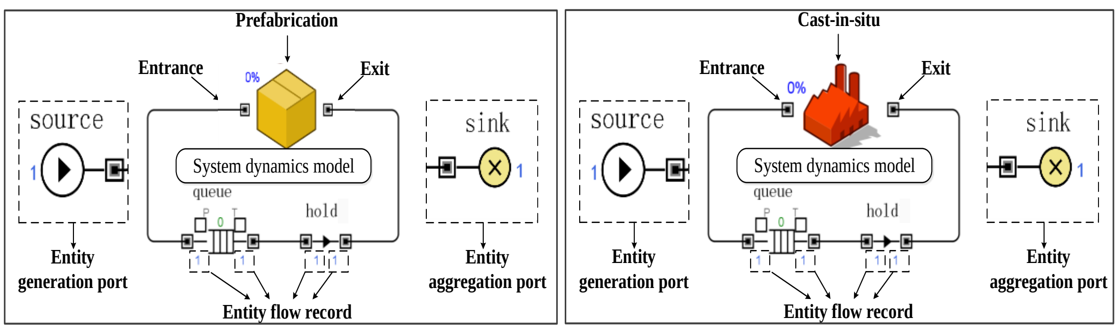


Figure 5.10 Encapsulation method

One major characteristics of the encapsulation technology adopted in the system model is that it is class-orientation. Through defining classes of objects, inheritance is achieved by the object-oriented programming, as opposed to the objects themselves. The behavior and structure of a module are defined by a class, which is a definition of objects of a definite kind. Encapsulation refers to the packaging and grouping of specific information into a logical unit in which related properties are wrapped. It ensures that as long as the interface structure are not changed, any changes of one single module will have no influence on the other module. User interface designed by the research is the only assess to the inside properties of the specific module. This technology not only maintain the integrality of properties within the module, but also helps enhance the scalability of discrete event simulation system. Another merit for applying encapsulation technology is to ensure reusability. Reusability refers to the reusable capability of software products, which is the key indicator to measure the success of software. In the hybrid dynamic model, code reuse rate is high due to the use of object-oriented programming coding method, and as a result the operating speed of the model is fast and large amount of efforts are saved.

As shown in the figure of the encapsulated discrete event module, system dynamic model is wrapped in the center of the figure, while other plug-ins are designed and placed along the model for a variety of purpose, such as data exchange among system dynamics model and discrete event module, data reading and collection, creating table function etc. All variables in the system dynamics model are connected to the database through program coding. When the model is trigger to operate, required data will be invoked from database to the encapsulated module for simulation and the generated results will also be stored in the database for further analysis. Moreover, a series of real-time visual interfaces and data output plug-ins are developed through the software to track, record and present the real-time modelling process of each module in the simulation. Please be noted that, two modules, namely, cast-in-situ module and prefabrication module, are developed based on the fact that these two kinds of activities have different characteristics and should be treated as two different class.

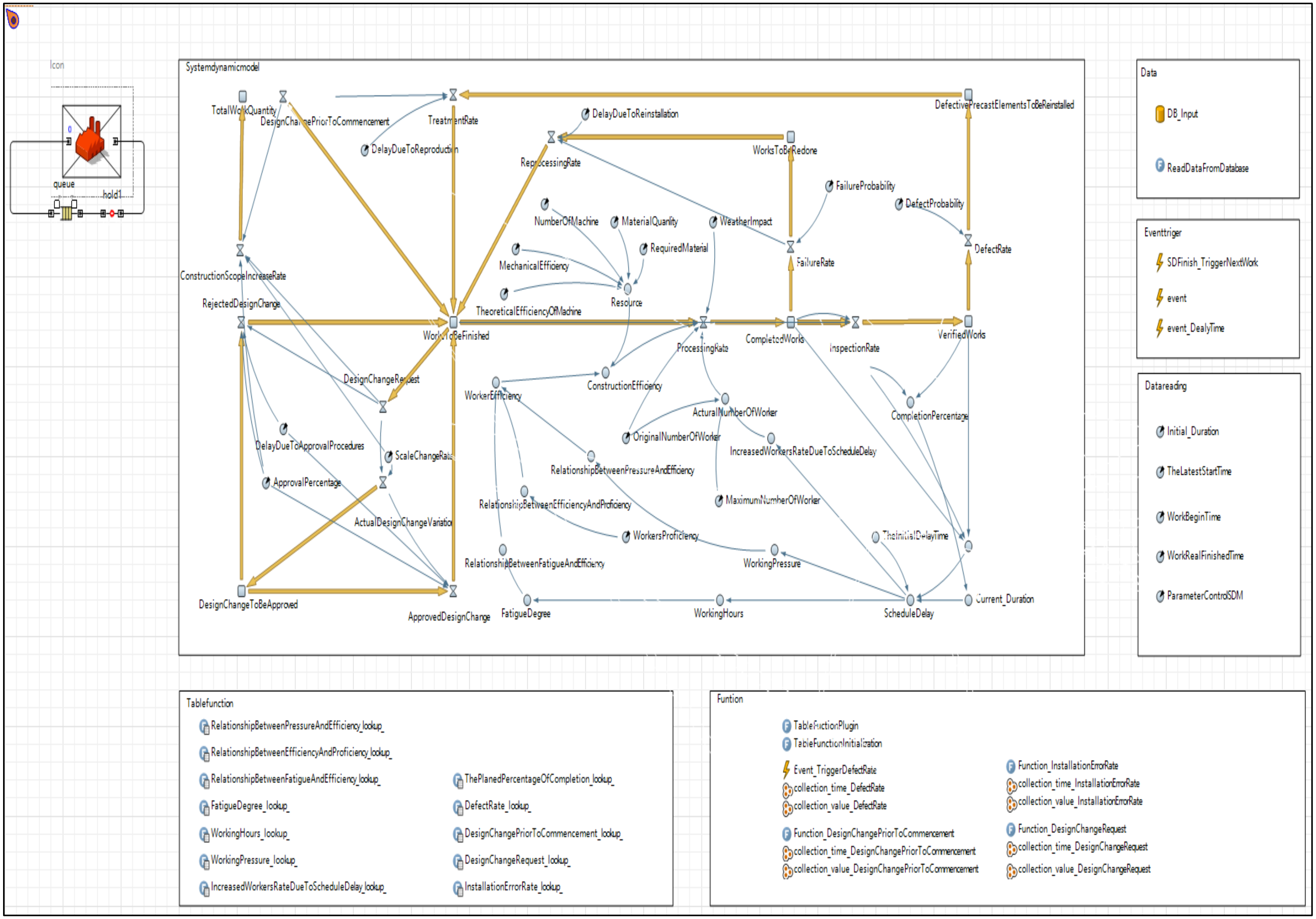
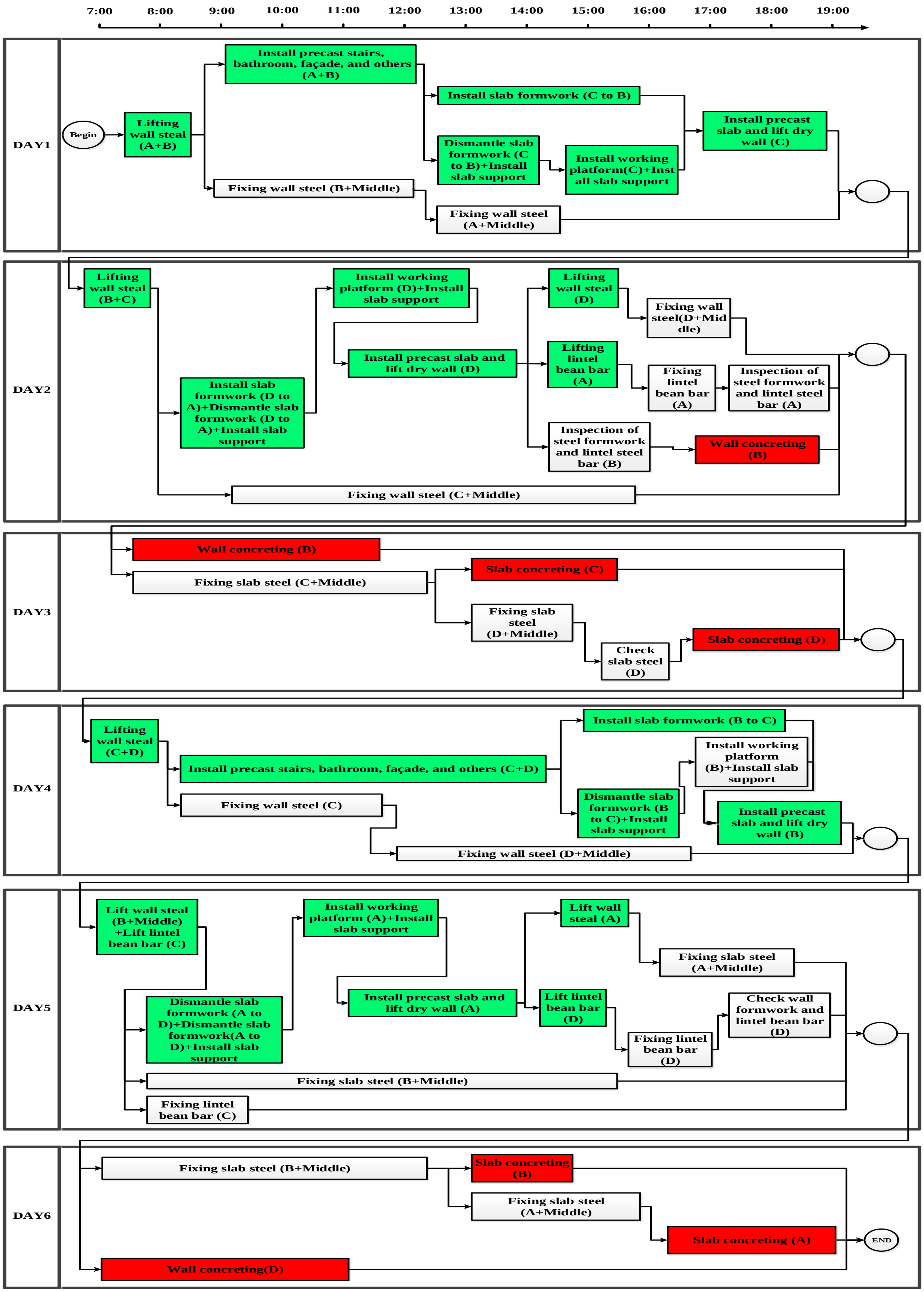


Figure 5.11 Typical example of cast-in-situ module

5.3.3 Connecting Discrete Event Modules

After the development of specific discrete event modules, they should be connected based on predecessor and successor relations according to the actual project. Take the six-day cycle installation plan for example, the plan is drawn by the manager to instruct corresponding workers to implement various tasks in different time across the six-day cycle, as shown in the Figure 5.12. This research first focuses on model development of six-day-cycle assembly, which is the most critical production unit of PHP. The typical floor of prefabrication building will be assembled in accordance with the six-day master plan, with each day assigned with different construction and assembly tasks. Each typical floor is supposed to be finished within six-day, so once one six-day-cycle assembly plan is delayed due to some causes the next plan will be consequently impacted. The overall schedule performance of the whole production is closely related to progress of six-day-cycle assembly plan. As such this research first emphasizes analyses on the how the schedule performance six-day-cycle assembly is influenced by various schedule risks of PHP, and then move further by developing model on the whole construction processes as shown in the Figure 5.13.



7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
DAY1
Begin
Lifting wall steal (A+B)
Install precast stairs, bathroom, façade, and others (A+B)
Install slab formwork (C to B)
Dismantle slab formwork (C to B)+Install slab support
Install working platform(C)+Install slab support
Install precast slab and lift dry wall (C)
Fixing wall steel (B+Middle)
Fixing wall steel (A+Middle)
DAY2
Lifting wall steal (B+C)
Install working platform (D)+Install slab support
Lifting wall steal (D)
Fixing wall steel(D+Middle)
Install precast slab and lift dry wall (D)
Lifting lintel bean bar (A)
Fixing lintel bean bar (A)
Inspection of steel formwork and lintel steel bar (A)
Install slab formwork (D to A)+Dismantle slab formwork (D to A)+Install slab support
Inspection of steel formwork and lintel steel bar (B)
Wall concreting (B)
Fixing wall steel (C+Middle)
DAY3
Wall concreting (B)
Slab concreting (C)
Fixing slab steel (C+Middle)
Fixing slab steel (D+Middle)
Check slab steel (D)
Slab concreting (D)
DAY4
Lifting wall steal (C+D)
Install slab formwork (B to C)
Install working platform (B)+Install slab support
Install precast stairs, bathroom, façade, and others (C+D)
Fixing wall steel (C)
Dismantle slab formwork (B to C)+Install slab support
Install precast slab and lift dry wall (B)
Fixing wall steel (D+Middle)
DAY5
Lift wall steal (B+Middle) +Lift lintel bean bar (C)
Install working platform (A)+Install slab support
Lift wall steal (A)
Fixing slab steel (A+Middle)
Install precast slab and lift dry wall (A)
Lift lintel bean bar (D)
Check wall formwork and lintel bean bar (D)
Dismantle slab formwork (A to D)+Dismantle slab formwork(A to D)+Install slab support
Fixing lintel bean bar (D)
Fixing slab steel (B+Middle)
Fixing lintel bean bar (C)
DAY6
Fixing slab steel (B+Middle)
Slab concreting (B)
Fixing slab steel (A+Middle)
Slab concreting (A)
END
Wall concreting(D)

Figure 5.12 The progress of six-day cycle assembly of PHP

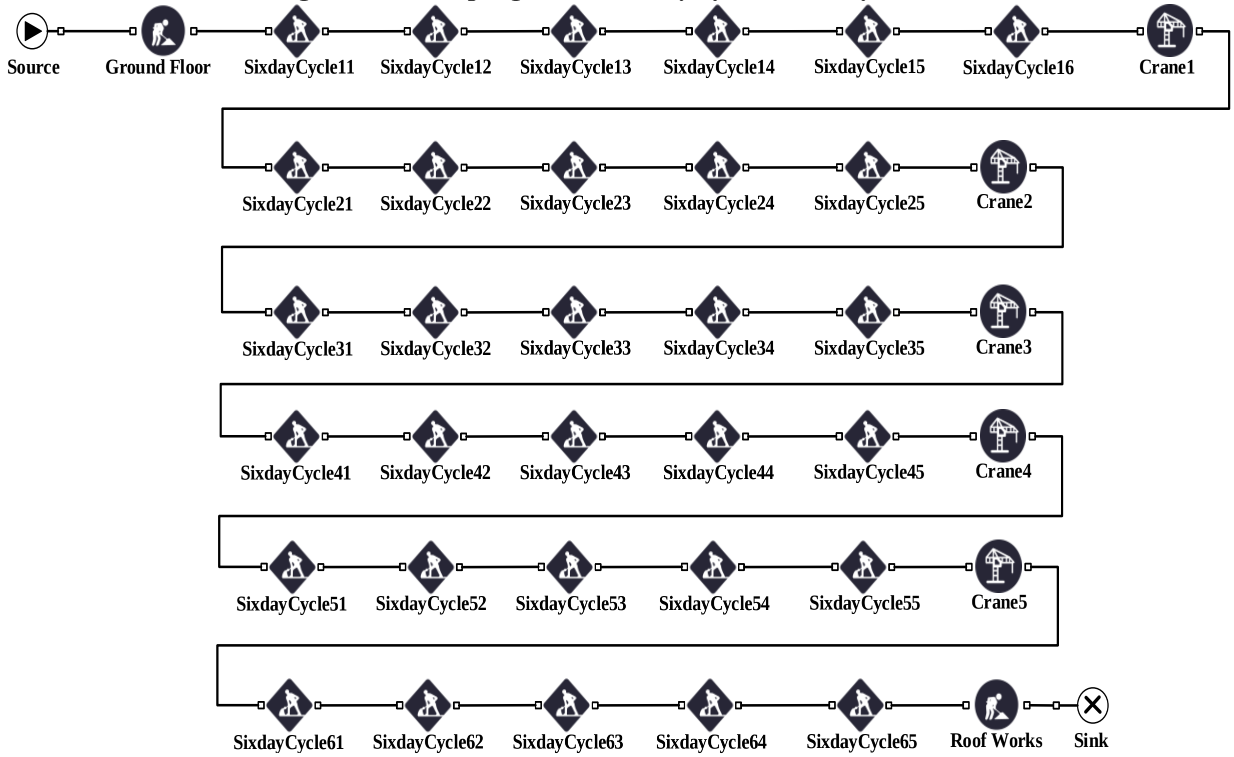


Figure 5.13 The progress of prefabricated construction

Through the use of encapsulation technology and Unified Modeling Language provided by Anylogic software, cast-in-situ and prefabrication modules are connected based on predecessor and successor relations presented by the above Figure. The connecting process can be quite convenient as the properties of the two modules are already defined through the above modelling process, such that corresponding template modules can be easily replicated to present the predecessor and successor relations rather than developing various model from a new start. The final hybrid dynamic model for six-day cycle installation plan and construction plan can be seen as shown in Figure 5.14 and Figure 5.15

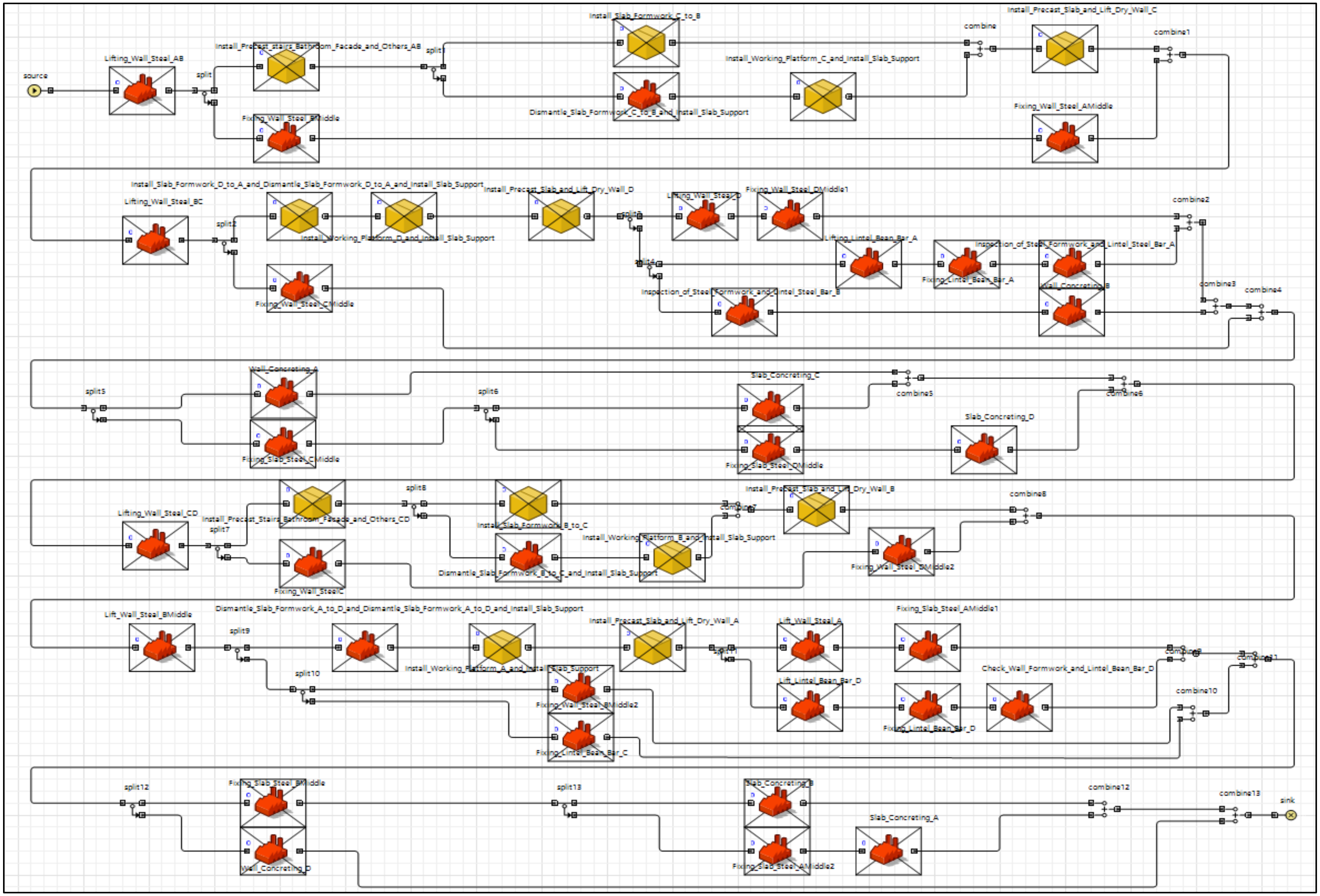


Figure 5.14 Hybrid dynamic model for a six-day-cycle assembly

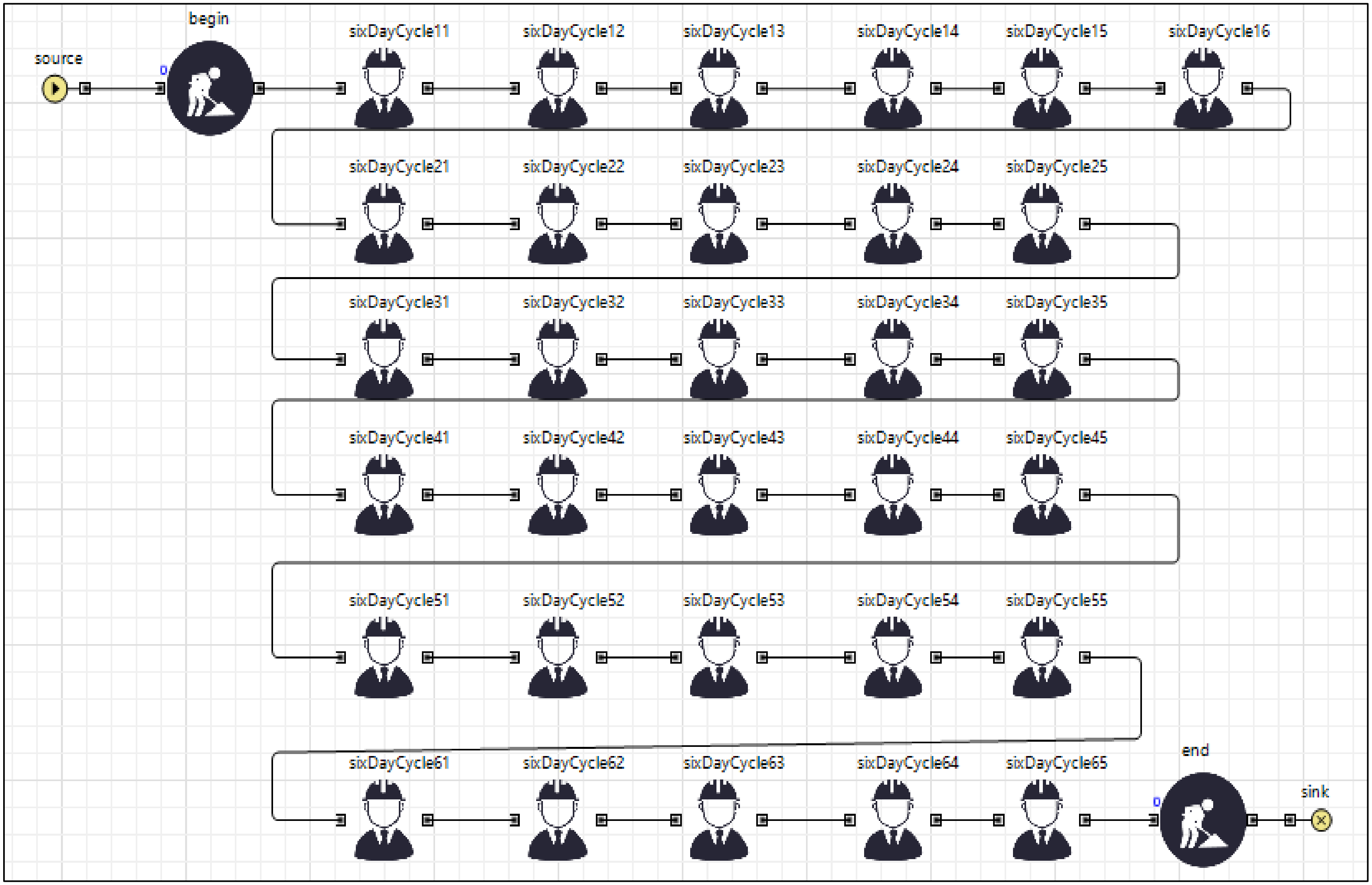


Figure 5.15 Hybrid dynamic model for prefabricated construction

5.3.4 Connecting the Hybrid Dynamic Model with Database

As a large amount of data are required to be input into the hybrid dynamic model and the generated simulation results are also needed to be stored for further analysis, a database should be developed and connected to the developed hybrid dynamic model. In this research, Access is taken as the database to store initial input data and simulated results. Besides, data reading and exchange plug-ins that assist the hybrid dynamic model communicate with the Access database, are developed through program coding, make it quickly read data from database, exchange required data among various modules and store simulation results generated from the model. Typical program coding written with the Anylogic software is shown in the Appendix II.

5.4 Chapter Summary

This chapter introduce the development procedures of the hybrid dynamic model. The purpose and boundary of the model are first defined, then structure of the model is determined. Stock flow diagrams of system dynamics sub models are developed based on the causal loop with the help of Vensim software. System dynamics model and its associated attributes are encapsulated into a discrete event module and consequently forming the final hybrid dynamic model. As a large amount of data are required to be input into the hybrid dynamic model and the generated simulation results are also needed to be stored for further analysis, a database is developed and connected to the hybrid dynamic model.

CHAPTER 6 Model Verification and Validation

6.1 Introduction

The previous chapter delivers explanations of how the hybrid dynamic model for evaluating and simulating potential impact of risks on the schedule of PHP is developed and visualized through the use of system dynamics and discrete event simulation methods. The hybrid dynamic model is designed as a tool to analyze and discuss the possible impact of major risks on the schedule of PHP and further served as an experiment platform for explaining and validating the benefits and weaknesses of specific strategies proposed to deal with identified major schedule risks. This chapter therefore is about to illustrate the application of the hybrid dynamics model by applying data from a prefabrication housing production project in Hong Kong. Prior to further analyses, confidence should be built up through applying the hybrid dynamic model to a practical PHP project. This chapter begins with a brief introduction of the selected PHP case located in Tuen Mun, Hong Kong, which to gain a better understanding on the background of the PHP project and how the data are collected. Then it moves on to the application of previously developed hybrid dynamic model to build up confidence. Methods for quantifying different kinds of factors in the hybrid dynamic model are introduced and the applicability of the hybrid dynamic model is validated through different tests required by the SD and DES method.

6.2 Background of the Selected Case

Prefabrication housing production in Hong Kong mainly consist of three specific and critical phases that are mostly concerned by HKHA, namely, prefabrication production, cross-border logistics and on-site assembly: (1) Prefabrication production involves the production and timely delivery of quality prefabricated construction components. The key users are HKHA and its collaborative prefabrication producers; (2) The cross-border logistics is the linkage between the production and on-site construction phases, which involves the transportation of the manufactured prefabricated components from the production plants to the construction sites for assembly. The proposed enhancements to prefabrication cross-border logistics service, as part of the proposed solution, aims to achieve real-time visibility of logistics status and just-in-time logistics operations to provide seamless linkage and delivery tracking between prefabrication factories and the construction sites; (3) On-site assembly of the prefabrication components is the last phase covered in this study for prefabricated public housing construction. It occurs after the prefabrication components are delivered through the cross-border logistics to the construction site. Given that, data collection activities are mainly conducted toward parties involved in the three phases

The selected case for validating the model in this research is the Tuen Mun project (Area 54, TM54), which proposes to build five 34-38 storey buildings, providing about 5,000 units and with the expectation of holding more than 14,000 people. The construction practice of Block 5 is taken as a case study for the developed model, as shown in the Figure 6.1. The studied building has a construction area of 15815 m2, consisting of 37-story residential buildings, with the expected project duration period of 509 days. Surveys are mainly conducted toward four major involved parties in the PHP management, namely Wing Hong Shun Ltd., Yingyun Transportation Ltd., and Gammon Construction Ltd., and HKHA.

Wing Hong Shun Ltd. (WHS) located in Huizhou, Guangdong Province is responsible for manufacturing the prefabricated components. It covers an area of 56,000 m2 with 12,500 m2 casting yards. Currently, the company has 12 benders, 2 accumulators, 3 air compressors, 25 crown blocks, 9 forklifts, and 8 iron-cutting machines. Each year, it produces 60,000 tons of prefabricated components, which includes façade, staircase, slab, and drywall, serving for construction projects in Hong Kong. Yingyun Logistics Co., Ltd (Yingyun) is responsible for shipping the prefabricated components from WHS to the assembly site. Gammon Construction Limited (Gammon, or GCL) is a leading construction and engineering contractor in Hong Kong and responsible for assembling the precast element delivered on site for the Tuan Men project. Besides of residential projects like TM54, Gammon also has construction and engineering projects such as the new Hong Kong International Airport terminal for the third runway; and a number of oversea developments such as in Vietnam, Singapore and United States. The Hong Kong Housing Authority (HKHA), which was established in 1973, is an agency of the Government of Hong Kong, and serves as the main developer for providing public houses for the citizens of Hong Kong. HKHA is the initial designer and the client of TM54, and plays an overall supervision role at the construction site.

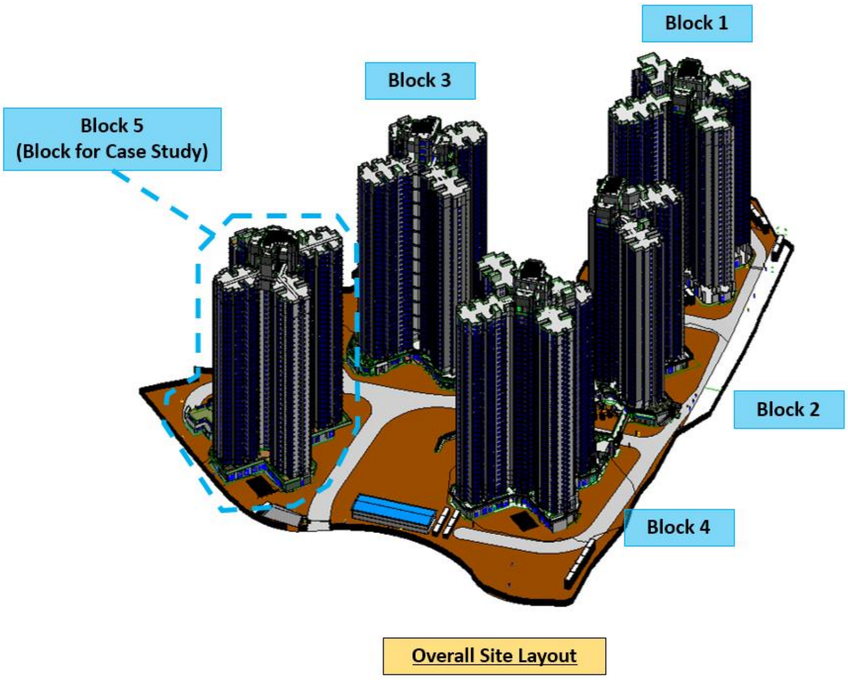


Figure 6.1 Surveyed case in Hong Kong

Data collection was carried out mainly through two sources. One is by referring to various field notes, documents and report records of the construction project, previous literature, and analysis of documents and reports from the companies involved in the Tuen Mun PHP project. The other is through a combination of qualitative methods, including on-site visits, semi-structured interviews and non-participant observation. A profile of interviewees and stakeholders from different parties is shown in the Table 6.1. The main cause for including these stakeholders in semi-structured interviews is their extensive experience in every process of offshore prefabrication housing production in Hong Kong. These stakeholders had at least five years of experience in their expertise at PHP industry and are well informed on the current practices of prefabrication housing production in Hong Kong. Semi-structured interviews were conducted in 2015, with each semi-structured interview lasting between 50 and 60 minutes.

Table 6.1 Profile of interviewees from different parties

N.	Position	Organization	Stakeholder group	N.	Position	Organization	Stakeholder group
1	Structural Engineer	Hong Kong Housing Authority	Client	6	Assistant Engineer	Gammon Construction Ltd	Main Contractor
2	Architect	Hong Kong Housing Authority	Client	7	Site Agent	Gammon Construction Ltd	Main Contractor
3	Contract Manager	Gammon Construction Ltd	Main Contractor	8	BIM Manager	Gammon Construction Ltd	Main Contractor
4	Senior Project Engineer	Gammon Construction Ltd	Main Contractor	9	Factory Manager	Wing Hong Shun Ltd	Production Company
5	Project Manager	Gammon Construction Ltd	Main Contractor	10	Business Manager	Yingyun Transportation Ltd	Logistics Company

6.3 Quantification of Collected Data

Before conducting further simulation analysis, the suitability of the collected data to be inputted for variables built in the hybrid dynamic model should be carefully examined. The schedule variables that have influence on the schedule performance of prefabrication housing production have been identified and built into the hybrid dynamic model in previous Chapter. these variables can be grouped as three types based on their attributes and roles, deterministic, and dependent, and uncertain. Each type of variable has its corresponding data sources and quantification method for its own.

6.3.1 Quantification for Deterministic Variables

Deterministic variable refers to the variable which remains the same in the process of simulation and set before the simulation. This type of variable will have influence on other variables while it self remains constant and will not be affected by other variables in the model. Take the variable AP which is a constant variable, AP have influence and can change the value of variables such as RDC, ADC and ISIR, while any of the variables will not affect its attribute. Data sources of deterministic variables can be from materials and records of construction project, previous literature and reports of involved parties.

6.3.2 Quantification for Dependent Variables

Another group of variables is regarded as dependent variables. Dependent variables are changeable and their attributes are decided by one or more than one variables that are defined to be interacted with dependent variables in the model. As such, interrelationships between dependent variables and other variables should be built into the model. With the help of Vensim and Anylogic, table function can be used to depict interrelationships among any two variables. The table function of the Vensim and Anylogic software provide an excellent way to describe interrelationships among dependent variables. Three typical examples are the relationships between working pressure and worker efficiency, the fatigue degree and worker efficiency, and worker proficiency and worker efficiency. Their relationships can be acquired based on previous research and depicted through the table function from Anylogic software.

According to the law of Yerkes-Dodson in Psychology, there is an inverted U-shaped relationship between working pressure and worker efficiency. Moderate level of pressure has a positive impact on working efficiency and increase along with efficiency, while once the pressure exceeds certain level the working efficiency would reverse the trend and decrease along with working pressure (Alluisi and Morgan 1976). In another word, too much or too little working pressure has negative influence on working efficiency (Hollands and Wickens 1999). Based on the research of Wang (2011), the relationship between job stress and work efficiency in this study is set to the table function (Wang 2011a), as shown in the following Figure 6.2.

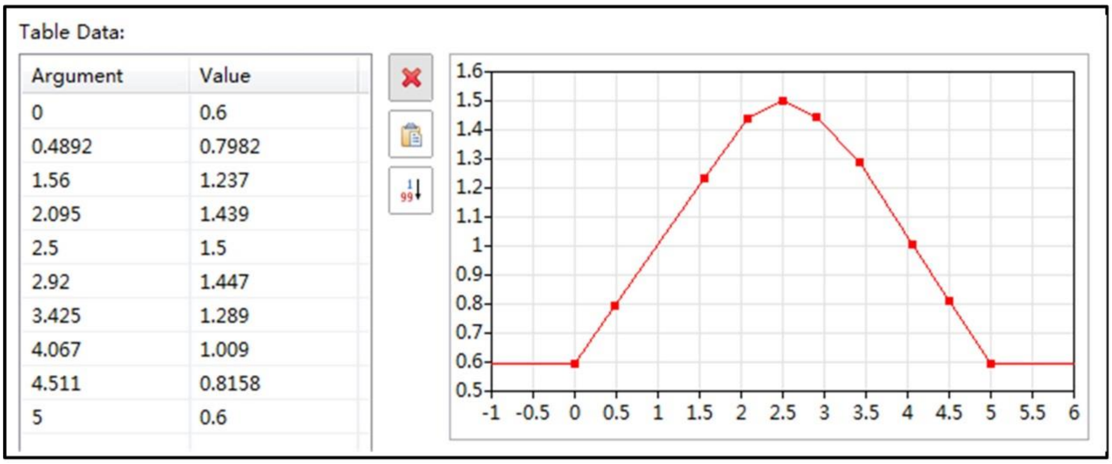


Figure 6.2 The relationship between working pressure and worker efficiency (Wang 2011a)

S-shaped curve shows the relationship between the fatigue degree and worker efficiency. With the increase of fatigue degree at the early stage, worker efficiency decreases sharply and the decrease speed of worker efficiency slows down when the fatigue degree raises at a certain level, as shown in the figure. Wang et al. used table function to describe the relationship between worker's efficiency and fatigue degree, as shown in Figure 6.3 (Wang 2011a).

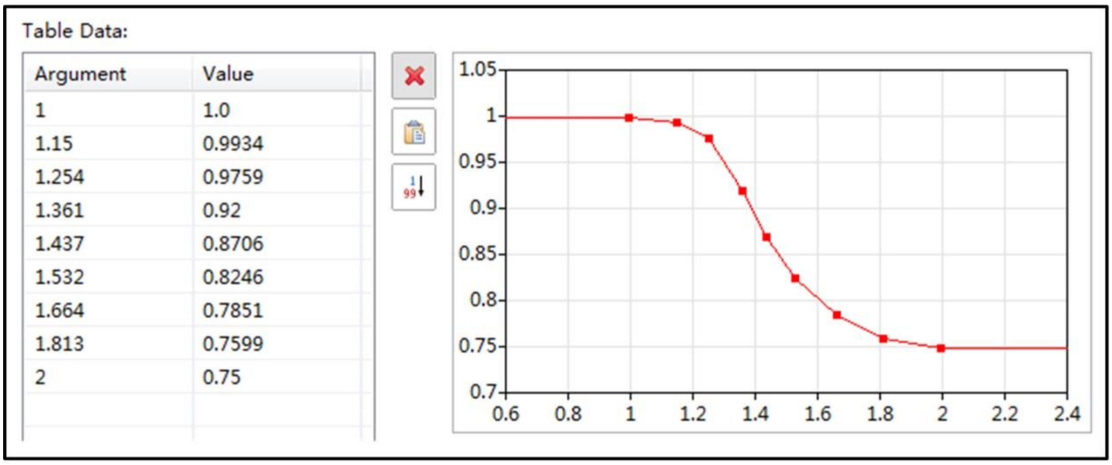
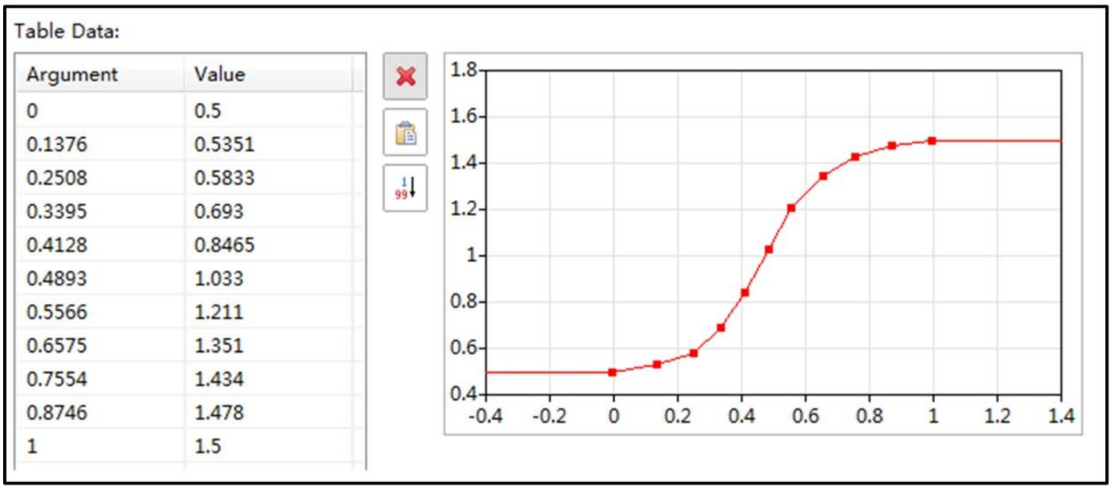


Figure 6.3 The relationship between fatigue degree and worker's efficiency(Wang 2011a)

S-shaped curve also is used to depict the relationship between worker proficiency and worker efficiency. At the early working stage, as workers are not familiar with the work environment and is not good at the skills, actual worker efficiency remains at a low level. Worker efficiency increases gradually along with the accumulation of practice and training, and reaching at the stable level, as shown in Figure 6.4.



Argument	Value
0	0.5
0.1376	0.5351
0.2508	0.5833
0.3395	0.693
0.4128	0.8465
0.4893	1.033
0.5566	1.211
0.6575	1.351
0.7554	1.434
0.8746	1.478
1	1.5

Figure 6.4 The relationship between worker proficiency and worker efficiency (Wang 2011a)

6.3.3 Quantification for Uncertain Variables

The last group of variable is uncertain variables. Uncertain variable refers to variables with data randomly chosen for the simulation, which is used to represent quantities with uncertainty. Probability distribution of these variables are needed for conducting Monte Carlo simulation. Take “Tower crane breakdown and maintenance” for example, “Tower crane breakdown and maintenance” is an uncertainty variable in the hybrid dynamic model. Though its value cannot be directly determined, the probability distribution of can be depicted through the historical data collected. As per the literature, this kind of variable can be illustrated through triangular distribution, such that what we need to do is to collect data required to draw the specific triangular distribution for the variable. Historical data required to draw the triangular distribution of “Tower crane breakdown and maintenance” can be either collected by past projects or managers with abundant project experience on the similar project. Through analyzing history data collected, the probability distribution of “Tower crane breakdown and maintenance” can be obtained for further Monte Carlo simulation. As discussed, the key process for quantifying uncertain variables is to determine their probability distribution. Besides, likelihood of identified schedule risks occurrence and their influence vary from project to another, so when different attributes from different project are input into the model, generated simulation results will be different. A database has been developed and connected to the developed hybrid dynamic model to store initial input data and simulated results.

6.3.3.1 Determination of Probability Distribution

According to different situations, three methods are adopted to determine the probability distribution of uncertain variables, namely (1) with reference to existing literature; (2) inference of probability distribution; and (3) generating probability through Anylogic software.

(1) With reference to existing literature

As to the variables with known probability distribution by previous research, the corresponding probability distribution can be directly picked to depict the properties of uncertain variables. With the reference of exiting literature, risks probability distributions are compiled as follows. Take the variable "design change" for instance, as there is existing literature indicating that the variable complies with uniform distribution under similar construction project. The researcher can first consider this kind of distribution to check whether or not it marches with the real construction practice of the selected case. If this distribution is accorded with the real situation, then this distribution will be selected and coded into the Anylogic software to depict the behavior of this variable.

Table 6.2 Probability distribution

Probability distribution	Applicability	References
Normal distribution	Under very general conditions, as the number of variables in the sum becomes large, which is suitable for cost related risks	Diekmann J E. Probabilistic estimating: mathematics and applications[J]. Journal of Construction Engineering and Management, 1983, 109(3): 297-308.
Lognomal distribution	Values have to be positive numbers, which is suitable for cost related risks	Touran A, Wiser E P. Monte Carlo technique with correlated random variables[J]. Journal of Construction Engineering and Management, 1992, 118(2): 258-272. Diekmann J E. Probabilistic estimating: mathematics and applications[J]. Journal of Construction Engineering and Management, 1983, 109(3): 297-308.
Triangular distribution	When the information regarding the most likely value is available, which is suitable for risks regarding to schedule, such as materials delay, weather condition, labour	Touran A, Wiser E P. Monte Carlo technique with correlated random variables[J]. Journal of Construction Engineering and Management, 1992, 118(2): 258-272. Bekr, G.A.R. (1990) Client's control of construction, Ph.D. thesis, University of Nottingham.

	productivity and soil condition	
Beta distribution	Values have to be positive numbers, which is suitable for cost related risks	Touran A, Wiser E P. Monte Carlo technique with correlated random variables[J]. Journal of Construction Engineering and Management, 1992, 118(2): 258-272.
Uniform distribution	When there are insufficient data regarding the mode of the distribution or where the range is relatively small, which is suitable for risks related to design change and incomplete design scope	Touran A, Wiser E P. Monte Carlo technique with correlated random variables[J]. Journal of Construction Engineering and Management, 1992, 118(2): 258-272. Bekr, G.A.R. (1990) Client' s control of construction, Ph.D. thesis, University of Nottingham.
Bernoulli distribution	Only two possibilities, which is suitable for risk regarding to equipment failure	Bekr, G.A.R. (1990) Client' s control of construction, Ph.D. thesis, University of Nottingham.

（2）Inference of unknown risk probability distribution

Probabilistic data of variables from previous similar project can be used to infer the probability distribution of uncertain variables. Generally, there are three pretreatment methods, namely, point statistics, histogram and probability graph.

Point statistics: the type of probability distribution is determined based on the characteristics of coefficient of variation of continuous distribution. The formula of the coefficient of variation can be denoted as:

$$\delta = \frac{\sqrt{\mathrm{Var}(x)}}{E(x)}$$

Where $\mathrm{Var}(x)$ and $E(x)$ is the variance and expectation of statistical data. The variance and expectation of sample data:

$$\bar{x}(n) = \sum_{i=1}^{n} \frac{x_i}{n}$$

$$S^2(n) = \sum_{i=1}^{n} \frac{\sum_{i=1}^{n}[x_i - \bar{x}(n)]^2}{(\mathrm{n}-1)}$$

The coefficient of variation of sample data:

$$\hat{\delta} = \frac{\sqrt{S^2(n)}}{\bar{x}(n)}$$

Through comparing the value $\hat{\delta}$ and with the coefficient of variation of existing theory probability distributions, the probability of distribution of the surveyed variable can be de determined. For example, if the coefficient of variation of the variable "design change" is the same or approximately equal as the coefficient of variation of triangular distribution, then the probability distribution of the variable is set to the triangular distribution.

Histogram: The range of the sample data $x_1, x_2, \dots, x_n$ will be divided into k equal intervals$[b_0, b_1), [b_1, b_2), \dots, [b_{k-1}, b_k)$, with $\Delta \mathrm{b} = b_j - b_{j-1} (j = 1,2, \dots, k)$. For any j, n_j is the number of observation points on the j-th interval, and $g_j = \frac{n_j}{n} (j = 1,2, \dots, k)$. The density function is

$$\mathrm{h}(x) = \begin{cases} 0 & x < b_0 \\ g_i & b_{j-1} \leq x < b_i \\ 0 & b_k \leq x \end{cases}$$

According to the density function, histogram of $\mathrm{h}(x)$ can be drew and compared with existing theory probability distributions, if the drew histogram is the same or approximately equal as the specific theory probability distribution, the observed sample data $x_1, x_2, \dots, x_n$ will be assumed to be comply with the distribution and corresponding parameters are calculated.

Probability graph: The sample data of the variable $x_1, x_2, \dots, x_n$ is assumed to have m number of value ($(m \leq n$), as there are some sample having the observation value) and the sample value is denoted as $x_{(1)}, x_{(2)}, \dots, x_{(m)}$ respectively. The distribution function of the variable is:

$$\bar{F}[x(i)] = \frac{n_i}{n} \; (i = 1,2, \dots, m)$$

Where n_i indicates the number of samples with value less or equal to $x(i)$ and $n_m = n$

Probability graph complies with the principle of quantile comparison method: assuming $0 < \mathrm{g} < 1$, the quantile $x_g = F^{-1}(g)$. Assume that $\mathrm{F}(x)$and $\mathrm{G}(y)$ are two probability distributions to be compared and analyzed, if the locus of (x_g, y_g) is not linear with the slope equals to 1, it would be inferred that the two probability distributions is different. If $\mathrm{F}(x)$ and $\mathrm{G}(y)$ are the same distribution function, then the locus of (x_g, y_g) tend to appear as a linear shape with slope equals to 1.

(2) Generating probability through Anylogic software

The above three methods are based on the assumption that there are existing standard probability distributions that are matched to represent characteristics of the distribution of the sample data. However, in real practice there are maybe no suitable standard distribution to depict the characteristics of the distribution of sample data as shown in the Figure 6.5. For this case, Anylogic software offers an excellent function that can be used to generate a new distribution to match with irregular distribution of the sample data.

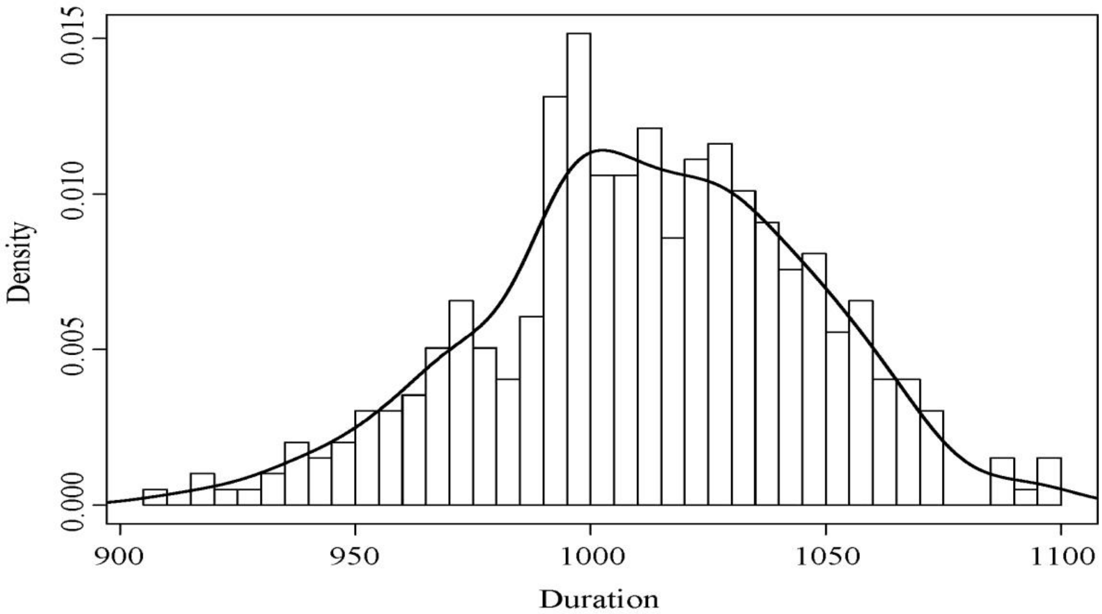


Figure 6.5 The histogram of h(x)

Firstly, the sample data $x_1, x_2, \ldots, x_n$ will be rearranged in descending order and divided into k equal intervals $[b_0, b_1), [b_1, b_2), \ldots, [b_{k-1}, b_k)$. Then, the numbers of sample data located in each of the interval are recorded and the table function that are used to depict the probability distribution of sample data is drew as shown in the Figure

6.6. Finally, the uncertain variable will be assigned value based on the probability distribution represented by the table function.

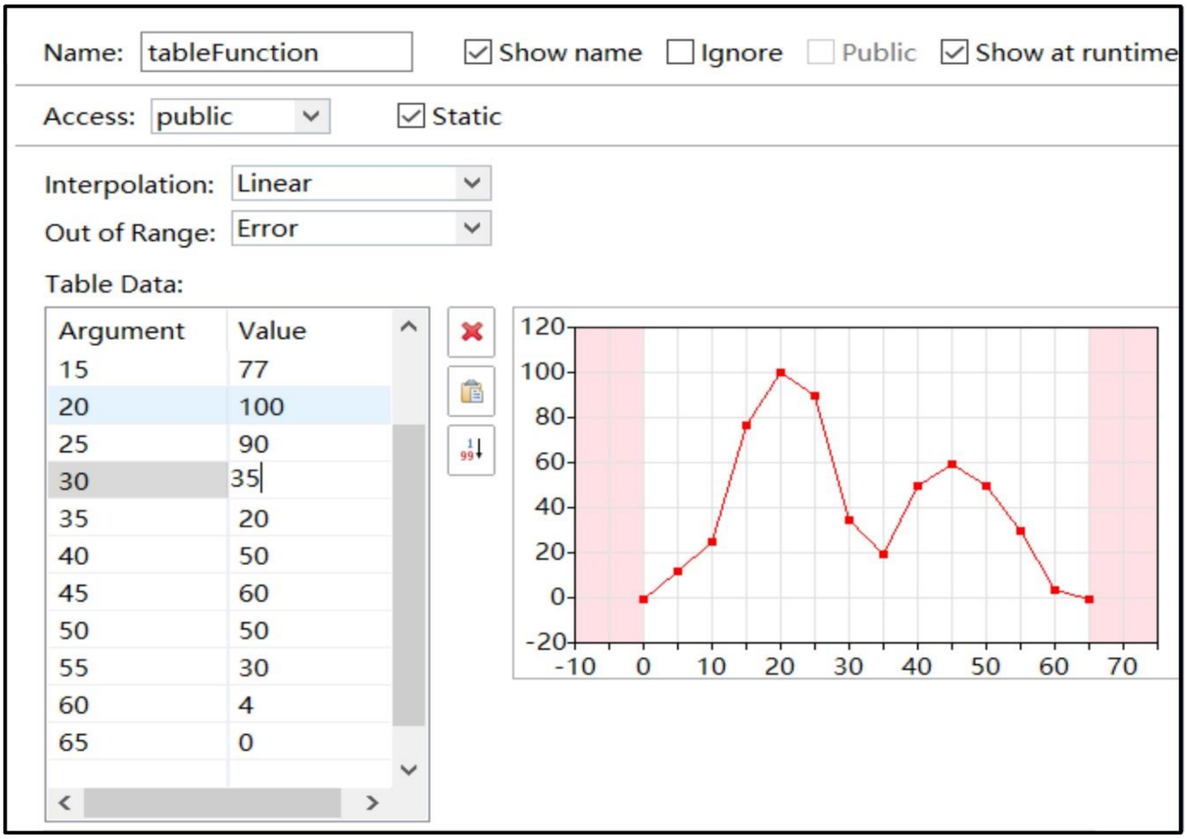


Figure 6.6 Table function that are used to depict the probability distribution

6.3.3.2 Program Code for Monte Carlo Simulation

Apart from the database built for storing inputs for the hybrid dynamic model, a database that specially devised for Monte Carlo simulation for all uncertain variables is developed. Based on risk probability distribution determined according to the method discussed above, the required data for depicting the characteristics of probability distribution of each uncertain variable is recorded into the database. In process of simulation, Anylogic software will automatically assign a value to the uncertain variable based on the probability distribution of the variable in each simulation run. For example, if the hybrid dynamic model is going to simulate 1000 times, value will be automatically assigned to each uncertain variable based on their specific probability distribution from database in each simulation. Along the increased times of simulation, the output of analysis will become more convincing from statistic point of view. Take the uncertain variable installation error rate for instance, there is a chance that precast component will be wrongly installed and the probability of inappropriate installation complies with binomial distribution. When the value of 1 is assigned to the uncertain variable, it indicates that the specific precast element is inappropriately installed and if assigning 0 to the variable, it means that the event of inappropriate installation does not happen. The allocation of value of 1 and 0 complies with binomial distribution. After the simulation, generated simulation results will be generated and stored into another database. The typical example of program coding of Monte Carlo simulation and storing simulation results into database can be shown in the Appendix.

6.4 Model Verification and Validation

Prior to further analysis, testing the verification and validation of the hybrid dynamic model, which contains model structure test and model behavior test, is crucial to build confidence into the model. Model structure test includes direct structure test and indirect structure test are conducted to verify whether this research build the model right, while model behavior test is conducted to validate whether this research build the right model. Model structure test includes direct structure test and indirect structure test (Barlas 1996; Barlas and Kanar 2000). Direct structure test, including dimensional consistency test, boundary adequacy test, parameter confirmation test, and structure confirmation test, checks model rationality by comparing the structure of developed model with real system structure from a qualitative point of view to help calibrate the model to fit real world situations (Barlas 1996; Lee and Peña-Mora 2007). The indirect test takes the advantages of both direct structure test and quantitative test, aiming to validate the model structure indirectly by conducting various behavior tests on model behavior patterns. Indirect test includes extreme-condition test, behavior sensitivity test, and integral error test (Barlas 1996). In general, major tests that are conducted in this research for building conference into the hybrid dynamic model include: (1) structure confirmation test, wherein the model structure should be in line with relative descriptive cognition from qualitative perspective; (2) parameter confirmation test, wherein all parameters incorporated in the model should have specific meaning in the actual project; (3) boundary adequacy test, wherein the model should contain all important variables required meet the research objective; (4) dimensional consistency test, to ensure the model have no illogical parameters; (5) extreme-condition test, to ensure the model to be reasonable even under extreme conditions; (6) behavior sensitivity test, wherein all sensitive parameters should have high accuracy; (7) integral error test, wherein the model outcomes should slightly change with different integrals; and (8) model behavior test, to ensure simulation outcomes of the model be in line with the actual project. Please kindly noted that given limited length, the research only shows the typical test examples of six-day cycle for model verification and validation.

6.4.1 Model Structure Test

(1) Direct Structure Test

Test 1 - structure confirmation test is conducted to check whether all cause-and-effect chains and feedback loops involved in the model are in line with the actual project experience. The causal-loop diagram in this research is based on existing literature (Wang 2011b; Ford and Sterman 1998; Lee et al. 2005) that summarize abundant knowledge regarding to prefabrication housing production on a practical basis. In addition, an on-site survey toward a practical PHP project had been conducted before model construction to ensure all cause-and-effect chains and feedback loops in line with both recognized knowledge and actual project experience.

Test 2 - parameter confirmation test is taken to verify the constant parameters in line with knowledge of the real PHP system in terms of conceptual confirmation and numerical confirmation (Forrester and Senge 1980). Conceptual confirmation requires the parameters of the model are in line with corresponding elements of actual project experience. Numerical confirmation requires the parameters of the model to have enough accuracy with clear data sources. In this study, all the parameters have their counterpart in the real system, and are attained from literature review, government reports, information from the internet, and a practical project with semi structure interviews. Thus, the model meets the requirement of parameter-confirmation test.

Test 3 - boundary adequacy test requires that all important variables incorporated in the model should be consistent with initial research objectives. It is validated by checking whether all related critical variables that used to build toward meeting the model purpose have been embodied in the causal-loop diagram (Yuan and Wang 2014). Through multi-round meetings toward site managers and professionals in this research field, all variables incorporated in the stock-flow diagram are verified to be closely related to the purpose of the model development. Test 4 - dimensional consistency test is performed through "units check" by manual inspection (Yuan and Wang 2014; Barlas 1996) and all variables of the hybrid dynamic model have passed the test.

(2) Indirect Structure Test

In test 5 - extreme-condition test, the model behaviour is inspected under extreme conditions (Barlas 1996). Design change and quality problem are widely acknowledged to have a strong effect on schedule of PHP (Wang 2011b). To set the extreme condition, 100% design change and 100% quality problem are set in the model. In other words, the risk is supposed to occur with the probability of 100% and have the largest influence on the schedule of PHP. Besides, a project with general risk situation is also taken as another extreme condition. Through simulation, the corresponding durations of the six-day cycle installation are 4200, 4280, and 4080 mins under the three extreme scenarios as shown in the Figure 6.9, while the durations of precast structure works are 750, 780 and 509 days as shown in the Figure 6.10, generally complying with practical experience according to the interview.

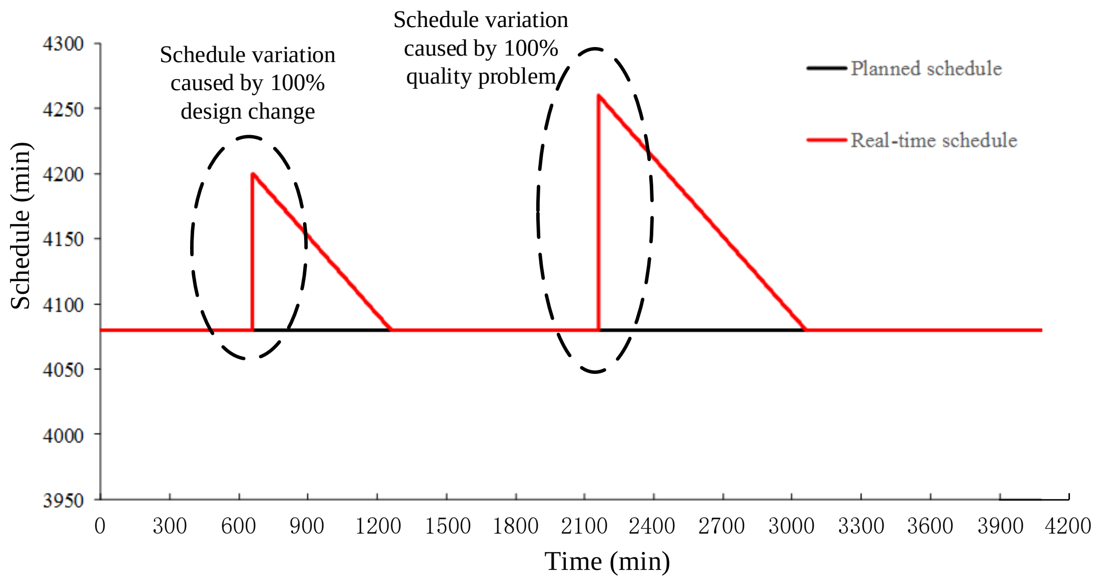


Figure 6.7 Extreme-condition test of six-day-cycle

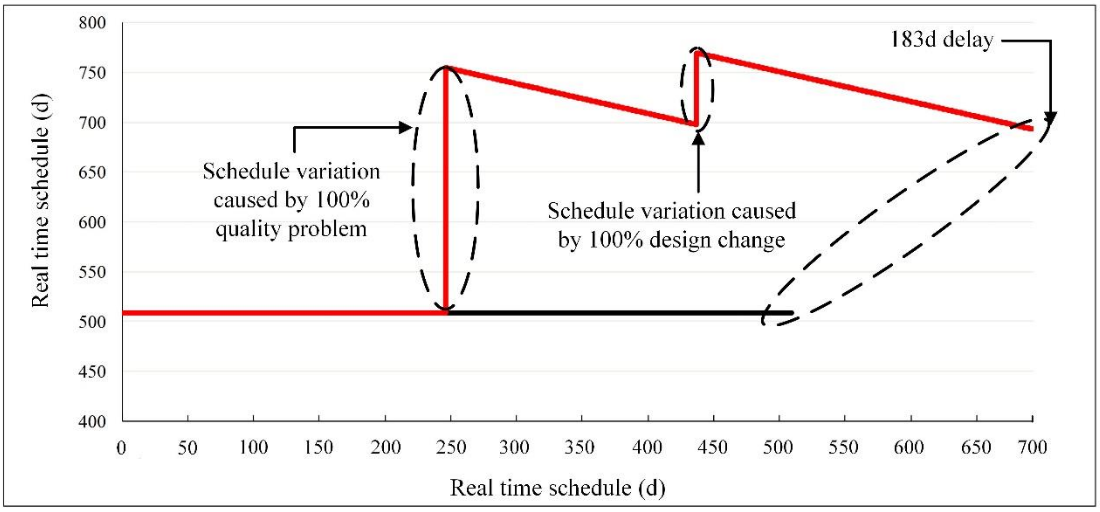


Figure 6.8 Extreme-condition test of precast structure works

Test 6 - behaviour sensitivity test is performed by observing the change in model behaviour by changing variables within reasonable range to determine which variables are sensitive and which are not. A sensitive variable is the focus for model correction given that its change would have significant effect on the schedule. In contrast, an insensitive variable does not require high accuracy because of only minor change in schedule caused by its change (Wang 2011b). Considering that demonstrating all variables in test 6 is not practical because of limited space, the variables "defect rate," "installation error rate," "design change prior to commencement," "scale change rate," "Delay due to reinstallation," and "Delay due to reproduction" are taken herein as examples for illustration. The five variables are assigned with three possible values, namely, the minimum value, value most likely to occur, and the maximum value, to test their potential effect on the schedule of PHP. The minimum value stands for the most optimistic value, while the maximum indicates the most pessimistic value. Take the defect rate as an example, the most optimistic scenario is that no defect exists; thus, the defect rate has the minimum value of 0. In contrast, the most pessimistic scenario is that the number of defects is the highest, in effect the defect rate has the maximum value of 0.1.

After simulation, three kinds of indicators are attained, namely, duration, variety degree, and range of variation, as shown in the Table 6.3 and Table 6.4. Variety degree involves two values, one is variety range of the minimum duration with respect to the most likely duration (the minimum value minus the most likely value and divide the most likely value); the other is the variety range of the maximum duration with respect to the most likely duration (the maximum value minus the most likely value and divide the most likely value). The sum of their absolute values is the range of variable. Twenty percent is set as the boundary (if the range of variation of a parameter exceeds 20%, it means that the parameter is a sensitive variable; otherwise, the parameter is an insensitive variable) (Wang 2011b) and the scale change rate, is found to be a sensitive variable. Based on the above process, all sensitive variables, including scale change rate and delay due to reproduction, delay due to reinstallation, are found and assigned with relatively accurate values.

Table 6.3 Result of sensitive test of six-day-cycle

Parameter	Duration (min) (min/most/max)	Variety degree (min/max)	Range of variety
Design change prior to commencement	4182.8/4362.7/4899	-4.30%/12.30%	16.60%
Scale change rate	4182.8/4486.1/5109.2	-7.25%/13.89%	21.14%
Delay due to reproduction	4182.8/9174.8/27894.8	-54.40%/204.04%	258.44%

Delay due to reinstallation	4182.8/10422.8/27823.7	-59.90%/166.95%	226.85%
Defect rate	4182.8/4182.8/4530	0.00%/8.30%	8.30%
Installation error rate	4182.8/4335.1/4625.5	-3.64%/6.70%	10.34%

Table 6.4 Result of sensitive test of precast structure works

Parameter	Duration (d) (min/most/max)	Variety degree (min/max)	Range of variety
Design change prior to commencement	509.18/517.36/544.00	-1.58%/5.15%	6.73%
Scale change rate	509.18/525.09/557.18	-3.03%/6.12%	9.15%
Delay due to reproduction	509.18/553.73/702.09	-8.05%/26.78%	34.83%
Delay due to reinstallation	509.18/568.36/737.18	-10.42%/29.70%	40.11%
Defect rate	509.18/509.18/524.26	0.00%/3.03%	3.00%
Installation error rate	509.18/517.27/529.64	-1.56%/2.40%	3.96%

In test 7 integral error test, the original integration step of the model is set at 1 day/per time. Through the change in the integration step to 0.5, 0.25, 0.125, and 0.0625 day/time, the corresponding model behaviors with duration of PHP in this research are 509.25, 509.25, 510.61, and 510.93 days, indicating that the model is in line with the requirement of the integral error test (Sterman 2000).

6.4.2 Model Behavior Test

Historical data comparison analysis was adopted for behavioural validity. The common practice is to check whether the simulation results of certain typical quantitative variables within the model agree with the corresponding historical data. This verification is performed by comparing the error percentage between the historical data and simulation results (Li et al. 2014b). Historical data comparison analysis is adopted for model behaviour test for both six-day cycle and precast structure works as shown in the Table 6.5 and Table 6.6. Planned schedule is chosen as bench mark indicators and the model simulated variable value is compared to its historical data of planned schedule. The planned schedule is the general situation of schedule performance of a PHP project. The model behaviour should comply with general situation before adding critical schedule risks for further analysis. The planned schedule will be adopted for comparison with the simulation results based on the tolerance analysis for verifying the credibility of the established model. The matching effect of the model will be considered as preferable if the variable, whose relative error is less than 5%, accounts for 70% or more of the total tested variables, and the average relative error of each variable is less than 10% (Maddala 1986). After the simulation, Table 6.5 and 6.6 show that the relative errors of all the tested variables of six-day cycle and precast structure works are lower than 10%, with an average error of 2.63% and 1.2% respectively. Moreover, to further validate the model, actual duration data of a PHP project is collected to compared with the simulation results by the hybrid dynamic model under the real project situation. That is, if the simulated results that already consider actual risk situation is in line with the actual duration, the model is effective. The actual duration of precast structure works of the studied project is 626 days, which reaches a delay of 117 days, while the simulated duration by the model is 645.74 days, with an error rate of 3.15%. All these above results demonstrate the satisfactory matching effect of the model and verify the established model could reflect the real-world situation. Thus, further simulation can be conducted to analyse the impact of related scenarios on the schedule performance of PHP.

Table 6.5 Model behavior test of six-day cycle assembly

No.	Tasks	Planned duration (min)	Model duration (min)	Error rate
1	Lifting Wall Steal AB	60	61.6	2.67%
2	Install Precast Stairs Bathroom Facade and Others AB	360	362.2	0.61%
3	Fixing Wall Steel B middle	180	183.0	1.67%
4	Install Slab Formwork C to B	180	183.0	1.67%
5	Dismantle Slab Formwork C to B and Install Slab Support	90	93.8	4.22%
6	Install Working Platform C and Install Slab Support	90	93.8	4.22%
7	Install Precast Slab and Lift Dry Wall C	90	93.8	4.22%
8	Fixing Wall Steel A middle	420	422.2	0.52%
9	Lifting Wall Steal BC	60	64.4	7.33%
10	Install Slab Formwork D to A and Dismantle Slab Formwork D to A and Install Slab Support	120	123.4	2.83%
11	Install Working Platform D and Install Slab Support	120	123.4	2.83%
12	Install Precast Slab and Lift Dry Wall D	150	153.2	2.13%
13	Lifting Wall Steal D	60	64.4	7.33%

No.	Tasks	Planned duration (min)	Model duration (min)	Error rate
14	Lifting Lintel Bean Bar A	60	64.4	7.33%
15	Inspection of Steel Formwork and Lintel Steel Bar B	60	63.8	6.33%
16	Fixing Wall Steel D Middle1	60	64.4	7.33%
17	Fixing Lintel Bean Bar A	60	62.8	4.67%
18	Wall Concreting B1	60	60.2	0.33%
19	Inspection of Steel Formwork and Lintel Steel Bar A	60	61.6	2.67%
20	Fixing Wall Steel C Middle	600	601.8	0.30%
21	Wall Concreting A	300	304.1	1.38%
22	Fixing Slab Steel C Middle	360	362.2	0.61%
23	Slab Concreting C	90	93.8	4.22%
24	Fixing Slab Steel D Middle	150	153.2	2.13%
25	Slab Concreting D	210	212.8	1.33%
26	Lifting Wall Steal CD	60	60.3	0.50%
27	Install Precast Stairs Bathroom Façade and Others CD	60	61.2	2.00%
28	Install Slab Formwork B to C	180	183.0	1.67%
29	Dismantle Slab Formwork B to C and Install Slab Support	90	93.8	4.22%
30	Install Working Platform Band Install Slab Support	90	93.8	4.22%
31	Install Precast Slab and Lift Dry Wall B	90	93.8	4.22%
32	Wall Concreting B2	300	302.4	0.80%
33	Fixing Wall Steel C	180	183.0	1.67%

No.	Tasks	Planned duration (min)	Model duration (min)	Error rate
34	Lift Wall Steal B Middle	60	60.4	0.67%
35	Dismantle Slab Formwork A to D and Dismantle Slab Formwork A to D and Install Slab Support	120	123.4	2.83%
36	Install Working Platform A and Install Slab Support	120	123.4	2.83%
37	Install Precast Slab and Lift Dry Wall A	150	153.2	2.13%
38	Lift Wall Steal A	60	60.4	0.67%
39	Lift Lintel Bean Bar D	60	61.2	2.00%
40	Fixing Slab Steel A Middle1	150	153.2	2.13%
41	Fixing Lintel Bean Bar D	60	60.4	0.67%
42	Check Wall Formwork and Lintel Bean Bar D	60	60.4	0.67%
43	Fixing Slab Steel B Middle2	360	362.2	0.61%
44	Fixing Lintel Bean Bar C	120	123.5	2.94%
45	Fixing Slab Steel B Middle	360	364.3	1.18%
46	Slab Concreting B	90	93.8	4.22%
47	Fixing Slab Steel A Middle 2	150	153.2	2.13%
48	Slab Concreting A	210	212.8	1.33%
49	Wall Concreting D	300	302.4	0.80%

Table 6.6 Model behavior test of precast structure works

No.	Task	Planned duration (d)	Model duration (d)	Error rate

1	Ground Floor and Transfer Structure	246	246.00	0.00%
2	Six-day Cycle11	6	6.01	0.09%
3	Six-day Cycle12	6	6.01	0.18%
4	Six-day Cycle13	6	6.02	0.35%
5	Six-day Cycle14	6	6.06	0.95%
6	Six-day Cycle15	6	6.07	1.12%
7	Six-day Cycle16	6	6.03	0.52%
8	Crane Lift 1	1	1.01	1.09%
9	Six-day Cycle21	6	6.05	0.83%
10	Six-day Cycle22	6	6.02	0.36%
11	Six-day Cycle23	6	6.03	0.50%
12	Six-day Cycle24	6	6.06	0.98%
13	Six-day Cycle25	6	6.06	0.97%
14	Crane Lift 2	1	1.07	6.91%
15	Six-day Cycle31	6	6.13	2.17%
16	Six-day Cycle32	6	6.09	1.48%
17	Six-day Cycle33	6	6.10	1.70%
18	Six-day Cycle34	6	6.08	1.41%
19	Six-day Cycle35	6	6.04	0.67%
20	Crane Lift 3	1	1.02	2.09%
21	Six-day Cycle41	6	6.19	3.20%
22	Six-day Cycle42	6	6.10	1.70%
23	Six-day Cycle43	6	6.04	0.68%

24	Six-day Cycle44	6	6.09	1.48%
25	Six-day Cycle45	6	6.02	0.32%
26	Crane Lift 4	1	1.01	1.27%
27	Six-day Cycle51	6	6.02	0.36%
28	Six-day Cycle52	6	6.04	0.68%
29	Six-day Cycle53	6	6.02	0.39%
30	Six-day Cycle54	6	6.08	1.29%
31	Six-day Cycle55	6	6.04	0.65%
32	Crane Lift 5	1	1.05	4.91%
33	Six-day Cycle61	6	6.07	1.17%
34	Six-day Cycle62	6	6.01	0.11%
35	Six-day Cycle63	6	6.03	0.52%
36	Six-day Cycle64	6	6.07	1.14%
37	Six-day Cycle65	6	6.07	1.12%
38	Roof Works	72	72.26	0.36%

6.5 Chapter Summary

This chapter illustrates how to quantify collected data for variables in the hybrid dynamic model for further application. Three kinds of variables, namely deterministic variable, dependent variable, and uncertain variable, are quantified with different methods. Prior to further analyses, confidence is built up in the model through a serial of verification and validation tests, including model structure tests and model behavior tests.

CHAPTER 7 Scenario Analysis of the Effect of Schedule Risks

7.1 Introduction

The previous chapter presents the verification and validation of the developed hybrid dynamic model. The devised strict structure and behavior tests have built up full confidence into the hybrid dynamic model. The following section explains how and to what extend the hybrid dynamic model can function as an experiment platform to analyze, assess and simulate the impacts of different schedule risks on the schedule performance of PHP project. Simulation results that considerate mixtures of various risk scenarios under different timeline of the PHP project will be summarized and presented. These provide insights into how the schedule of the same PHP project will vary when different schedule risks occur under different timeline. A range of risk scenarios are devised on the basis of practice project experience and previous related literature, while analyses are conducted toward the simulation results of these scenarios. Comparison analysis will be conducted between simulation results of each devised scenario, and especially comparing each devised scenario with the baseline scenario. Recommendations for improving the schedule performance of the studied project are proposed.

7.2 General Analysis Results of Baseline Scenario

7.2.1 Dynamic Analysis of Schedule Risks

Based on the social network analysis in the Chapter 2, 12 critical schedule risks that significantly influence the schedule of PHP are identified as follows: inefficiency of design approval (IDA), design change (DC), inefficient design data transition (IDDT), logistics information inconsistency because of human errors (LIIBHE), low information interoperability between different enterprise resource planning systems (LIIBDERPS), design information gap between designer and manufacturer (DIGBDM), delay of the delivery of precast element to site (DDPES), misplacement on the storage site because of carelessness (MSSBC), tower crane breakdown and maintenance (TCBM), inefficient verification of precast components because of ambiguous labels (IVPCBAL), and slow quality inspection procedures (SQIP). The critical schedule risks are incorporated into the hybrid dynamic model for further in-depth evaluation and analysis. After 200 simulations, a bundle of curves of density function of all schedule risks under the whole timeline can be attained. Those curves of density function are similar to a normal distribution but not statistically normal distribution according to curve fittings and statistical analysis. For this kind of curve, a median can be used to reflect the average duration under all risks (Lu et al. 2015). In this research, R software is used to analyze simulated data and draw the various curves to depict schedule performance under different schedule risks.

One of the major indicators to measure schedule performance via simulation is the real-time simulated schedule. The schedule reflects the simulated schedule based on possible schedule risks that occur along the entire process of a six-day-cycle assembly and precast structure works. The larger value of real-time planned schedule indicates greater effect on the schedule of the assembly that is imposed by such specific schedule risks. Via real-time simulation by the hybrid dynamic model, the dynamic schedule performance of a six-day-cycle assembly and precast structure works can be shown as Figure 7.1 and 7.2. The horizontal axis refers to "time," while vertical axis denotes "real-time simulated schedule." Curve 1 refers to originally planned schedule. In six-day cycle, four days are scheduled for 12 working hours per day, whereas another two days are scheduled for 11 working hours per day, such that the original schedule for a six-day-cycle assembly is 4200 mins, while the original schedule of precast structure works is 509 days. If the real-time simulated schedule overlaps with the originally planned schedule, no risks generally occur during the simulation process of the assembly. Once schedule risks occur on a special point of the timeline, the value of the real-time simulated schedule would increase and rise above the originally planned schedule, thereby indicating that the hybrid dynamic model predicts schedule delay to occur for the assembly. Along with the movement of time, the real-time simulated schedule will decline to some extent because of the efforts of expediting work and will eventually fall upon Curve 2 at the simulation end. To gain robust statistical data, the hybrid dynamic model will be run hundreds or even thousands of times. Furthermore, the generated simulation results will form thousands of curves. Figure 7.1 and 7.2 can also indicate the schedule risk that has the most significant effect on the studied schedule performance. The endpoint of each curve constitutes Curve 2, named as the node set of the simulation end. The Curve 2 is linear equation with slope of 1, with horizontal axis referring to the real-time simulated schedule, thereby indicating the end of the simulation of the assembly. The point with no schedule delay of (4200, 4200) of six-day cycle and (509,509) of precast structure works indicate that the assembly is exactly in line with the originally planned schedule. In addition to this point, all other points indicate to some extent that simulation is postponed. Via evaluation and simulation that is offered by the hybrid dynamic model, the characteristics and the influence of schedule risks can be understood from the following three perspectives: (1) the effect of various risks on the schedule performance at the same point of the timeline; (2) the effect of various risks on the schedule performance under different points of the timeline; (3) the combined effect of various risks on the schedule performance under different points of the timeline. The schedule risks can be evaluated and simulated via the hybrid dynamic model, such that the insight of uncertain nature of schedule risks can be attained from different angles. Furthermore, the simulation results can be used by the decision makers with different risk attitudes to propose corresponding risk treatment strategies to prevent schedule delay.

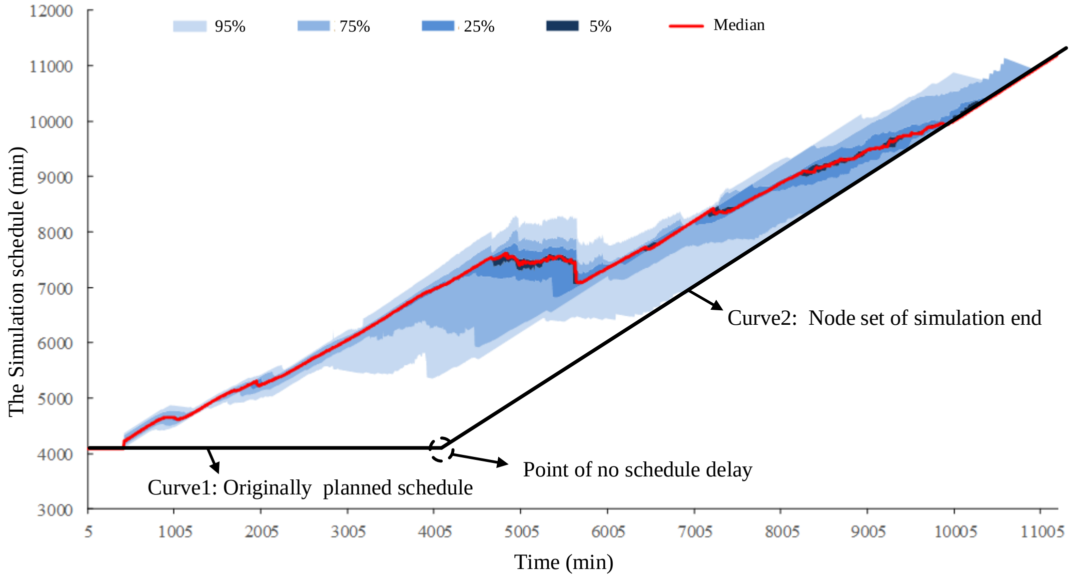


Figure 7.1 Dynamic analysis of schedule performance of six-day cycle

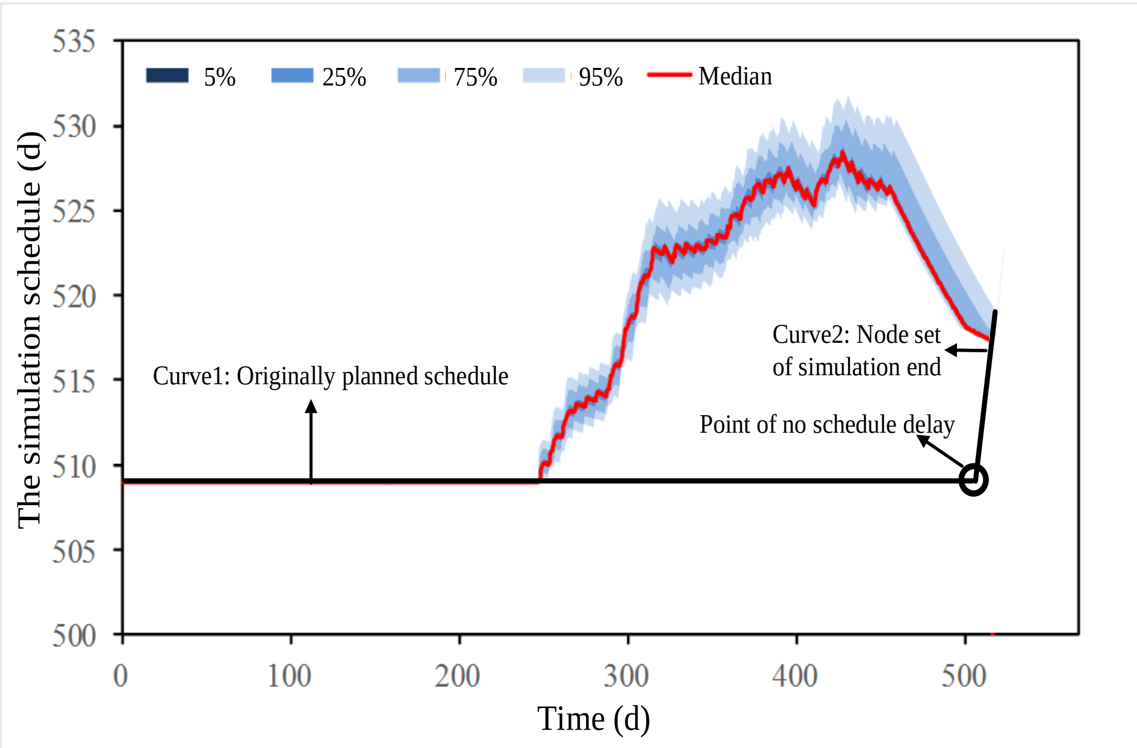


Figure 7.2 Dynamic analysis of schedule performance of precast structure works

Statistical analysis toward probability distribution of real-time simulated schedule on a point-by-point basis can also be conducted to gain in-depth understanding on how schedule risks affect the schedule performance of six-day-cycle assembly and precast structure works across the entire timeline from a dynamic perspective. Via the analysis of probabilistic statistics of the simulated results that are shown on the curves, insights on the distribution of real-time planned schedules at each point of the timeline can be attained under various schedule risks. An example is the point of the 500th minute as shown in Figure 7.3. By analyzing 200 simulation results generated at the point of the 500th minute, the probability distribution of the schedule can be drawn as shown in the figure. There is 95% probability for the real-time simulated schedule ending between 6190 and 9070 mins if predicting from the time point of the 500th minute based on the risk situation. The maximum and minimum schedule values are 9434 and 5943 mins, respectively, whereas others scatter at the range between 5943 and 9434 mins. Another example is the point of the 300th day as shown in Figure 7.4. The real-time simulated schedule has 95% probability of ending between 519.17 and 525.03 days if predicting from the time point of the 300th day based on the risk situation. The maximum and minimum schedule values are 527.92 and 519.10 days, respectively, whereas others scatter at the range between 519.10 and 527.92 days. Based on the statistical analysis of real-time simulated schedule, project managers can rearrange the construction plan from any point in time such that the entire management can be dynamically implemented.

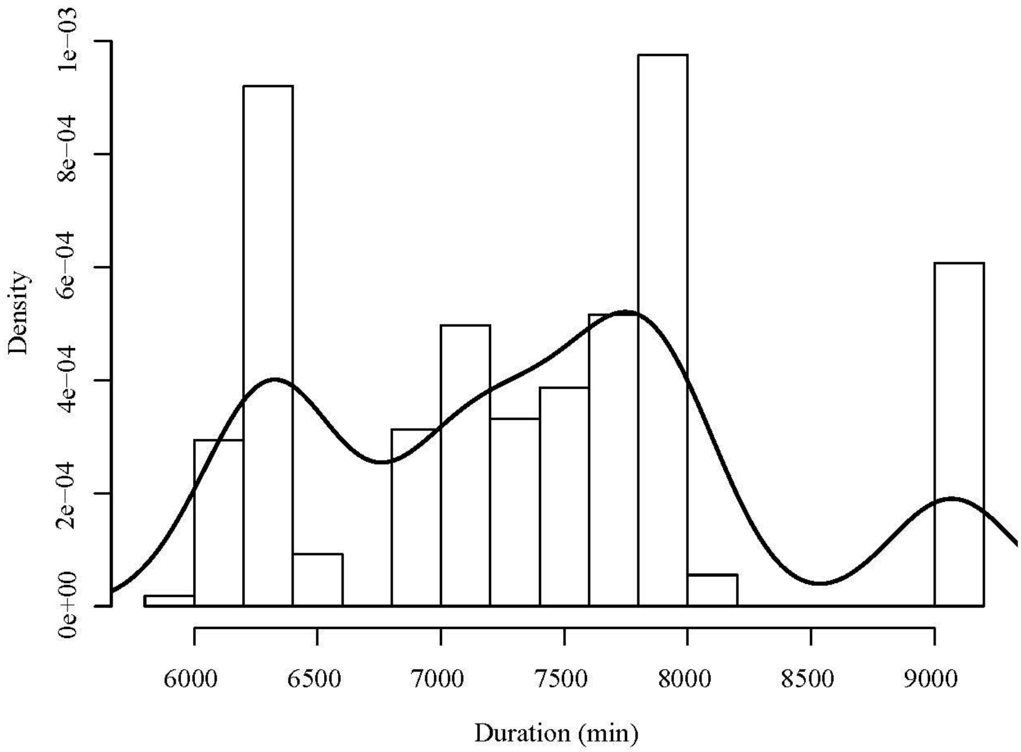


Figure 7.3 Typical example of histogram of the probability distribution at a specific point of the timeline of six-day cycle

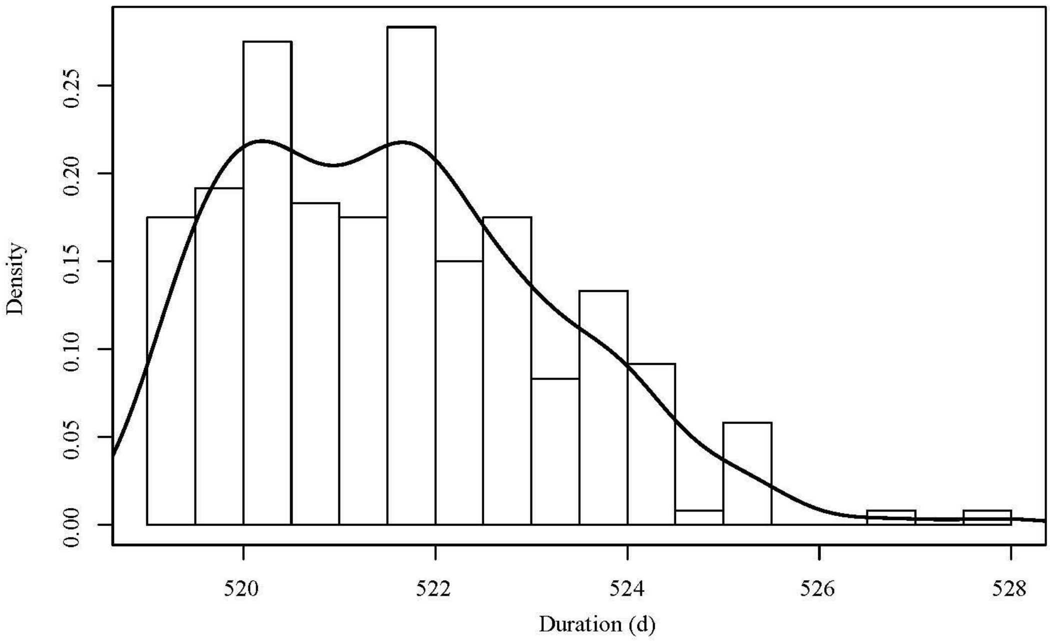


Figure 7.4 Typical example of histogram of the probability distribution at a specific point of the timeline of precast structure works

7.2.2 Criteria of Assessment of Schedule Risks

Further analysis can be conducted to quantify the effect of risks on the schedule performance of six-day-cycle assembly and precast structure works via a box diagram. As shown in Figure 7.5 and Figure 7.6, the horizontal axis indicates the occurrence time of schedule risks, and the vertical axis represents the real-time simulated schedule from the angle of the end of the simulation. Box plot diagrams are used to describe the characteristics of schedule risks. Generally, the length of the boxes indicates the degree of variation of the schedule performance with the following implication: the larger the box is, the more significant influence the risks have on the schedule performance. Based on the simulation results that are generated by the hybrid dynamic model, three types of information indicated by the box plot diagram can be acquired as follows: (1) the bottom and top of the box are the lower quartile and upper quartile values, respectively, and the band inside the box represents the median value. The ends of the whiskers respectively indicate the upper and lower hinges, with 95% simulation values included within the rang while the scattered values indicate outliers of the specific simulation. (2) The degree of effect of the same risk that occur at different times; for example, DDPES1 that occurs at the 100th minute of the simulation has a different degree of influence on the schedule performance compared with the situation in which DDPES2 occurs at the later stage of the simulation at the 3500th minute, and MSSBC1 that occurs at the middle stage of the simulation of precast structure works has a different degree of influence on the schedule performance compared with the situation in which MSSBC2 occurs at the later stage of the simulation of precast structure works at the later stage, as shown in the Figure 7.6. To be measured by the median value, DDPES1<DDPES2 and MSSBC1 > MSSBC2 under different point and stage of the timeline. (3) The comparison of the influence degree between any two schedule risks under the same or different points of the simulation timeline. In any two schedule risks, such as IVPCBAL2 and IEPE, their central points of the two boxes can constitute a right triangle. The length of horizontal distance indicates the difference of the occurrence time of the two risks, whereas the length of the vertical distance represents the difference of the median real-time simulated schedule. As shown in Figure 7.5, the triangle indicates that IVPCBAL2 occurs 200 mins earlier than does IEPE, and the schedule delay caused by IVPCBAL2 is 789 minutes more than the schedule delay caused by IEPE.

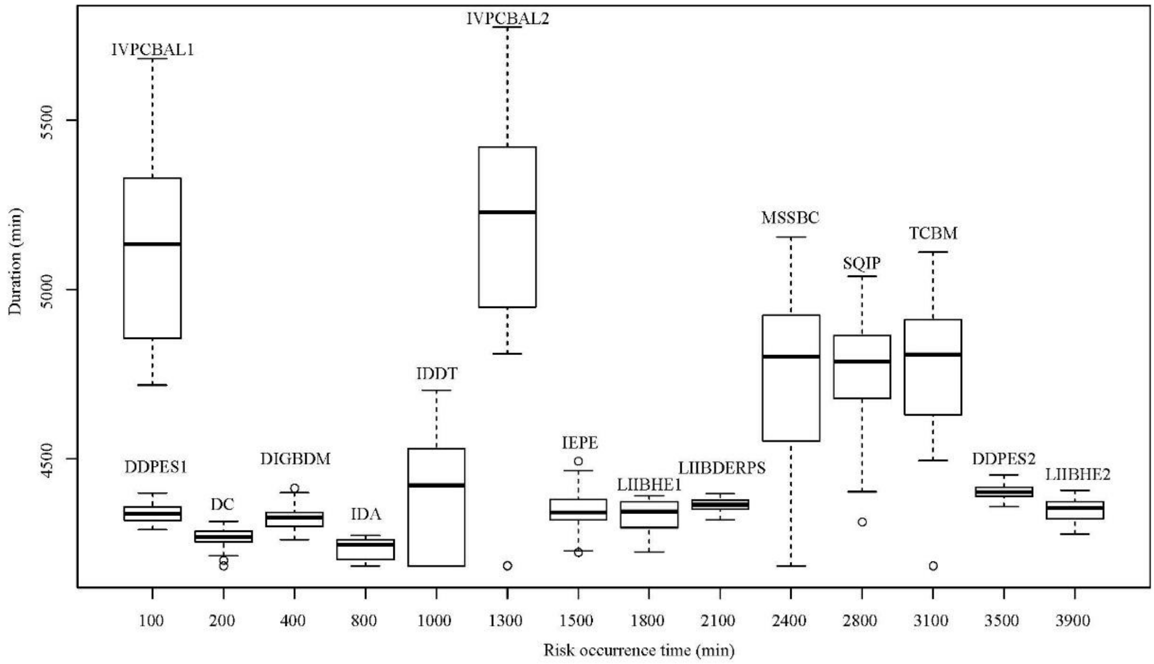


Figure 7.5 Box plot diagrams of schedule risks of six-day cycle

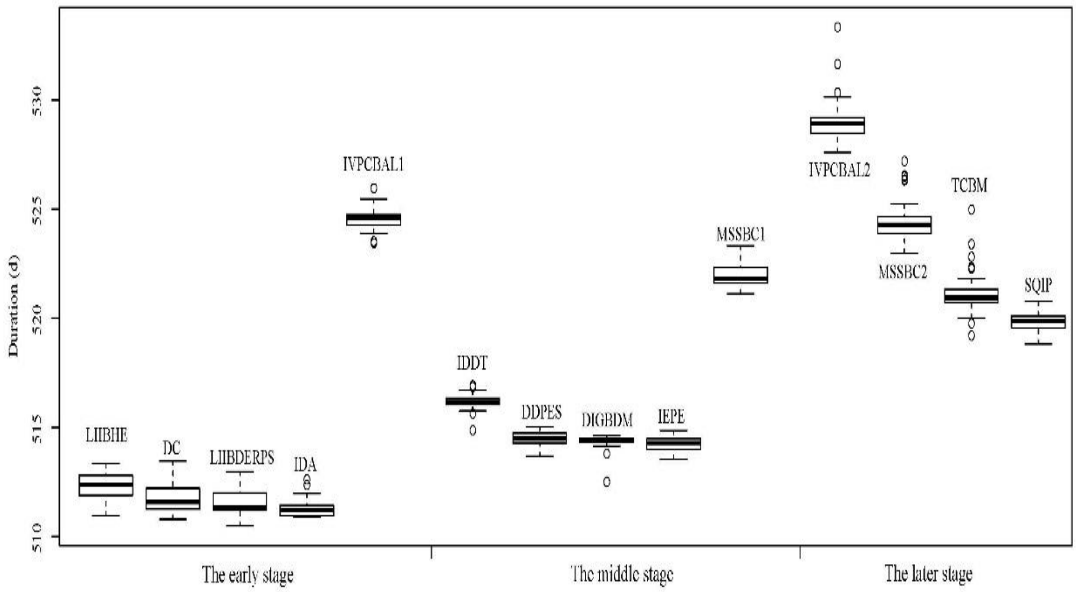


Figure 7.6 Box plot diagrams of schedule risks of precast structure works

7.3 Analysis on Single-Risk Scenarios

7.3.1 Influence on Schedule under Different Single risk

In order to determine which risk contributes most to the schedule delay of the six-day-cycle assembly under the same point of the simulation timeline, each schedule risk will be separately placed in the hybrid dynamic model for simulation. After 200 simulations, a bundle of curves of density function of all schedule risks under the entire timeline can be attained. Those curves of density function are similar to a normal distribution but not statistically the normal distribution, based on curve fittings and statistical analysis. The results are divided into different parts following their influence degree for better analysis, as shown in Figure 7.7. Figure 7.7a shows the curves of density functions of the duration under the first eight schedule risks that have relatively less influence on the schedule, whereas Figure 7.7b shows the other four risks that have more significant effects on the schedule performance. Clearly, the risks SQIP, IVPCBAL, TCBM, and MSSBC have more significant effects on the schedule performance than do the other eight risks in terms of the median value of schedule performance.

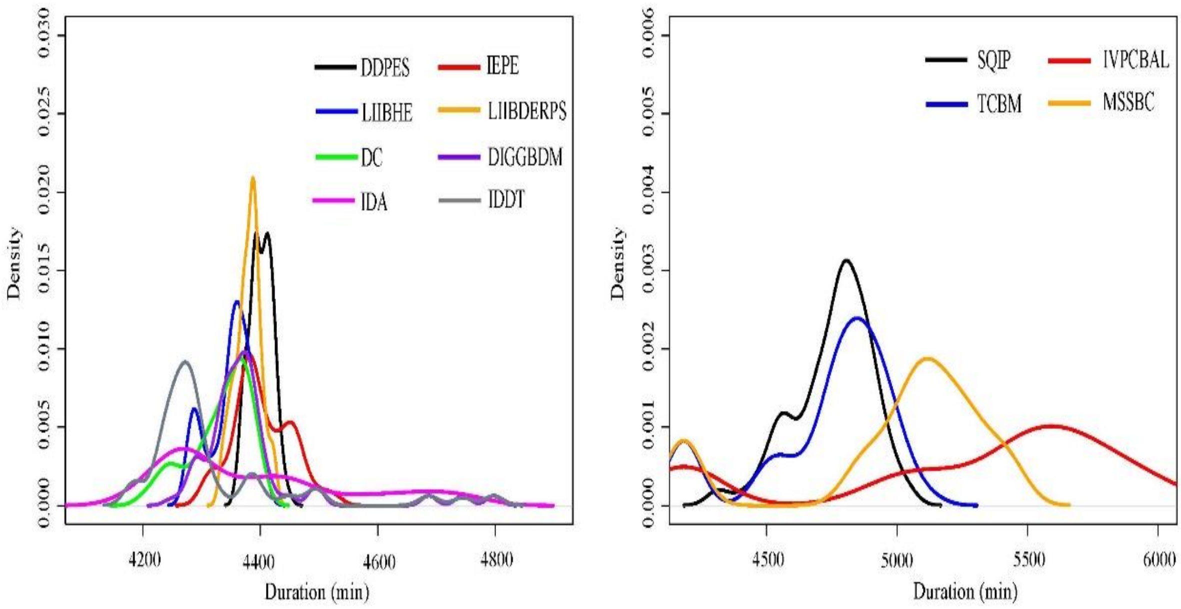


Figure 7.7 Curves of density function of the critical schedule risks of six-day cycle

Table 7.1 Statistical information of duration under different risks of six-day cycle

Schedule risk	**Mean (min)**	**Median (min)**	**Min (min)**	**Max (min)**	**Standard deviation**
IVPCBAL	5135.55	5227.4	4182.8	5775.0	399.26
MSSBC	4813.55	4816.4	4182.8	5090.6	188.06
TCBM	4522.51	4461.8	4182.8	4814.6	152.19
SQIP	4453.66	4424.6	4260.4	4795.0	125.73
IDDT	4406.85	4421.6	4182.8	4635.4	171.57

DDPES	4338.87	4337.4	4290.2	4399.0	27.14
DIGBDM	4324.52	4326.6	4261.2	4412.6	32.40
IEPE	4306.34	4299.0	4214.4	4458.2	44.82
LIIBHE	4302.54	4307.6	4207.6	4368.0	33.66
DC	4262.14	4269.0	4182.8	4315.2	36.51
LIIBDERPS	4250.22	4249.6	4184.0	4330.6	34.46
IDA	4233.52	4246.8	4182.8	4272.8	31.42

Table 7.1 shows the risk ranking in terms of mean, range, median, and standard deviations. In general, schedule risks that affect the schedule performance of a six-day-cycle assembly can be divided into three levels based on their effect on the schedule performance in terms of simulated mean schedule value. The first most influential level contains five schedule risks, namely, IVPCBAL, MSSBC, TCBM, SQIP, and IDDT that cause average schedule delays of more than 300 mins. The second most influential level includes DDPES, DIGBDM, IEPE, and LIIBHE; the average schedule delays that they caused are less than 300 mins and greater than 200 mins. DC, LIIBDERPS, and IDA belong to the third level and are modest risks that contribute the least to the schedule delay of the assembly. The modest risks caused less than 20 mins in their average schedule delays. From the simulation, the integrated effect of all 12 schedule risks on the schedule performance of the assembly is greater than the simple sum of the single separated risks.

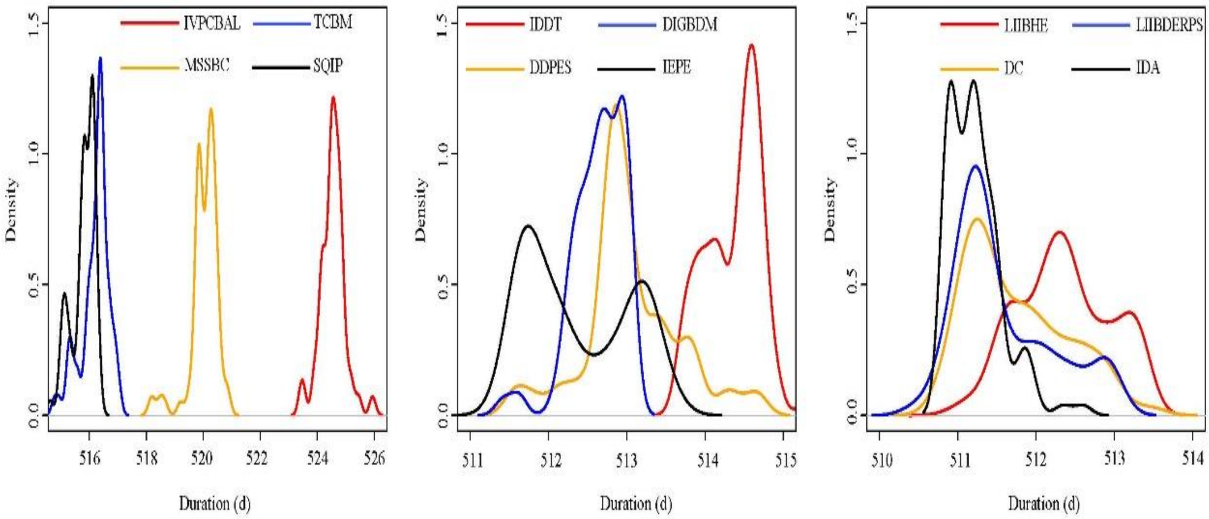


Figure 7.8 Curve of density functions of the critical schedule risks of precast structure works

Table 7.2 Statistical information of duration under different risks of precast structure works

Schedule risk	Mean (d)	Median (d)	Min (d)	Max (d)	Standard deviation
IVPCBAL	524.5419	524.5636	523.4364	525.9455	0.429317
MSSBC	520.0335	520.1636	518.1818	520.8727	0.485380
TCBM	516.2070	516.3455	514.7636	517.0545	0.486158
SQIP	515.7879	515.8545	514.6182	516.3455	0.401943
IDDT	514.3640	514.4545	513.6909	515.3091	0.351619
DDPES	513.04850	512.9091	511.5455	514.6545	0.621390
DIGBDM	512.6416	512.7273	511.4182	513.0364	0.330822
IEPE	512.3689	512.1636	511.4182	513.5818	0.664842
LIIBHE	512.3578	512.3636	510.9273	513.3273	0.583301
DC	511.7442	511.5818	510.7818	513.4545	0.636103
LIIBDERPS	511.5845	511.3273	510.4727	512.9636	0.633180
IDA	511.2255	511.2000	510.8727	512.6000	0.335730

Similarly, the results of precast structure works are divided into different parts following their influence degree for better analysis, as shown in Figure 7.8. Figure 7.8a shows the curves of density functions of the duration under the first four schedule risks that have relatively more influence on the schedule, whereas Figure 7.8b shows another four risks that have less significant effects on the schedule performance and Figure 7.8c shows the rest four risks that have least significance. Table 7.2 shows the risk ranking in terms of mean, range, median, and standard deviations. In general, schedule risks that affect the schedule performance of precast structure works can be divided into three levels based on their effect on the schedule performance in terms of simulated mean schedule value. The first most influential level contains four schedule risks, namely, IVPCBAL, MSSBC, TCBM, and SQIP that cause average schedule delays of more than 6.78 days. The second most influential level includes IDDT, DDPES, DIGBDM, IEPE, and LIIBHE; the average schedule delays that they caused are less than 6 days and greater than 3 days. DC, LIIBDERPS, and IDA belong to the third level and are modest risks that contribute the least to the schedule delay of precast structure works. The average schedule delays of modest risks are about 2 days.

7.3.2 Influence on Schedule under Different Timeline

The curves of density function of PHP duration for the twelve schedule risks occurring at different stages for both six-day cycle and precast structure works are created and shown in Figure 7.9- Figure 7.32. All the curves are similar to a normal distribution but are not statistically normal distributions. Based on the discussion above, using a median as benchmark duration to generally measure these risks is reasonable. Most of curves of density functions of duration have two or more curve peaks. Generally, when the probability distribution of a risk complies with triangular distribution and the "most possible delay" is closer to the "maximum delay", the additional small peaks are more likely to appear.

For DC in the six-day cycle simulation as shown in Figure 7.9, if DC occurs at the early stage, the rang of schedule ends at (4182.80, 4315.20), while at the middle and later stage, the schedule respectively ends at the range (4187.50, 4357.50) and (4192.20, 4399.80). The median schedule as a result of DC for early stage, middle stage and later stage are 4269.00, 4307.40 and 4345.80, while the maximum schedule for the three period are 4315.20, 4357.50 and 4399.80.

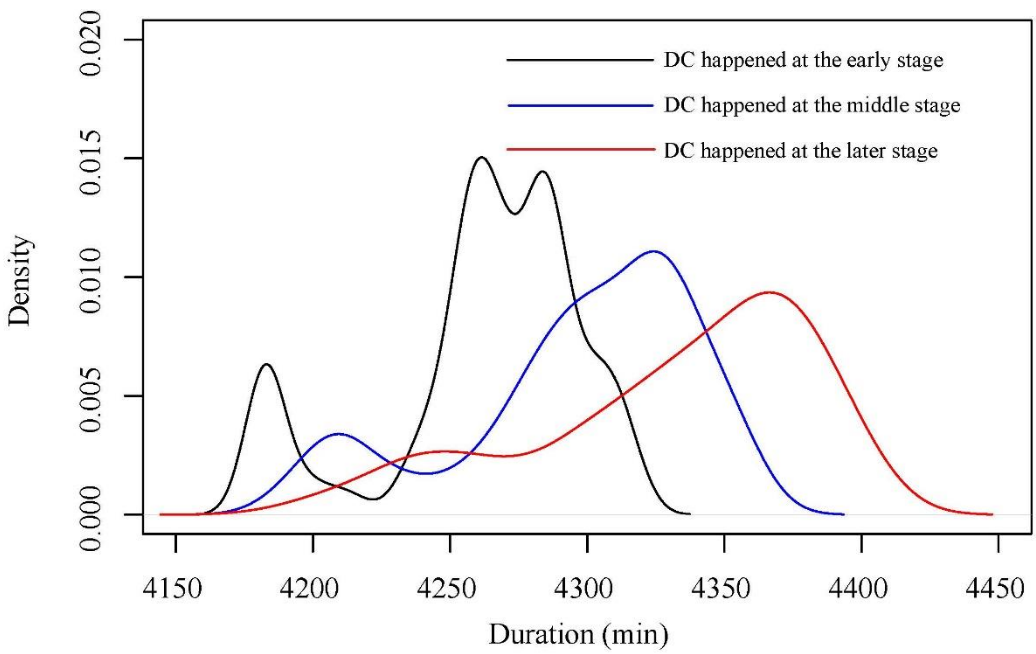


Figure 7.9 The curves of density function of DC at different stages of six-day cycle

For DC in the simulation of precast structure works as shown in Figure 7.10, if DC occurs at the early stage, the rang of schedule ends at (510.78,513.45), while at the middle and later stage, the schedule respectively ends at the range (512.47, 513.84) and (514.91, 517.71). The median schedule as a result of DC for early stage, middle stage and later stage are 511.58, 513.4 and 516, while the maximum schedule for the three period are 513.45, 513.84 and 517.71.

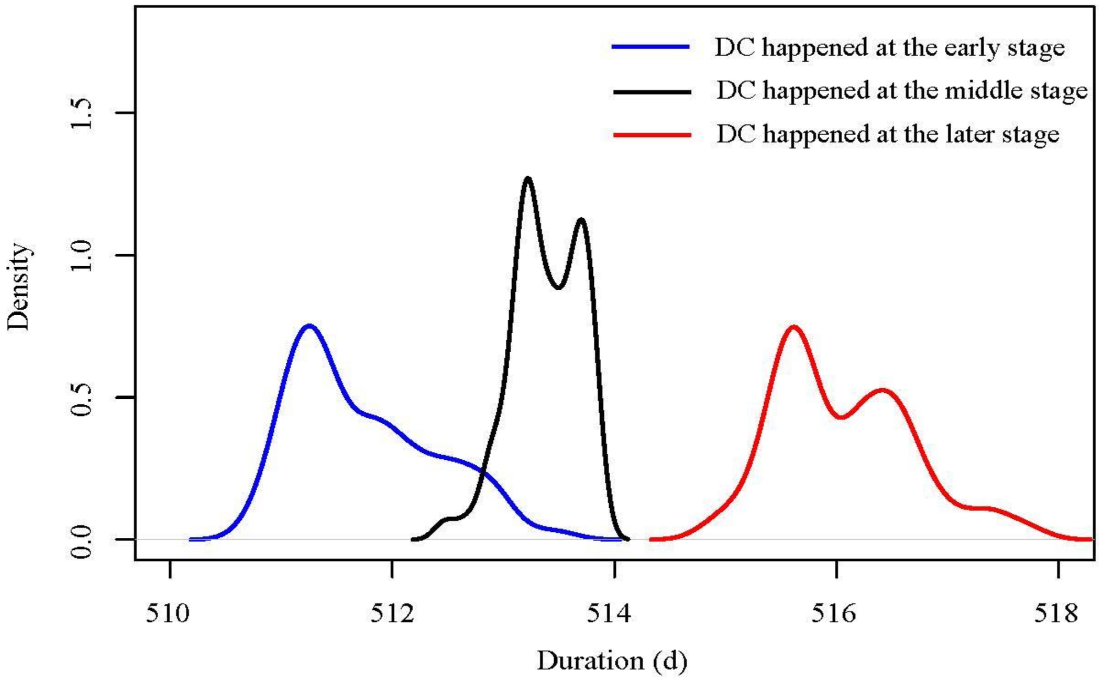


Figure 7.10 The curves of density function of DC at different stages of precast structure works

For DDPES in the six-day cycle simulation as shown in Figure 7.11, if DDPES occurs at the early stage, the rang of schedule ends at (4290.20, 4399.00), while at the middle and later stage, the schedule respectively ends at the range (4314.80, 4399.20) and

(4358.40, 4452.20). The median schedule as a result of DC for early stage, middle stage and later stage are 4337.40, 4390.80 and 4401.60, while the maximum schedule for the three period are 4399.00, 4399.20 and 4452.20.

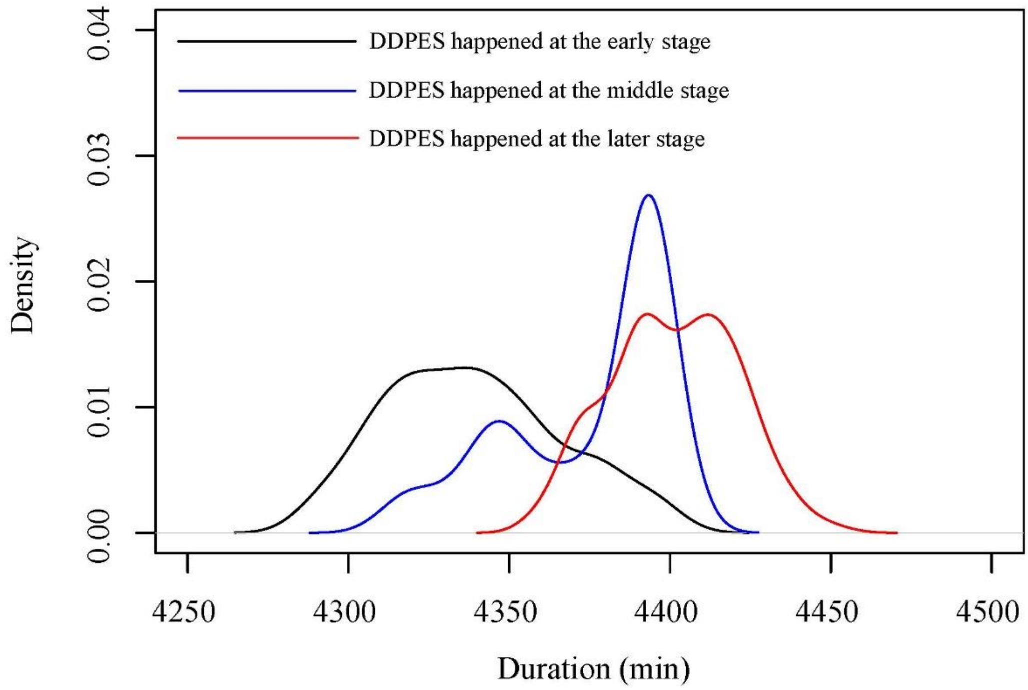


Figure 7.11 The curves of density function of DDPES at different stages of six-day cycle

For DDPES in the simulation of precast structure works as shown in Figure 7.12, if DDPES occurs at the early stage, the rang of schedule ends at (511.55, 514.65), while at the middle and later stage, the schedule respectively ends at the range (513.67, 515.02) and (515.76, 517.71). The median schedule as a result of DC for early stage, middle stage and later stage are 512.91, 514.49 and 517.22, while the maximum schedule for the three period are 514.65, 515.02 and 517.71.

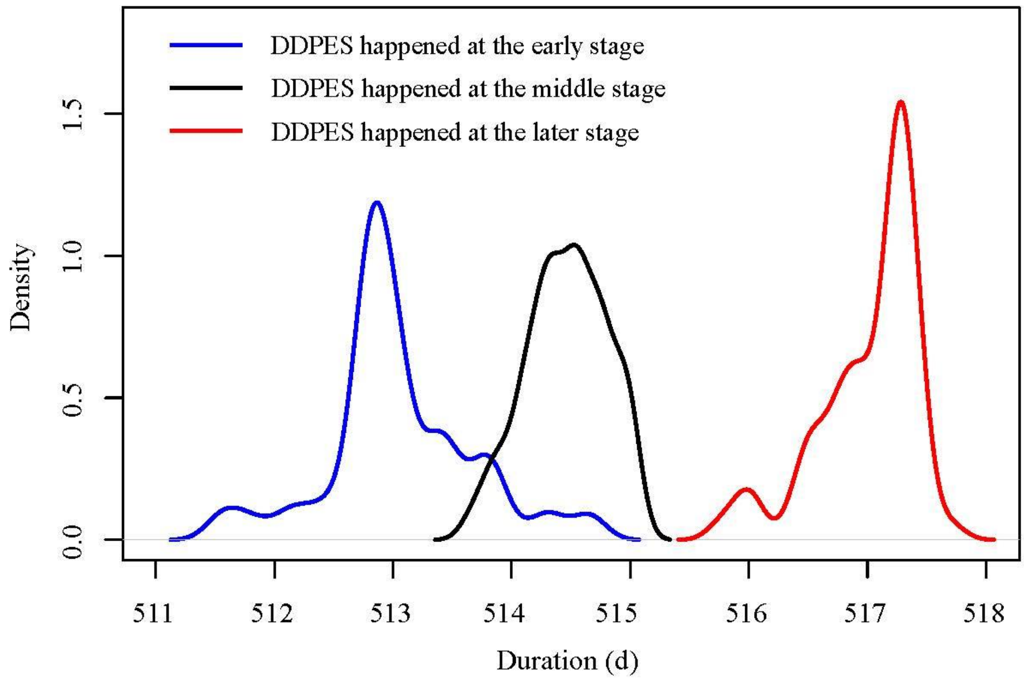


Figure 7.12 The curves of density function of DDPES at different stages of precast structure works

For DIGBDM in the six-day cycle simulation as shown in Figure 7.13, if DIGBDM occurs at the early stage, the rang of schedule ends at (4261.20, 4412.60), while at the middle and later stage, the schedule respectively ends at the range (4253.70, 4605.00) and (4246.20, 4797.40). The median schedule as a result of DIGBDM for early stage, middle stage and later stage are 4326.60, 4345.50 and 4364.40, while the maximum schedule for the three period are 4412.60, 4605.00 and 4797.40.

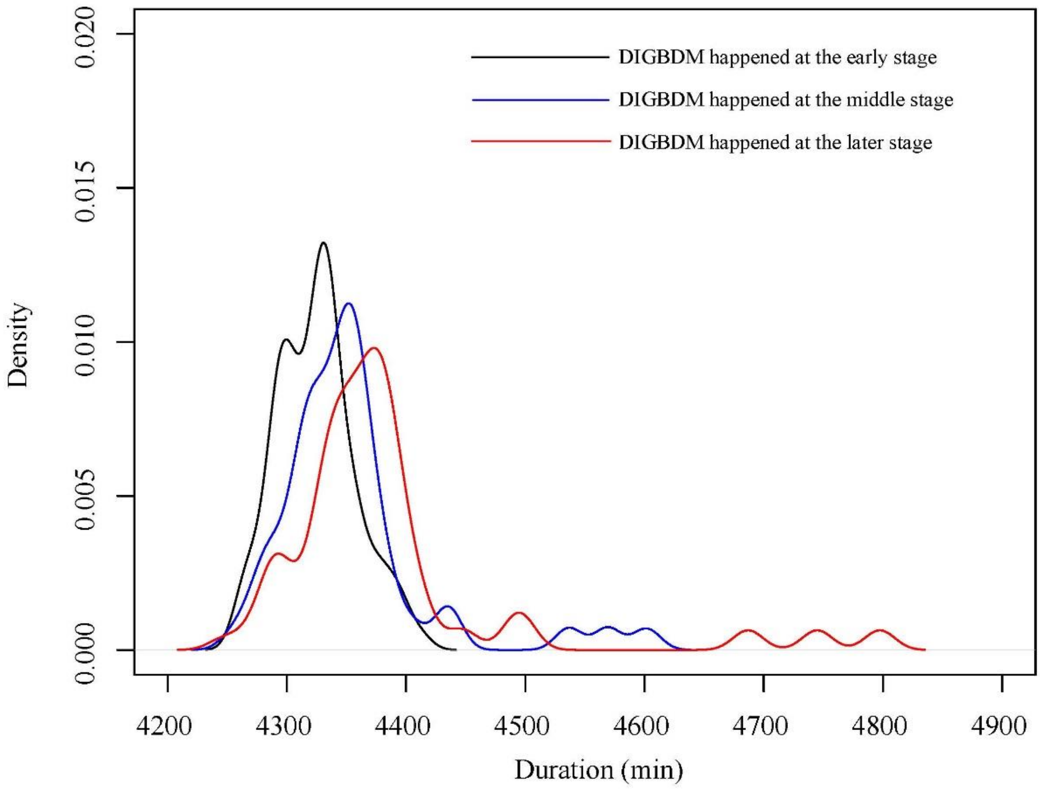


Figure 7.13 The curves of density function of DIGBDM at different stages of six-day cycle

For DIGBDM in the simulation of precast structure works as shown in Figure 7.14, if DIGBDM occurs at the early stage, the rang of schedule ends at (511.42, 513.04), while at the middle and later stage, the schedule respectively ends at the range (512.49, 514.62) and (514.69, 518.07). The median schedule as a result of DIGBDM for early stage, middle stage and later stage are 512.73, 514.38 and 516.61, while the maximum schedule for the three period are 513.04, 514.62 and 518.07.

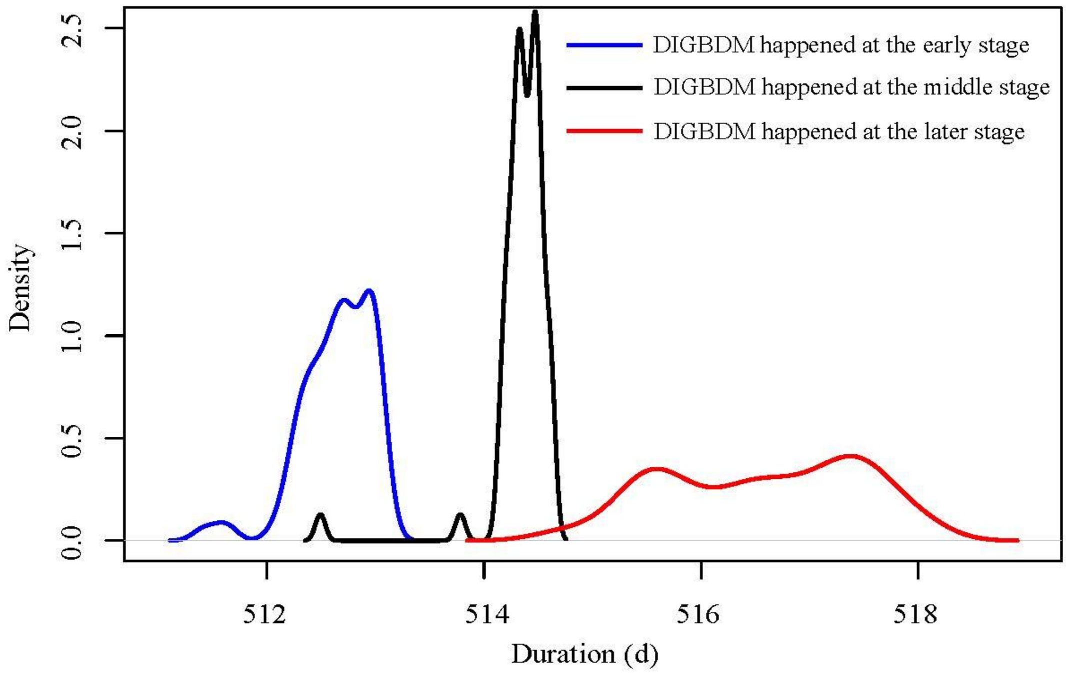


Figure 7.14 The curves of density function of DIGBDM at different stages of precast structure works

For IDA in the six-day cycle simulation as shown in Figure 7.15, if IDA occurs at the early stage, the rang of schedule ends at (4182.80, 4272.80), while at the middle and later stage, the schedule respectively ends at the range (4182.80, 4767.00) and (4182.80, 4767.00). The median schedule as a result of IDA for early stage, middle stage and later stage are 4246.80, 4456.60, and 4347.60, while the maximum schedule for the three period are 4272.80, 4767.00 and 4767.00.

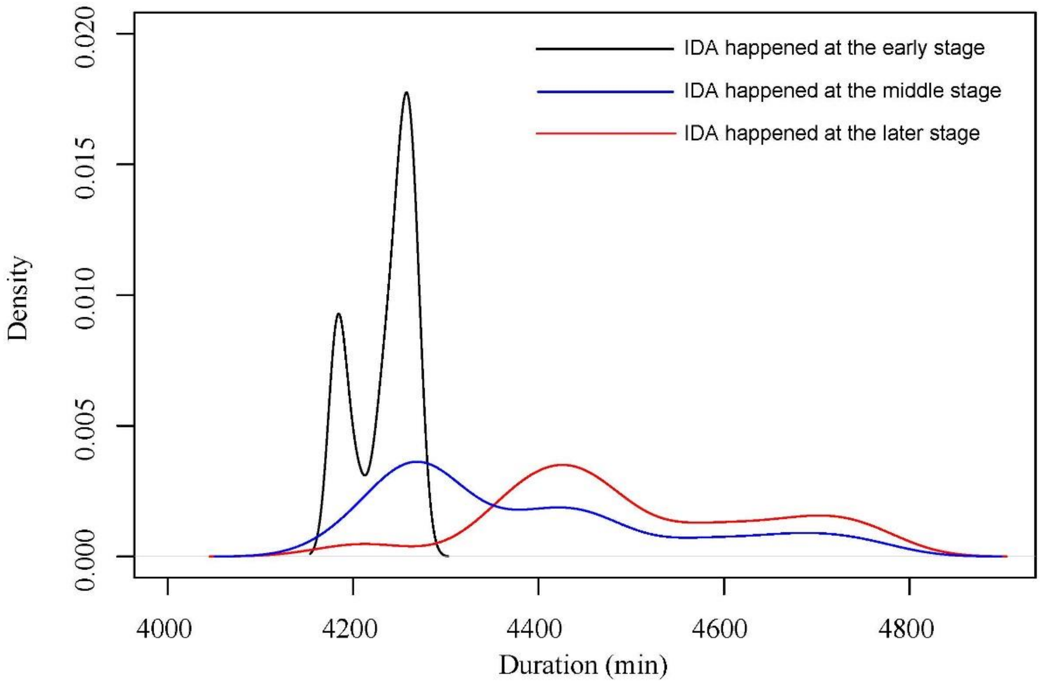


Figure 7.15 The curves of density function of IDA at different stages of six-day cycle

For IDA in the simulation of precast structure works as shown in Figure 7.16, if IDA occurs at the early stage, the rang of schedule ends at (510.87, 512.60), while at the middle and later stage, the schedule respectively ends at the range (512.69, 513.62) and (514.78, 516.84). The median schedule as a result of IDA for early stage, middle stage and later stage are 511.20, 513.02, and 515.43, while the maximum schedule for the three period are 511.23, 513.01 and 515.45.

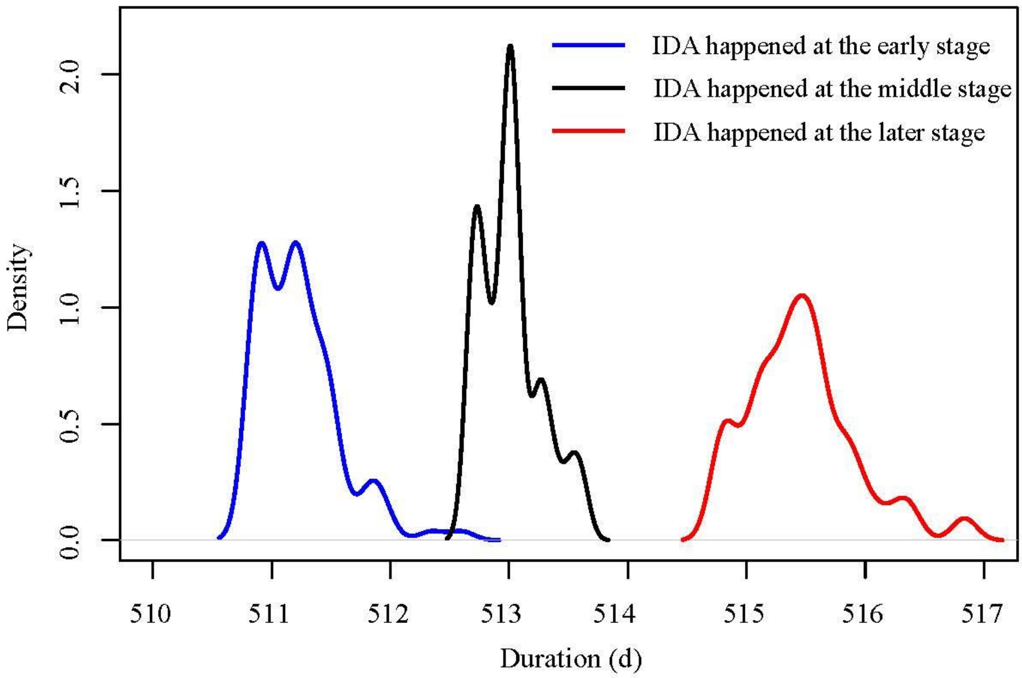


Figure 7.16 The curves of density function of IDA at different stages of precast structure works

For IDDT in the six-day cycle simulation as shown in Figure 7.17, if IDDT occurs at the early stage, the rang of schedule ends at (4182.80, 4635.40), while at the middle and later stage, the schedule respectively ends at the range (4182.80, 4716.40) and (4182.80, 4797.40). The median schedule as a result of IDDT for early stage, middle stage and later stage are 4421.60, 4349.20 and 4276.80, while the maximum schedule for the three period are 4635.40, 4716.40 and 4797.40.

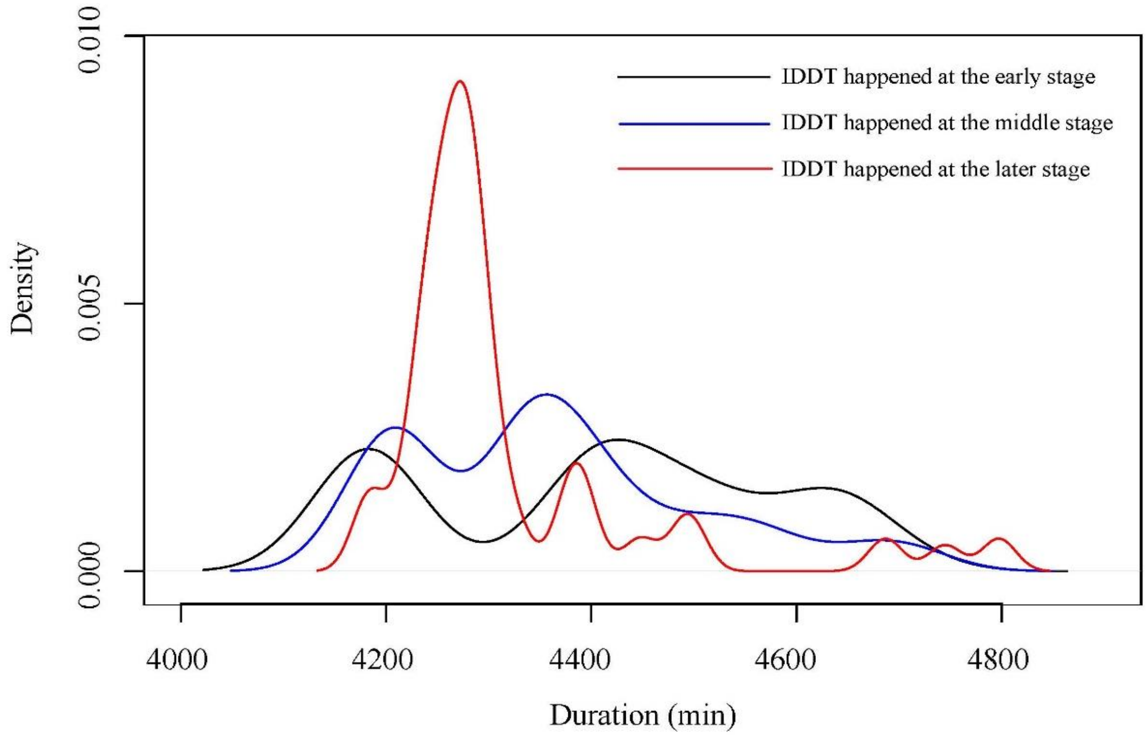


Figure 7.17 The curves of density function of IDDT at different stages of six-day cycle

For IDDT in the simulation of precast structure works as shown in Figure 7.18, if IDDT occurs at the early stage, the rang of schedule ends at (513.69, 515.31), while at the middle and later stage, the schedule respectively ends at the range (514.85, 516.91) and (517.60, 519.27). The median schedule as a result of IDDT for early stage, middle stage and later stage are 514.45, 516.15 and 518.95, while the maximum schedule for the three period are 515.31, 516.91 and 519.27.

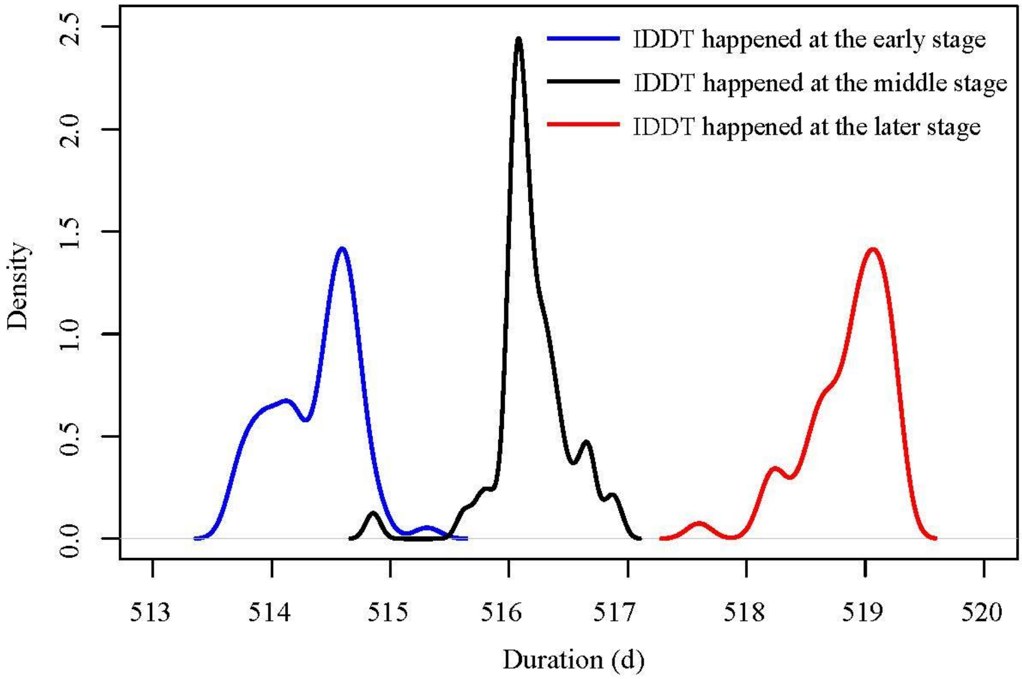


Figure 7.18 The curves of density function of IDDT at different stages of precast structure works

For IEPE in the six-day cycle simulation as shown in Figure 7.19, if IEPE occurs at the early stage, the rang of schedule ends at (4214.40, 4458.20), while at the middle and later stage, the schedule respectively ends at the range (4222.83, 4492.20) and (4301.20, 4459.60). The median schedule as a result of IEPE for early stage, middle stage and later stage are 4299.00, 4341.60 and 4388.80, while the maximum schedule for the three period are 4458.20, 4492.20 and 4459.60.

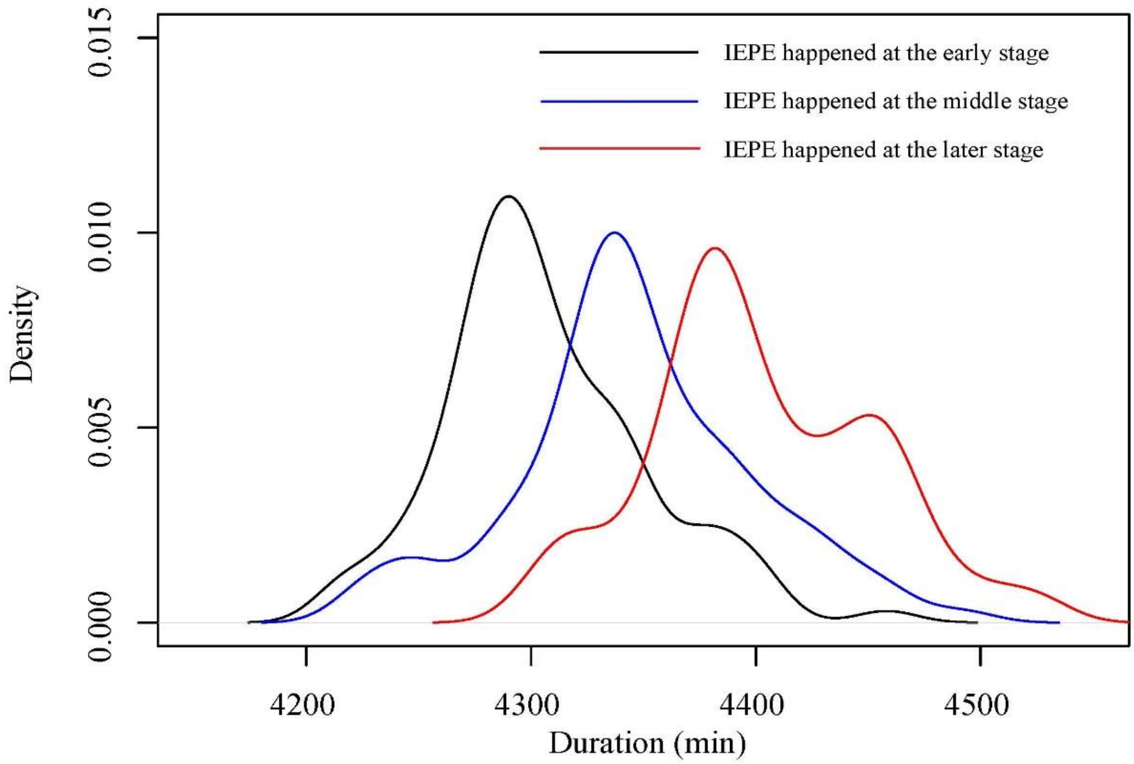


Figure 7.19 The curves of density function of IEPE at different stages of six-day cycle

For IEPE in the simulation of precast structure works as shown in Figure 7.20, if IEPE occurs at the early stage, the rang of schedule ends at (511.42, 513.58), while at the middle and later stage, the schedule respectively ends at the range (513.53, 514.85) and (514.85, 518.38). The median schedule as a result of IEPE for early stage, middle stage and later stage are 512.16, 514.27 and 516.89, while the maximum schedule for the three period are 513.58, 514.85 and 518.38.

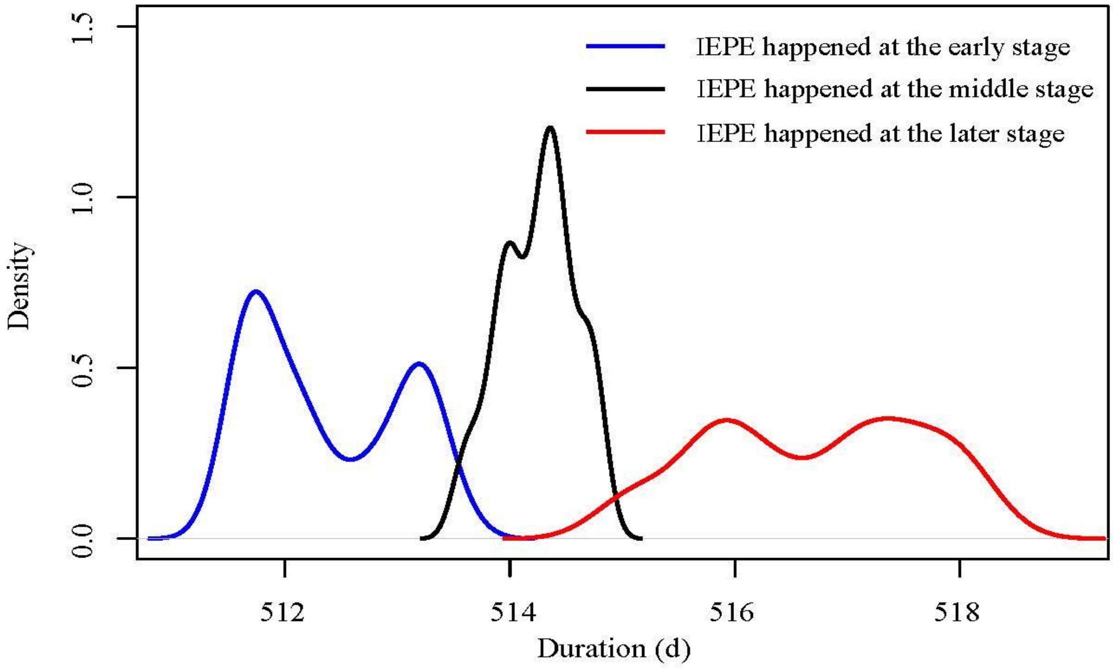


Figure 7.20 The curves of density function of IEPE at different stages of precast structure works

For IVPCBAL in the six-day cycle simulation as shown in Figure 7.21, if IVPCBAL occurs at the early stage, the rang of schedule ends at (4182.80, 5775.00), while at the middle and later stage, the schedule respectively ends at the range (4182.80, 5626.40) and (4182.80, 6069.00). The median schedule as a result of IVPCBAL for early stage, middle stage and later stage are 5227.40, 5202.00 and 5484.20, while the maximum schedule for the three period are 5775.00, 5626.40 and 6069.00.

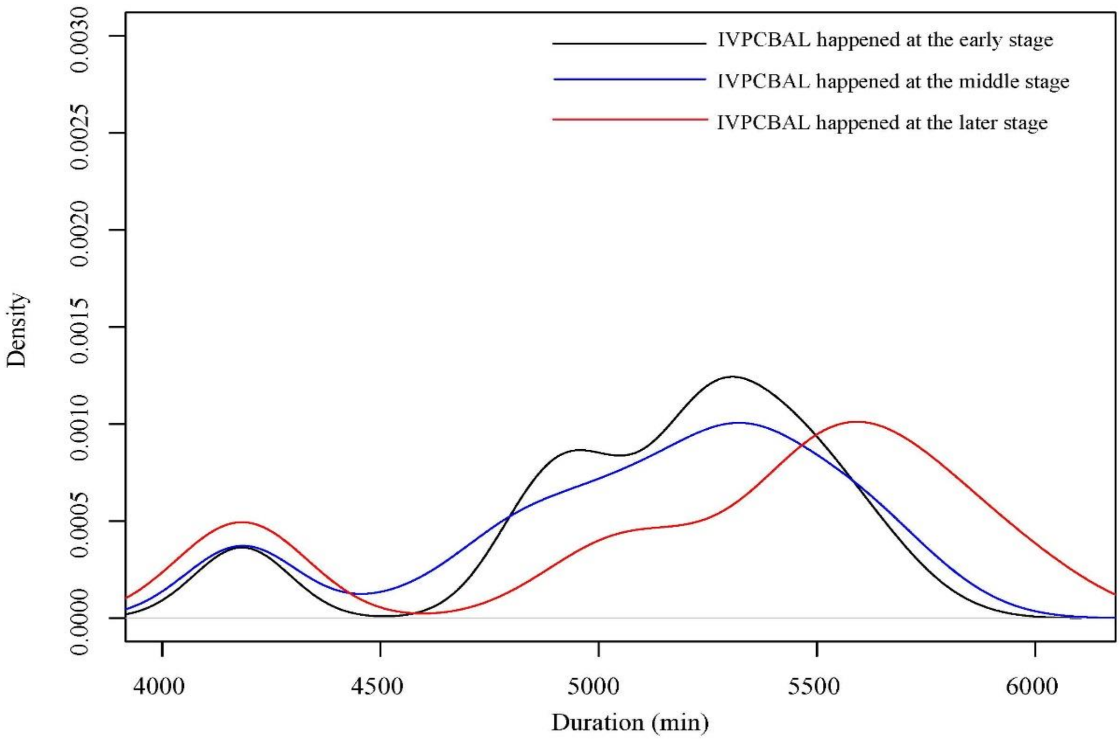


Figure 7.21 The curves of density function of IVPCBAL at different stages of six-day cycle

For IVPCBAL in the simulation of precast structure works as shown in Figure 7.22, if IVPCBAL occurs at the early stage, the rang of schedule ends at (523.44, 525.95), while at the middle and later stage, the schedule respectively ends at the range (525.29, 528.20) and (527.60, 533.33). The median schedule as a result of IVPCBAL for early stage, middle stage and later stage are 524.56, 526.40 and 528.93, while the maximum schedule for the three period are 525.95, 528.20 and 533.33.

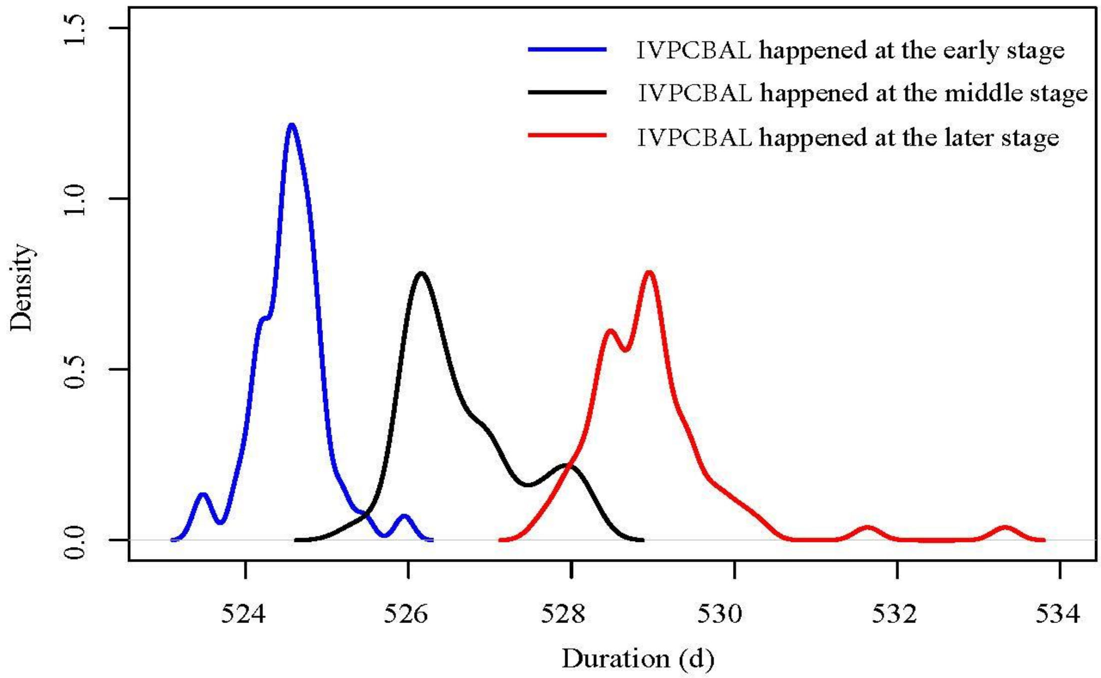


Figure 7.22 The curves of density function of IVPCBAL at different stages of precast structure works

For LIIBDERPS in the six-day cycle simulation as shown in Figure 7.23, if LIIBDERPS occurs at the early stage, the rang of schedule ends at (4184.00, 4330.60), while at the middle and later stage, the schedule respectively ends at the range (4319.40, 4396.20) and (4329.60, 4424.60). The median schedule as a result of LIIBDERPS for early stage, middle stage and later stage are 4249.60, 4364.60 and 4383.60, while the maximum schedule for the three period are 4330.60, 4396.20 and 4424.60.

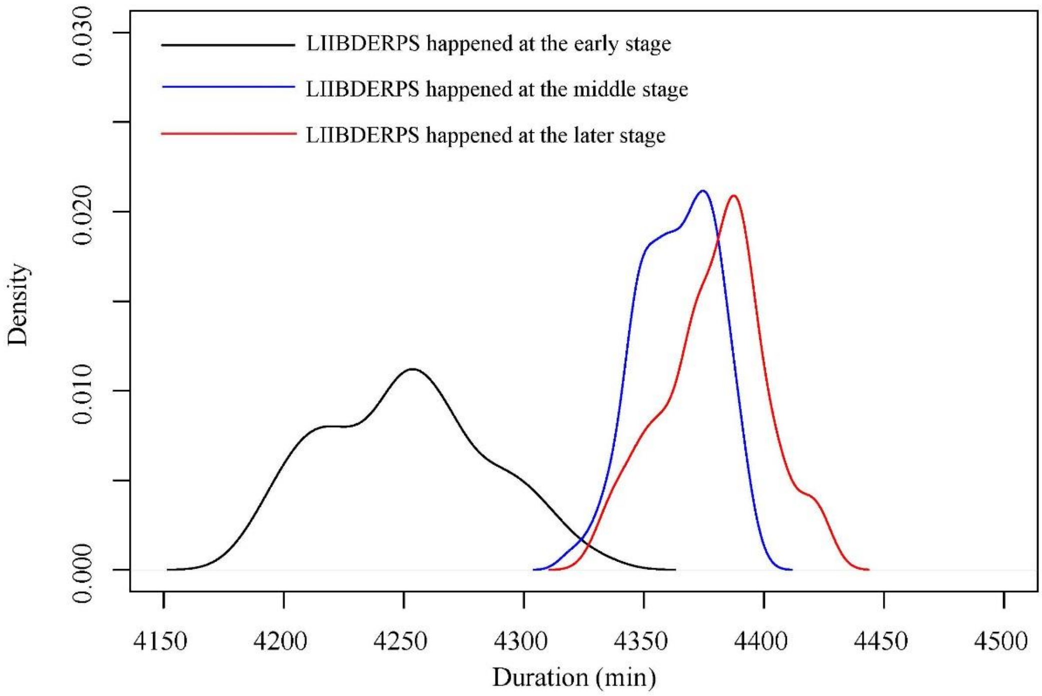


Figure 7.23 The curves of density function of LIIBDERPS at different stages of six-day cycle

For LIIBDERPS in the simulation of precast structure works as shown in Figure 7.24, if LIIBDERPS occurs at the early stage, the rang of schedule ends at (510.93, 513.33), while at the middle and later stage, the schedule respectively ends at the range (513.45, 514.65) and (514.87, 518.13). The median schedule as a result of LIIBDERPS for early stage, middle stage and later stage are 511.33, 513.37 and 516.04, while the maximum schedule for the three period are 512.96, 514.33 and 518.31.

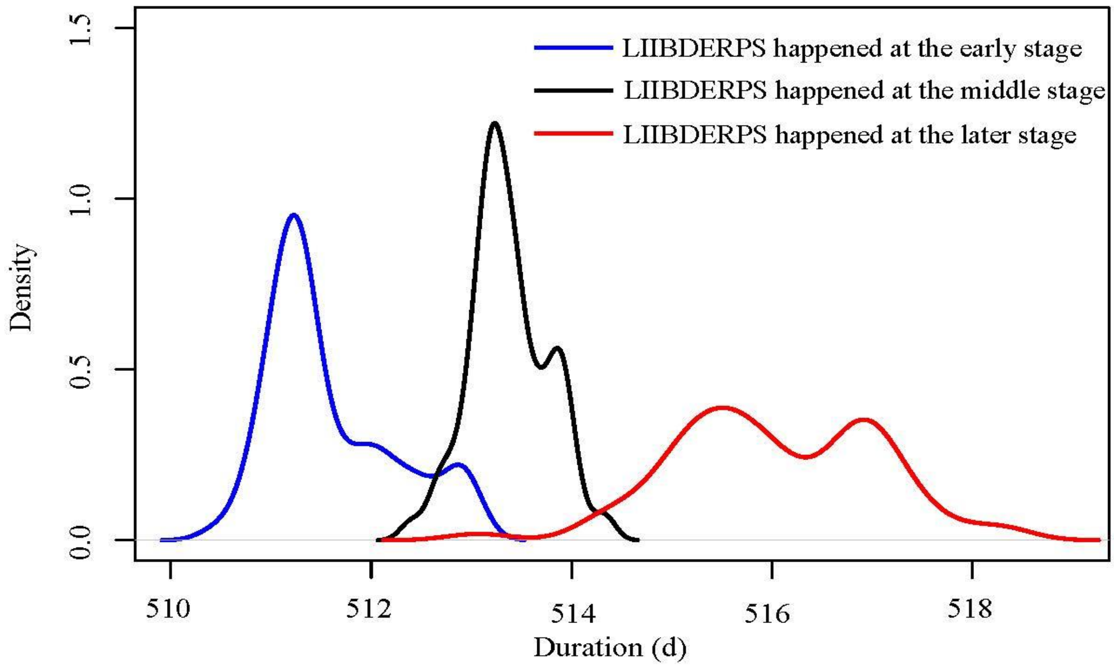


Figure 7.24 The curves of density function of LIIBDERPS at different stages of precast structure works

For LIIBHE in the six-day cycle simulation as shown in Figure 7.25, if LIIBHE occurs at the early stage, the rang of schedule ends at (4207.60, 4368.00), while at the middle and later stage, the schedule respectively ends at the range (4225.00, 4390.80) and (4277.40, 4406.80). The median schedule as a result of LIIBHE for early stage, middle stage and later stage are 4307.60, 4344.00 and 4354.60, while the maximum schedule for the three period are 4368.00, 4390.80 and 4406.80.

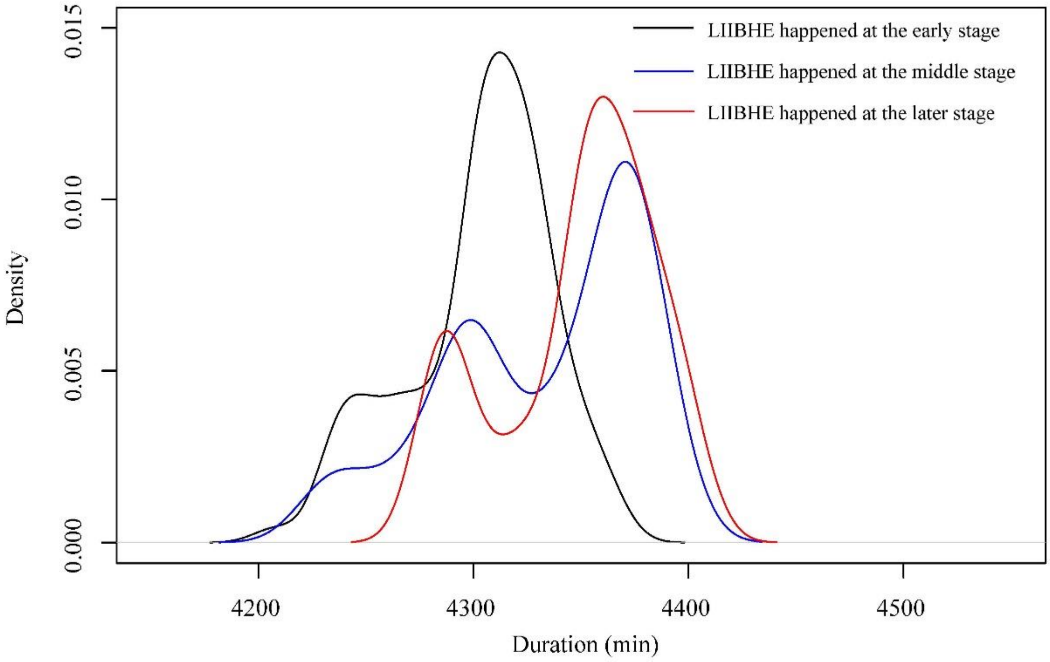


Figure 7.25 The curves of density function of LIIBHE at different stages of six-day cycle

For LIIBHE in the simulation of precast structure works as shown in Figure 7.26, if LIIBHE occurs at the early stage, the rang of schedule ends at (510.93, 513.33), while at the middle and later stage, the schedule respectively ends at the range (513.53, 514.85) and (514.87, 518.13). The median schedule as a result of LIIBHE for early stage, middle stage and later stage are 512.36, 514.05 and 516.75, while the maximum schedule for the three period are 513.33, 514.65 and 518.13.

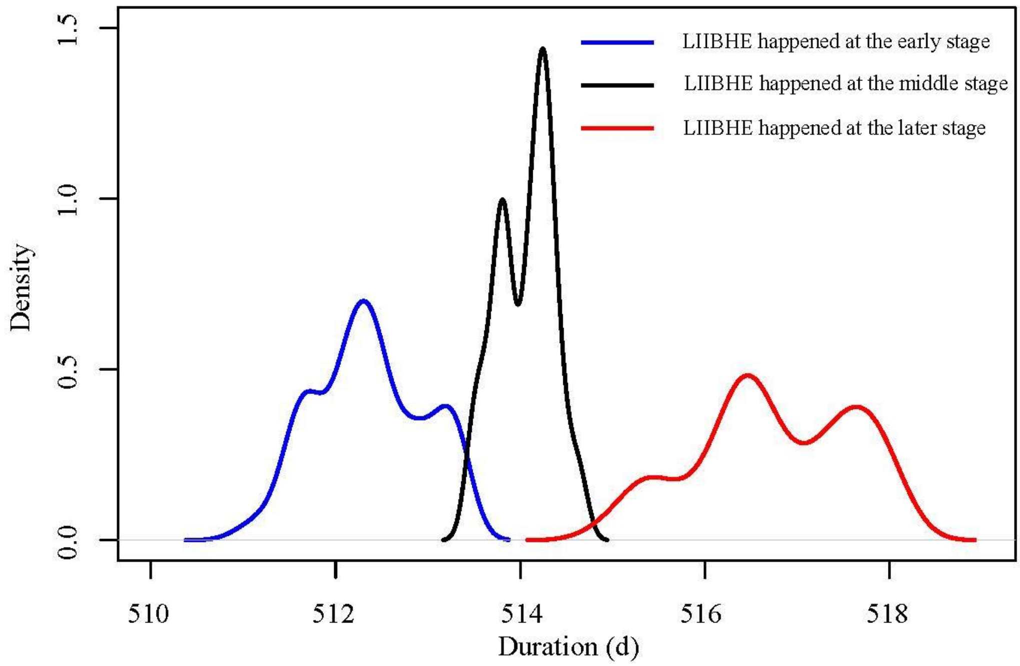


Figure 7.26 The curves of density function of LIIBHE at different stages of precast structure works

For MSSBC in the six-day cycle simulation as shown in Figure 7.27, if MSSBC occurs at the early stage, the rang of schedule ends at (4182.80, 5090.60), while at the middle and later stage, the schedule respectively ends at the range (4430.00, 5155.20) and (4182.80, 5443.00). The median schedule as a result of MSSBC for early stage, middle stage and later stage are 4816.40, 4802.40 and 5094.40, while the maximum schedule for the three period are 5090.60, 5155.20 and 5443.00.

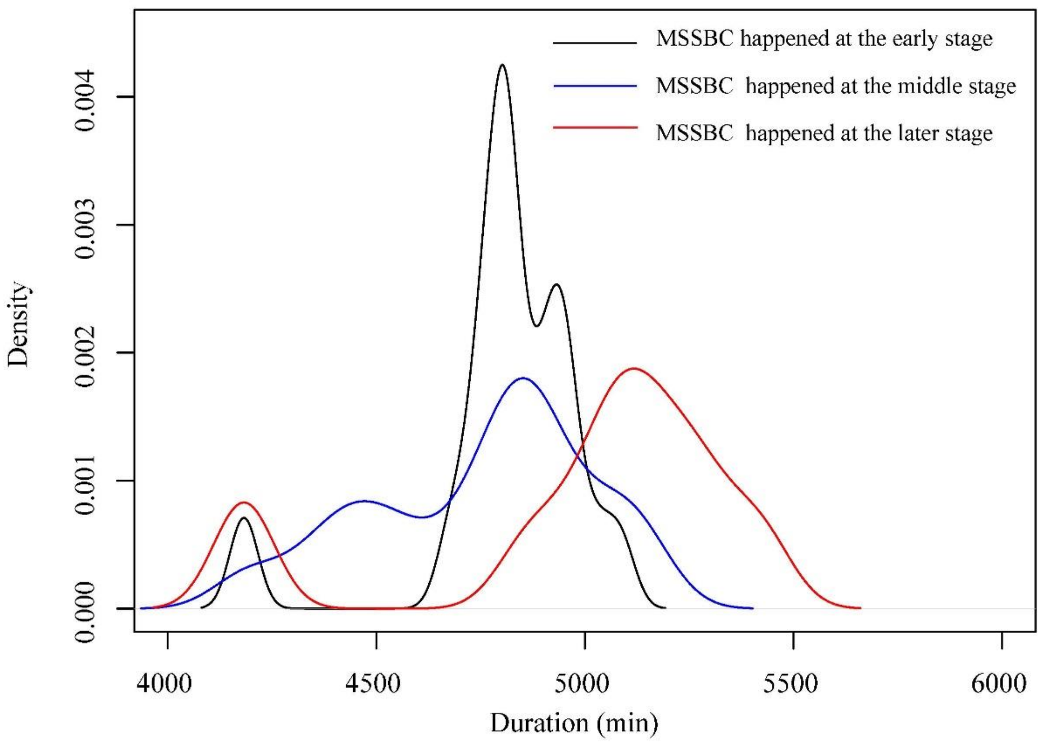


Figure 7.27 The curves of density function of MSSBC at different stages of six-day cycle

For MSSBC in the simulation of precast structure works as shown in Figure 7.28, if MSSBC occurs at the early stage, the rang of schedule ends at (518.18, 520.87), while at the middle and later stage, the schedule respectively ends at the range (521.13, 523.33) and (522.98, 527.18). The median schedule as a result of MSSBC for early stage, middle stage and later stage are 520.16, 521.80 and 524.29, while the maximum schedule for the three period are 520.87, 523.33 and 527.18.

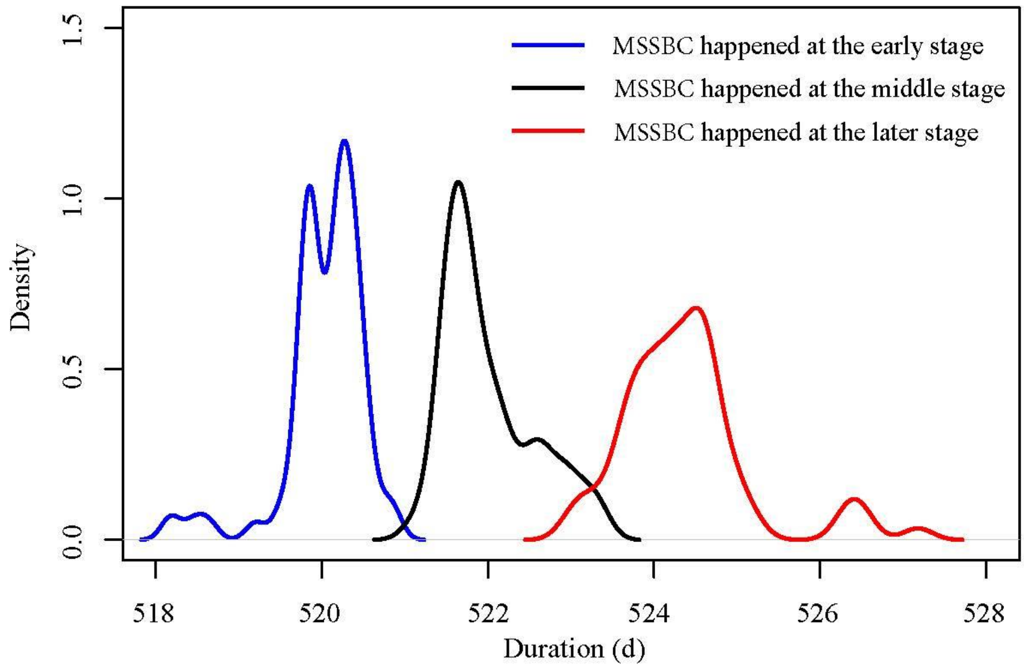


Figure 7.28 The curves of density function of MSSBC at different stages of precast structure works

For SQIP in the six-day cycle simulation as shown in Figure 7.29, if SQIP occurs at the early stage, the rang of schedule ends at (4260.40, 4795.00), while at the middle and later stage, the schedule respectively ends at the range (4266.40, 4811.60) and (4312.60, 5038.80). The median schedule as a result of SQIP for early stage, middle stage and later stage are 4424.60, 4458.40 and 4787.00, while the maximum schedule for the three period are 4795.00, 4811.60 and 5038.80

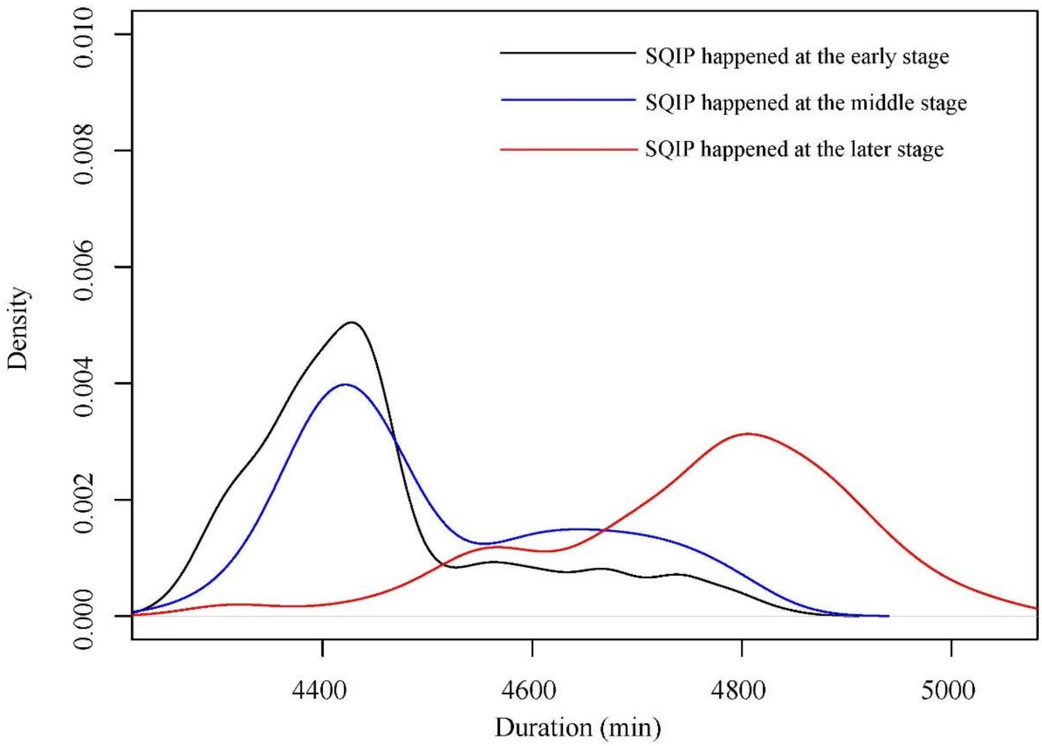


Figure 7.29 The curves of density function of SQIP at different stages of six-day cycle

For SQIP in the simulation of precast structure works as shown in Figure 7.30, if SQIP occurs at the early stage, the rang of schedule ends at (514.62, 516.35), while at the middle and later stage, the schedule respectively ends at the range (516.75, 519.58) and (518.82, 520.76). The median schedule as a result of SQIP for early stage, middle stage and later stage are 515.85, 517.62 and 519.86, while the maximum schedule for the three period are 516.35, 519.58 and 520.76

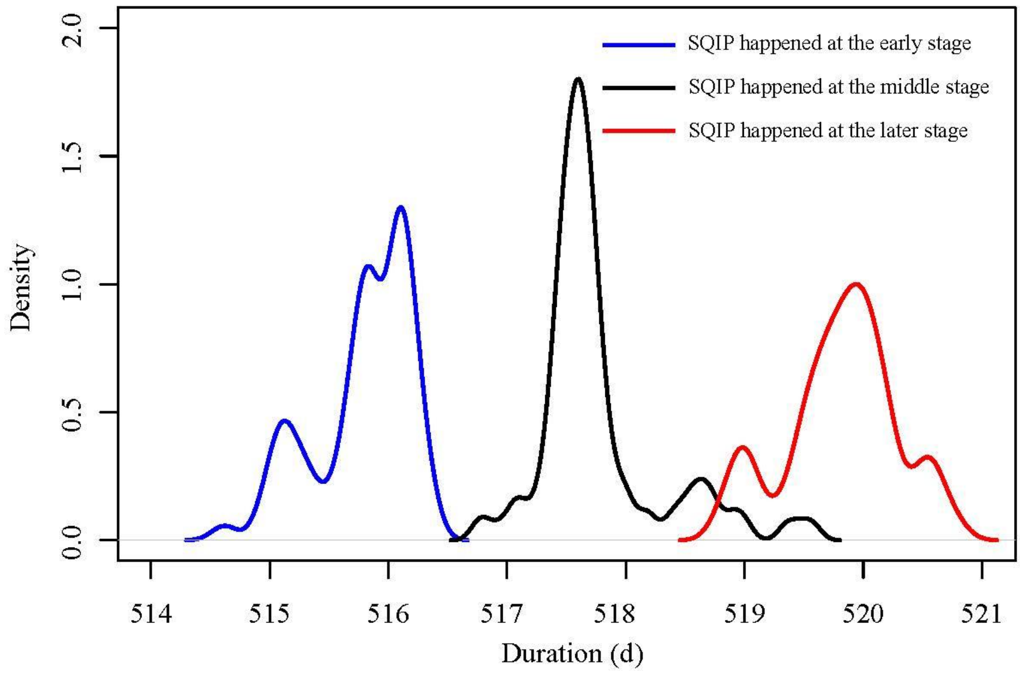


Figure 7.30 The curves of density function of SQIP at different stages of precast structure works

For TCBM in the six-day cycle simulation as shown in Figure 7.31, if TCBM occurs at the early stage, the rang of schedule ends at (4182.80, 4814.60), while at the middle and later stage, the schedule respectively ends at the range (4182.80, 4789.40) and (4182.80, 5110.40). The median schedule as a result of TCBM for early stage, middle stage and later stage are 4461.80, 4578.60 and 4807.60, while the maximum schedule for the three period are 4814.60, 4789.40 and 5110.40.

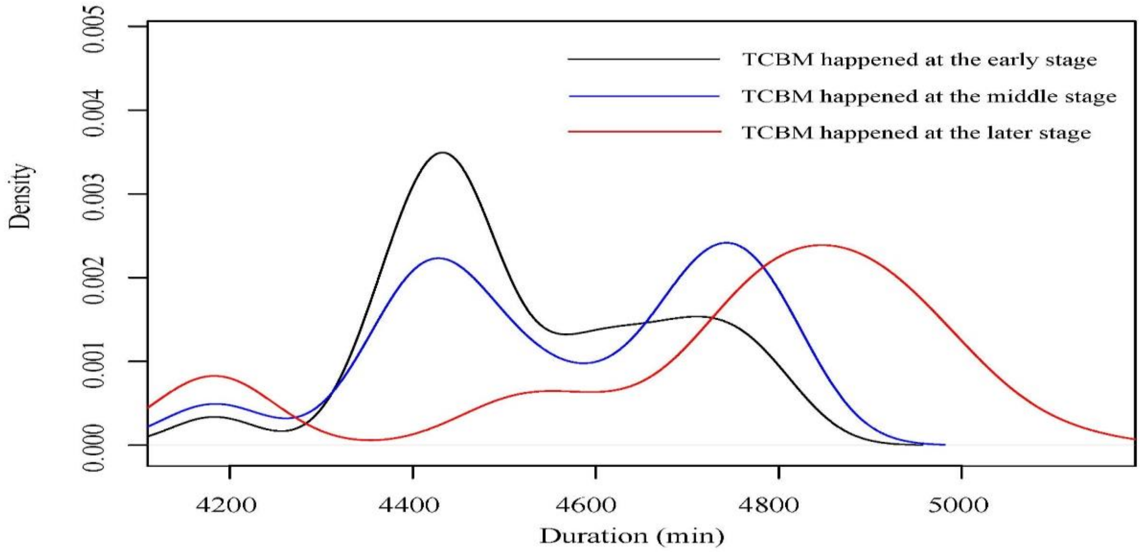


Figure 7.31 The curves of density function of TCBM at different stages of six-day cycle

For TCBM in the simulation of precast structure works as shown in Figure 7.32, if TCBM occurs at the early stage, the rang of schedule ends at (514.76, 517.05), while at the middle and later stage, the schedule respectively ends at the range (517.44, 519.87) and (519.20, 524.96). The median schedule as a result of TCBM for early stage, middle stage and later stage are 516.35, 518.21 and 520.94, while the maximum schedule for the three period are 517.05, 519.87 and 524.96.

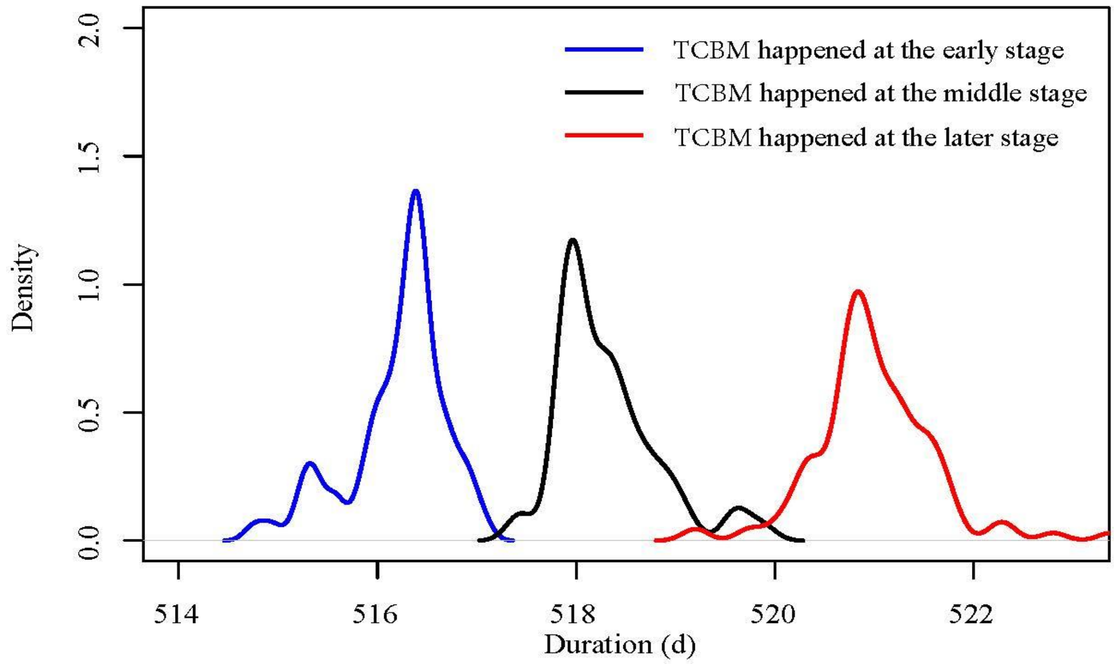


Figure 7.32 The curves of density function of TCBM at different stages of precast structure works

Table 7.3 Simulation results of all the twelve schedule risks under three different stages of six-day cycle

Category	Mean (min)	Median (min)	Min (min)	Max (min)	Standard deviation
DDPES1	4338.87	4337.40	4290.20	4399.00	27.14
DDPES2	4375.04	4390.80	4314.80	4399.20	25.39
DDPES3	4400.98	4401.60	4358.40	4452.20	19.55
IEPE1	4306.34	4299.00	4214.40	4458.20	44.82
IEPE2	4346.24	4341.60	4222.83	4492.20	53.14
IEPE3	4402.37	4388.80	4301.20	4459.60	49.77
LIIBHE1	4302.54	4307.60	4207.60	4368.00	33.66
LIIBHE2	4332.41	4344.00	4225.00	4390.80	46.23
LIIBHE3	4348.14	4354.60	4277.40	4406.80	36.45

LIIBDERPS1	4250.22	4249.60	4184.00	4330.60	34.46
LIIBDERPS2	4364.02	4364.60	4319.40	4396.20	16.32
LIIBDERPS3	4379.40	4383.60	4329.60	4424.60	21.34
DC1	4262.14	4269.00	4182.80	4315.20	36.51
DC2	4296.74	4307.40	4187.50	4357.50	43.55
DC3	4331.35	4345.80	4192.20	4399.80	51.07
SQIP1	4453.66	4424.60	4260.40	4795.00	125.73
SQIP2	4512.38	4458.40	4266.40	4811.60	137.01
SQIP3	4755.37	4787.00	4312.60	5038.80	149.48
TCBM1	4522.51	4461.80	4182.80	4814.60	152.19
TCBM2	4564.78	4578.60	4182.80	4789.40	183.50
TCBM3	4729.63	4807.60	4182.80	5110.40	256.10
DIGBDM1	4324.52	4326.60	4261.20	4412.60	32.40
DIGBDM2	4354.23	4345.50	4253.70	4605.00	65.74
DIGBDM3	4383.95	4364.40	4246.20	4797.40	102.66
IDA1	4233.52	4246.80	4182.80	4272.80	31.42
IDA2	4500.84	4456.60	4182.80	4767.00	146.82
IDA3	4392.50	4347.60	4182.80	4767.00	162.28
IDDT1	4406.85	4421.60	4182.80	4635.40	171.57
IDDT2	4364.41	4349.20	4182.80	4716.40	142.95
IDDT3	4321.98	4276.80	4182.80	4797.40	135.84
IVPCBAL1	5135.55	5227.40	4182.80	5775.00	399.26
IVPCBAL2	5101.80	5202.00	4182.80	5626.40	447.85
IVPCBAL3	5269.66	5484.20	4182.80	6069.00	588.09
MSSBC1	4813.55	4816.40	4182.80	5090.60	188.06
MSSBC2	4751.16	4802.40	4430.00	5155.20	263.00
MSSBC3	5000.43	5094.40	4182.80	5443.00	377.07

Table 7.4 Simulation results of all the twelve schedule risks under three different stages of precast structure works

Category	Mean (d)	Median (d)	Min (d)	Max (d)	Standard deviation
DDPES1	513.05	512.91	511.55	514.65	0.62
DDPES2	514.46	514.49	513.67	515.02	0.34
DDPES3	517.01	517.22	515.76	517.71	0.42
IEPE1	512.37	512.16	511.42	513.58	0.66
IEPE2	514.25	514.27	513.53	514.85	0.33
IEPE3	516.70	516.89	514.85	518.38	0.96
LIIBHE1	512.36	512.36	510.93	513.33	0.58
LIIBHE2	514.05	514.09	513.45	514.65	0.30
LIIBHE3	516.75	516.64	514.87	518.13	0.85
LIIBDERPS1	511.58	511.33	510.47	512.96	0.63
LIIBDERPS2	513.37	513.29	512.40	514.33	0.38
LIIBDERPS3	516.04	515.93	513.07	518.31	1.01
DC1	511.74	511.58	510.78	513.45	0.64
DC2	513.38	513.40	512.47	513.84	0.31
DC3	516.07	516.00	514.91	517.71	0.62
SQIP1	515.79	515.85	514.62	516.35	0.40
SQIP2	517.76	517.62	516.75	519.58	0.52
SQIP3	519.82	519.86	518.82	520.76	0.46
TCBM1	516.21	516.35	514.76	517.05	0.49
TCBM2	518.31	518.21	517.44	519.87	0.51
TCBM3	521.03	520.94	519.20	524.96	0.72
DIGBDM1	512.64	512.73	511.42	513.04	0.33
DIGBDM2	514.35	514.38	512.49	514.62	0.27
DIGBDM3	516.57	516.61	514.69	518.07	0.90
IDA1	511.23	511.20	510.87	512.60	0.34

IDA2	513.01	513.02	512.69	513.62	0.25
IDA3	515.45	515.43	514.78	516.84	0.45
IDDT1	514.36	514.45	513.69	515.31	0.35
IDDT2	516.19	516.15	514.85	516.91	0.32
IDDT3	518.85	518.95	517.60	519.27	0.35
IVPCBAL1	524.54	524.56	523.44	525.95	0.43
IVPCBAL2	526.64	526.40	525.29	528.20	0.71
IVPCBAL3	528.96	528.93	527.60	533.33	0.85
MSSBC1	520.03	520.16	518.18	520.87	0.49
MSSBC2	522.01	521.80	521.13	523.33	0.55
MSSBC3	524.37	524.29	522.98	527.18	0.79

Table 7.4 and Table 7.5 summarizes the simulation results of all the twelve schedule risks under three different stage in terms of mean, range, median, and standard deviations for both six-day cycle assembly and precast structure works. In general, risks IVPCBAL, MSSBC, TCBM and SQIP have more significant influence on schedule performance of prefabrication housing production project, followed by IDDT, DDPES, DIGBDM, IEPE, LIIBHE, DC, LIIBDERPS and IDA in terms of mean schedule. Besides, risks occurring at the later stage tend to have more significant impact on the schedule performance of PHP than occurring at early and middle stage of six-day cycle construction. The possible reason accounting for this phenomenon might be that when schedule risks occur at later stage, there might be no enough time for the manager to deal with the risks and implement work expediting activities to make up the time loss caused by the occurred risks and thus leading to more serious schedule delay.

7.4 Analysis on Multi-Risk Scenarios

To understand the effect of schedule risks under different situations, four risks, namely IVPCBAL, MSSBC, TCBM, SQIP, and their combined effect are selected for scenario analysis. The scenario analysis involves a base case scenario and two modified scenarios, i.e., risk decreased by 50% and risks increased by 50%. Please be noted that risk is measured by two criteria in this research, including impact and likelihood. So, if risk is decreased by 50%, it means that the impact and likelihood of the risk are simultaneously decreased by 50%. Take a risk of which the impact on schedule performance complies with triangle distribution with probability of occurrence of 0.4 for example, the risk decrease by 50% means that the three values adopted for triangle distribution shrinks by 50% and the probability of occurrence is cut by 50% to 0.2.

(1) Scenario A

In the scenario, the value of IVPCBAL is set at initial value (A1). The value is decreased by 50% (A2) and increased by 50% (A3). Simulation results are shown in Figure 7.33 and Table 7.5. The width of the range (1.9) in A2 decreased by 24.28%, while the width of the range (2.19) in A3 increased by 87.32%, which indicates that the width of range is more sensitive to the increase of IVPCBAL than that to the decrease of IVPCBAL. In contrast, the average delay (increased by 71.79%) in A3 shows a greater sensitive than that (decreased by 44.67%) in A2.

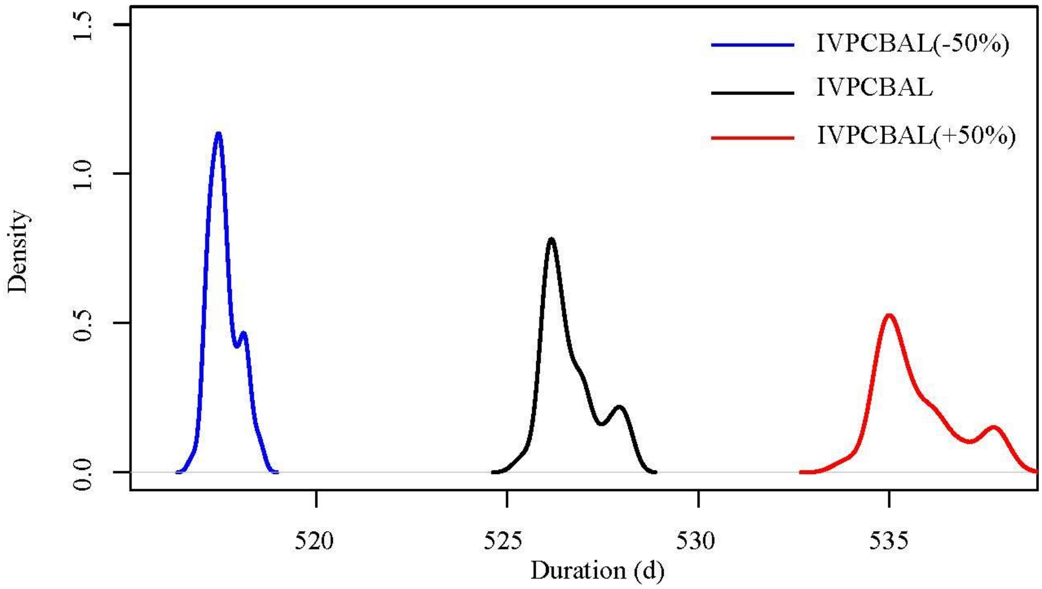


Figure 7.33 Curves of density function IVPCBAL (–50%), IVPCBAL, and IVPCBAL (+50%)

(2) Scenario B

In scenario B, the width of range (1.6) in B2 decreased by 40.54%, while the width of range (3.8) in B3 increased by 41.22%. The width of range shows the similar sensitivity for the increase and decrease of MSSBC. Besides, average delay decreased by 42.00% in B2 shows less sensitive than that in (increased by 81.27%) B3 (Figure 7.34 and Table 7.5).

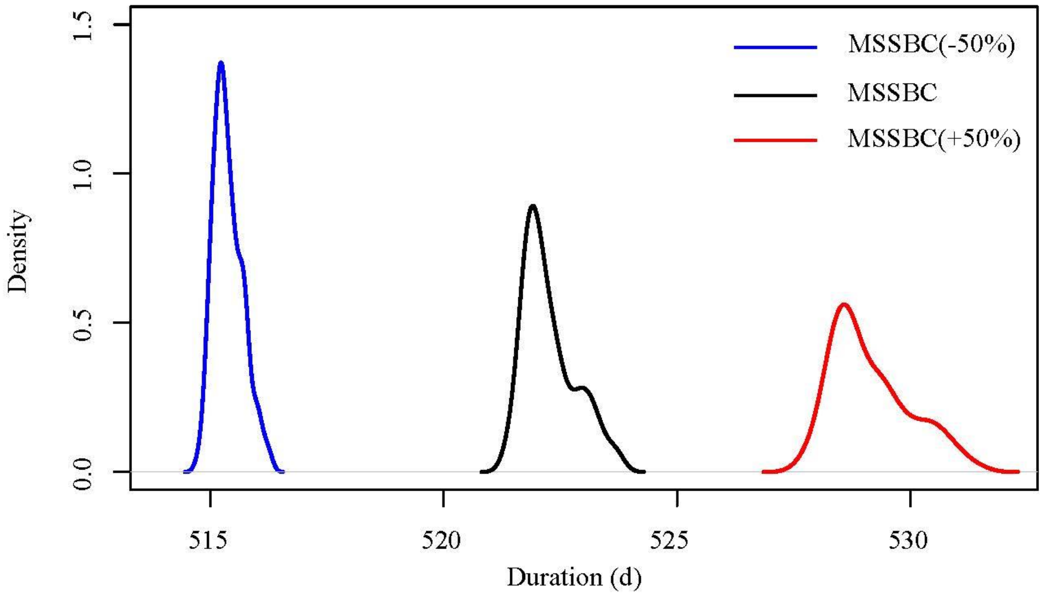


Figure 7.34 Curves of density function MSSBC (–50%), MSSBC, and MSSBC (+50%)

(3) Scenario C

The width of range (1.6) in C2 decreased by 30.16%, while the width of range (3.8) in C3 increased by 65.87%. The average delay decreased by 38.95% in C2 (4.4) and increased by 101.19% (14.5) in C3. TCBM and IVPCBAL have almost the same trend as the width of range is more sensitive to the increase of TCBM than that to the decrease of TCBM. Average delay decreased by 38.95% in C2 shows less sensitive than that in C3 which increased by 101.19%.

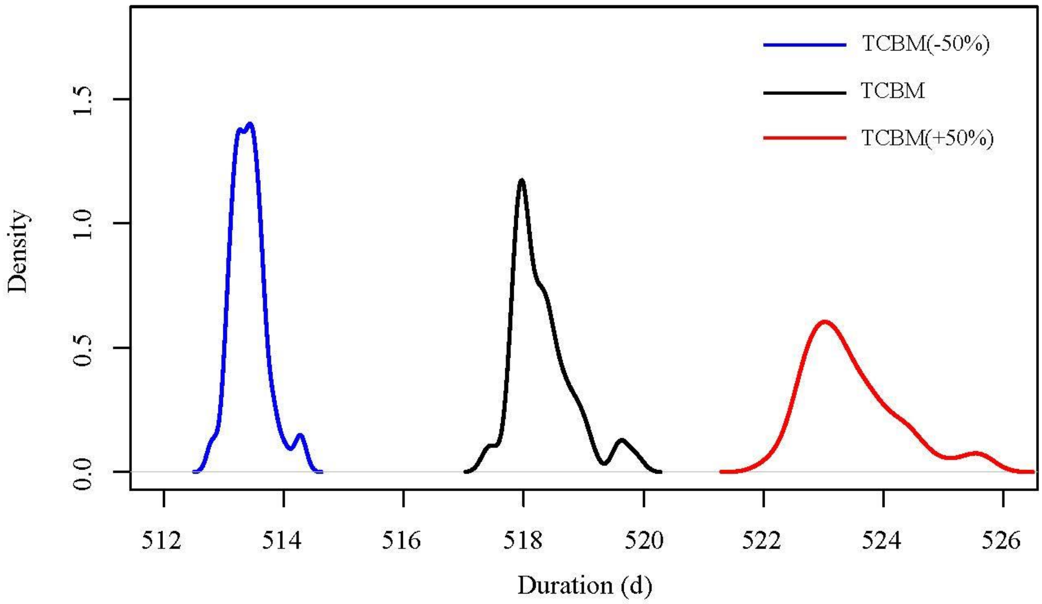


Figure 7.35 Curves of density function TCBM (–50%), TCBM, and TCBM (+50%)

(4) Scenario D

The width of range (1.9) in D2 decreased by 10.00%, while the width of range (4.5) in D3 increased by 160.52%, in which the sensitivity for decrease is much smaller and the sensitivity for increase is much larger compared with the first three scenarios. The average delay decreased by 44.02% in D2 and increased by 101.83% in D3, as shown in Figure 7.36 and Table 7.5. Therefore, controlling SQIP is important. Once SQIP increases, the duration would substantially increase.

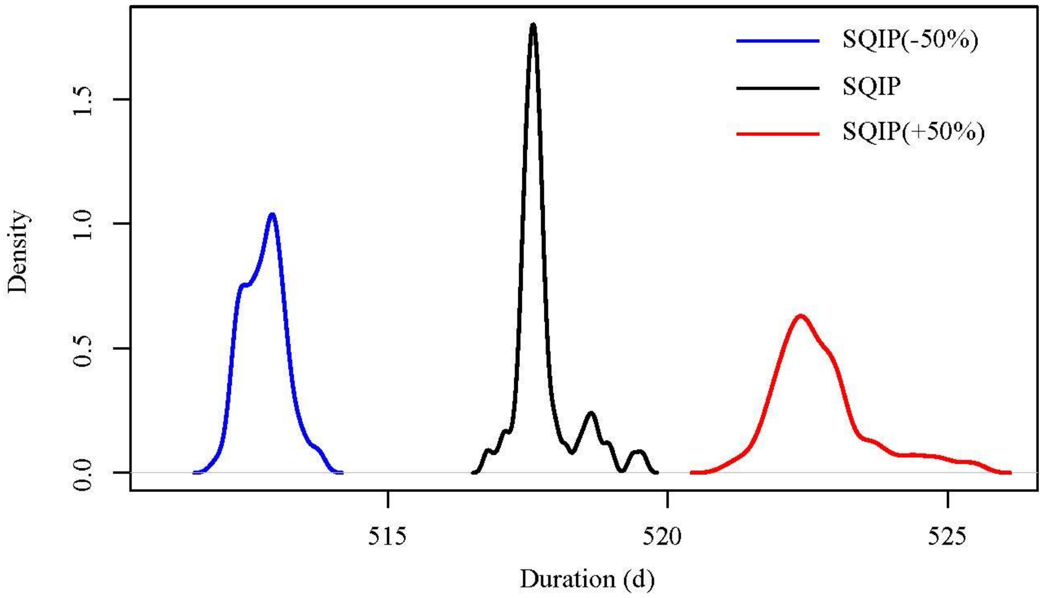


Figure 7.36 Curves of density function SQIP (–50%), SQIP, and SQIP (+50%)

(5) Scenario E

The width of range (28.3) in E2 decreased by 4.71%, while the width of range (34.4) in E3 increased by 15.83%. The average delay decreased by 41.57% in E2 (36.4) and increased by 44.78% in E3 (90.2), as shown in Figure 7.37 and Table 7.5. Based on the above analysis, IVPCBAL contributes most to the combination. Therefore, controlling IVPCBAL can reduce the effect of the combination effectively.

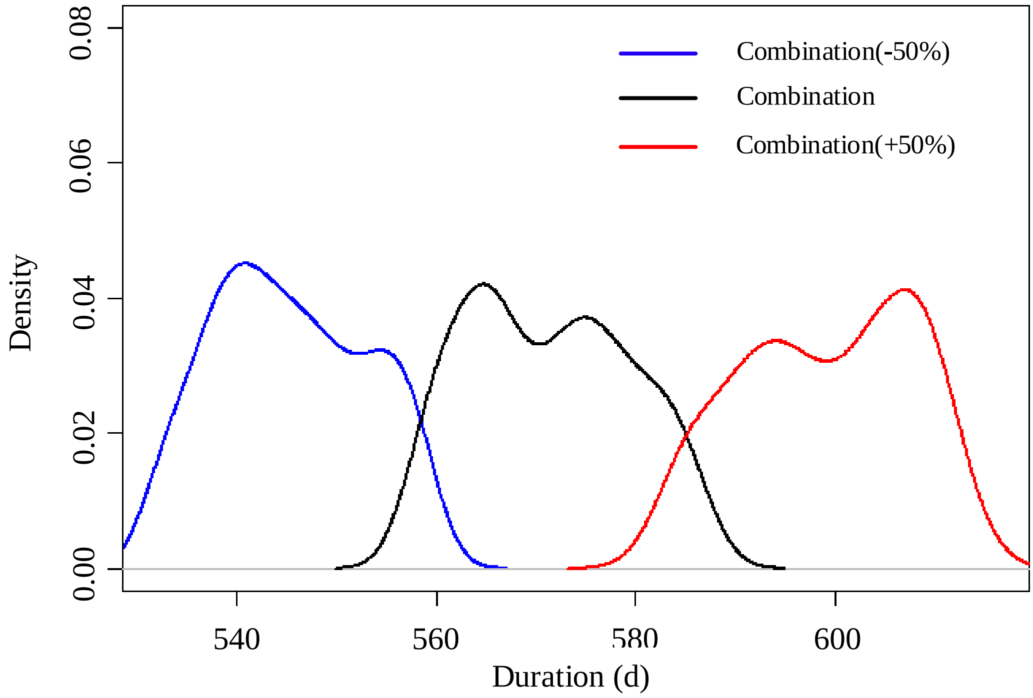


Figure 7.37 Curves of density function Combination (–50%), Combination and Combination (+50%)

Table 7.5 Statistical information of duration under different risks

Category	Mean (d)	Median (d)	Range (d)	Standard deviation
IVPCBAL (–50%)	517.6	517.5	516.7-518.6	0.39
IVPCBAL (+50%)	535.7	535.3	533.6-538.3	1.08
MSSBC (–50%)	515.4	515.3	514.7-516.3	0.31
MSSBC (+50%)	529.0	528.9	527.7-531.5	0.85
SQIP (–50%)	512.8	512.8	511.9-513.8	0.37
SQIP (+50%)	522.7	522.5	521.0-525.5	0.86

TCBM (–50%)	513.4	513.4	512.8-514.4	0.30
TCBM (+50%)	523.5	523.3	522.0-525.8	0.79
Combination (–50%)	545.4	544.9	531.7-560.0	7.62
Combination	571.3	571.3	557.6-587.3	8.11
Combination (+50%)	599.2	599.5	581.2-615.6	8.60

Overall, the top four schedule risks can be divided into two level. The schedule risks of weak level contain MSSBC, TCBM, and SQIP. When they decreased by 50%, the average schedule delays are between 3 and 8 days, and the ranges of schedule are between 511 and 517 days; when they are increased by 50%, the average schedule delays are between 13 and 20 days, and the ranges of schedule are between 521 and 532 days. The typical strong schedule is IVPCBAL, which contributes more to the schedule delay. When it is decreased by 50%, the average schedule delay (8.6) is still larger than that of the risks in the weak level, and the ranges of schedule (516.7, 518.6) is larger than risks in the weak level. When it is increased by 50%, the average schedule delay of 26.7 is much more than that of the risk in weak level, and the ranges of schedule (533.6, 538.3) are also much greater than the risks in the weak level category. Moreover, the average delay of E1, is 34.88% larger than the simple sum of A1, B1, C1, and D1; the average delay of E2, are 32.26% larger than the simple sum of A2, B2, C2, and D2; the average delay of E3, are 16.96% larger than the simple sum of A3, B3, C3, and D3.

The scenario simulation results indicate that schedule risks are not isolated with each other, with interrelationships and interactions existing among different schedule risks. The integrated effect of multiple schedule risks on the schedule performance of PHP tends to be greater than the simple sum of the single separated risk, showing amplified effectiveness.

7.5 Chapter Summary

In summary, the above simulation results demonstrate that (1) schedule risks are not isolated, with interrelationships and interactions existing among different schedule risks; (2) the degree of the influence on schedule performance varies across the timeline of the project. Generally, the later the occurrence time of risks, the more significant influence the risks would have on the schedule performance of PHP; (3) the integrated effect of multiple schedule risks on the schedule performance of PHP is greater than the simple sum of the single separated risk. This finding implies that the PHP system is an organic whole that operates in a highly iterative manner, such that one verified factor within the system may result in another enhancement in a blown-up feedback loop, thereby leading to amplified effectiveness. A deeper understanding of this "systemic" behavior can provide a valuable perspective to managers, in which the combined effect of possible risk mitigation measures should be fully considered to achieve the expected performance. The process of devising scenarios of risk mitigation solution offers specific guides on proposing simulation scenarios for the hybrid dynamic model. The simulation results are informative in facilitating promising solutions for mitigating schedule risks and enhancing schedule performance of the PHP project.

CHAPTER 8 Solutions for Mitigating Schedule Risks in Prefabrication Housing Production

8.1 Introduction

After the risk identification in Chapter 4, model development for risk assessment in Chapter 5 and 6, risk scenario analysis in Chapter 7, this chapter intends to put forward possible solutions for handling the surveyed schedule risks in prefabrication housing production. RFID-enabled platform deploying BIM to re-engineer offshore prefabricated construction processes, which are proposed based on the analyzed schedule risks for solving schedule delay problems in prefabrication housing production, offers various technical and managerial solutions for mitigating potential schedule risks and improving schedule management level of PHP in Hong Kong.

8.2 Critical Schedule Risks and Corresponding Challenges

In consolidating the results of SNA indicators and schedule performance by the hybrid dynamic model in previous chapters, a list of 12 critical schedule risks and relationships is listed as shown in Table 8.1. The next step is to comprehend the actual meanings of these critical risks and links to ultimately summarize the major challenges faced by stakeholders in PHP under intricate concern interactions. This step can be accomplished by categorizing the critical risks and interactions based on their actual meanings, as presented in Table 8.1.

Table 8.1 Critical stakeholder risks and interactions

Challenges in the schedule management of PHP	Critical risks	Risk description	Associated stakeholder	Associated critical links
(1) Inefficiency in transportation and high cost of cross-border logistics	S5R24	Logistics information inconsistency because of human errors	Logistics	S2R3-S3R15
	S2R3	Low information interoperability between different enterprise resource planning systems	Designer	S2R3-S4R16
(2) Inefficient installation management because of compact space	S3R15	Delay of the delivery of precast element to site	Main contractor	S5R24-S3R15
	S6R29	Installation error of precast elements	Assembly company	S4R16-S6R29
(3) Inefficient information transmission between the	S2R7	Design change	Designer	S2R7-S1R2
	S1R2	Inefficiency of design approval	Client	S2R7-S1R2

design and prefabrication stages				
(4) Lack of interoperability between various stakeholders and their heterogeneous enterprise information systems (EIS)	S6R28	Tower crane breakdown and maintenance	Assembly company	S6R28-S3R15
	S6R27	Slow quality inspection procedures	Assembly company	S2R3-S6R27
(5) Information gaps among stakeholders, technologies, and processes	S2R10	Inefficient design data transition	Designer	S2R10-S6R29
	S4R16	Design information gap between designer and manufacturer	Manufacturer	S4R16-S2R7
(6) Insufficient information storage method of precast elements	S3R11	Inefficient verification of precast components because of ambiguous labels	Main contractor	S4R16-S5R24
(7) Lack of real-time information visibility and traceability	S4R20	Misplacement on the storage site because of carelessness	Manufacturer	S2R3-S4R20

Two relationships (including "S2R3-S3R15" and "S2R3-S4R16") describe risks about information inconsistency among different enterprise systems, which may delay the delivery of precast elements to the site in the process of PHP, whereas the two critical risks "S5R24" and "S2R3" also shed light on the logistics information inconsistency and low information interoperability. Consequently, they are put under the same category, and one major stakeholder challenge is determined: "Inefficiency in transportation and high cost of cross-border logistics". Following the same principle, a total of seven major challenges encountered by stakeholders in the management of PHP project are summarized: (1) Inefficiency in transportation and high cost of cross-border logistics, (2) Inefficient installation management because of compact space, (3) Inefficient information transmission between the design and prefabrication stages , (4) Lack of interoperability between various stakeholders and their heterogeneous enterprise information systems (EIS), and (5) Information gaps among stakeholders, technologies, and processes, (6) Insufficient information storage method of precast elements, (7) Lack of real-time information visibility and traceability. In the next section, these seven challenges are further investigated, and the corresponding managerial and technical solutions are developed according to the SNA results to handle the identified challenges and mitigate critical schedule risks in PHP project.

8.3 BIM-centered Platform for Handling the Challenges

The introduced SNA indicators and schedule performance simulated by the hybrid dynamic model provide useful information to help project teams understand the direct schedule risks and propagated interactions, whereas this section mainly focuses on proposing effective risk mitigation solutions to handle the critical risks and interactions obtained in the previous sections. These managerial and technical solutions are proposed as shown in the Table 8.2, in an attempt to achieve the following three fundamental goals: (1) to resolve critical schedule risks, (2) mitigate critical schedule risk interactions, and (3) enhance communication among critical stakeholders. With these goals, an RFID-enabled Platform is proposed in this study to resolve risks, mitigate interactions, and enhance communication among stakeholders in the PHP.

Table 8.2 RFID-enabled platform and corresponding schedule risks and challenges to be handled

Development of RFID-enabled Platform	Required Functions to handle challenges and mitigate schedule risks in PHP	Challenges in PHP	Critical Schedule Risks
RFID-enabled platform deploying BIM to re-engineer offshore prefabricated construction processes: Step 1 - map the offshore prefabrication processes in the HK-PRD setting;	Just-In-Time (JIT) delivery and assembly in compact site area	Inefficient installation management because of compact space	Delay of the delivery of precast element to site
			Installation error of precast elements
	Production information sharing between Prefabrication manufacturer and logistics and assembly companies that lead to extra negotiation time	Inefficiency in transportation and high cost of cross-border logistics	Logistics information inconsistency because of human errors
			Low information interoperability between different

Step 2 - obtain information flow throughout the offshore prefabricated construction processes; Step 3 - develop a Web portal based on service-oriented architecture; Step 4 - integrate Auto-ID technologies to improve information interoperability as well as real-time information visibility and traceability of offshore prefabrication construction; Step 5 - integrate people, offshore prefabrication processes, information flow, and technologies in a BIM-centered system.			enterprise resource planning systems
	Embedding the design information in the prefabrication components for further use	Lack of interoperability between various stakeholders and their heterogeneous enterprise information systems (EIS)	Tower crane breakdown and maintenance
			Slow quality inspection procedures
	Efficient communication among stakeholders and managers	Inefficient information transmission between the design and prefabrication stages	Design change
			Inefficiency of design approval
	Passing the design information to the manufacturers without any ambiguity	Information gaps among stakeholders, technologies, and processes	Inefficient design data transition
			Design information gap between designer and manufacturer
	Efficient identification and verification of proper precast components	Insufficient information storage method of precast elements	Inefficient verification of precast components because of ambiguous labels
		Lack of real-time information visibility and traceability	Misplacement on the storage site because of carelessness

The innovative platform is developed by deploying BIM as the basic infrastructure underlying the system structure to meet with required functions to handle challenges and mitigate schedule risks in prefabrication housing production as shown in the Figure 8.1.

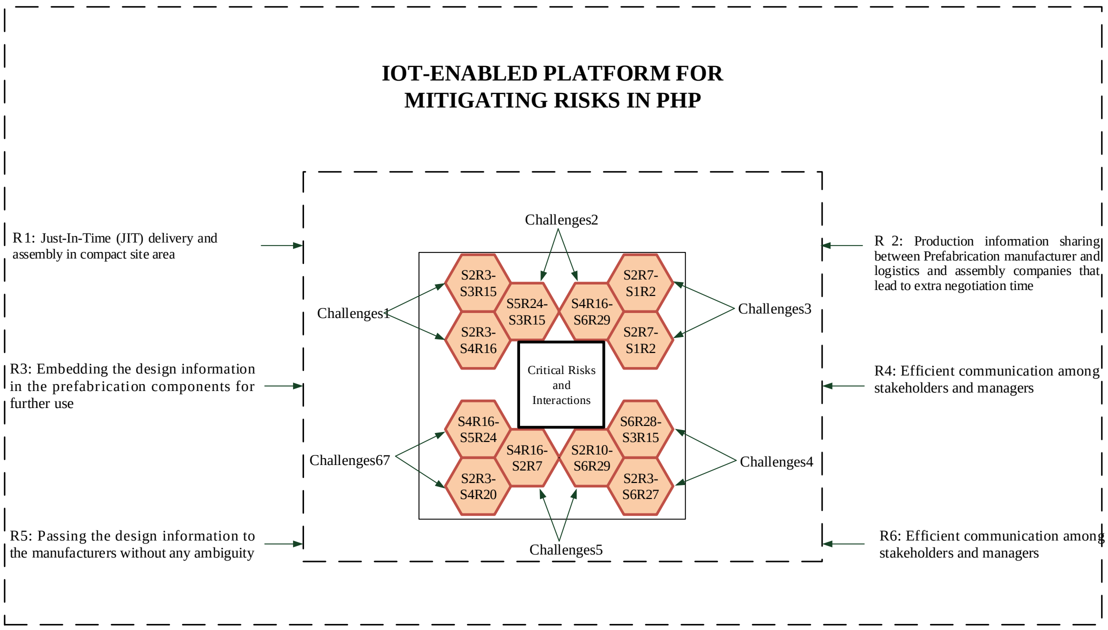


Figure 8.1 Framework for understanding risks, challenges, and required functions for RFID-enabled platform

The platform may position Hong Kong as the leading region in the use of BIM to re-engineer architecture, engineering, and construction processes, particularly for offshore prefabricated construction processes. The platform emphasizes the integration of stakeholders to encourage communication and coordination based on BIM. An innovation on the structural design of the proposed platform is the use of BIM as an information hub to connect smart construction objects (SCOs) and create an intelligent construction environment. BIM currently deposits a hub of information received from designers and engineers. RFID systems will be connected to BIM models by developing further existing application program interface (API). This process may lead to a popular plug-in to integrate RFID technologies with BIM. Currently, only few plug-ins, such as clash detection and BQ generation, have been observed in the industry, while the investigations the methods to link RFID and BIM are few and far between. These limitations may also provide an opportunity to connect BIM and RFID given that materials based on BIM can be easily purchased, and other resources are available around the world. Besides, using the graphic information generated from the RFID-enabled BIM platform to instruct the entire offshore prefabrication housing production is considered an innovation. For example, one may perceive IKEA furniture and its “assembly instruction” as a highly innovative approach. Currently, 2D tools, such as Gantt chart, are adopted to indicate progress in processes. BIM is used only in conducting construction rehearsals for a standard floor to optimize the configuration of construction resources. This platform should be able to generate innovative visual “instructions” to configure resources, trace and track prefabrication components alongside the logistics and supply chain, and to assemble them on site, such that the weaknesses and threats identified in the SWOTs can be solved. Detailed development function and development processes can be divided into 5 steps as follow.

Step 1: Map the offshore prefabrication processes in the HK-PRD setting

Effort should be exerted in understanding the processes and relevant constraints to enable the separation of design, manufacturing, storage, transportation, and assembly from one another. Previous studies have explored the processes in construction project management to plan resource allocation. However, the management skills and relevant information required by prefabrication construction differ significantly from what on-site projects often encounter in the construction industry. Therefore, mapping offshore prefabrication processes for further analysis, which is mainly the concern of HKHA (particularly in the HK-PRD setting), is necessary.

The aforementioned innovative platform serves as a framework for mapping the offshore prefabrication processes; however, more effort should be focused on developing a more detailed description of these processes. For this purpose, case studies should be conducted in three types of offshore prefabrication plants, namely manufacturing, logistics, and on site assembly. A case study research of three companies should be conducted to allow the exploration and understanding of complex issues based on collected primary data. This method can be considered as robust, particularly when a holistic, in-depth investigation is required. A combination of qualitative methods (e.g., semi-structured interviews, focus group meetings, non-participant observation, field notes, and analysis of documents and materials) should be used to investigate information flow throughout the processes.

Step 2: Obtain information flow throughout the offshore prefabricated construction processes

Achieving the objective of enhancing housing production by re-engineering the offshore prefabrication processes requires that all involved parties, particularly HKHA and its associated entities, align the processes based on available information to form better decisions. Information is recognized as a core element for successful management. Mapping the offshore prefabrication processes eases obtaining the information flow throughout these processes.

The data flow diagram (DFD) originally developed by IBM will be adopted. DFD is a significant modeling technique used in analyzing and constructing information processes. DFD refers to an illustration that explains the course or movement of information in a process. Fisher and Shen (1992) utilized this tool to map the flow of data within a construction company to facilitate better information management.

The current study will focus on the use of DFD on three specific and critical scenarios, including prefabricated construction, cross-border logistics, and on-site assembly, which are mostly HKHA concerns. The first focus is on how design information is composed and decomposed by designers and passed on to the precast component plants. Analysis of the drawings will identify such information as design drawing and rationales created by using ArchiCAD or other BIM software. Parallel to this analysis is the information of the client’s order sent to the plant. Formal and informal communications (e.g., drawings, briefings, and e-mails) among the different parties (e.g., clients, designers, and manufacturers) involved in offshore prefabricated construction processes will be obtained, analyzed, and mapped using DFD. The interoperability of information flow will be of particular interest in aligning the processes.

The second focus is on information flow from storage and transportation to sites. Transporting prefabricated building components to HKHA construction sites, such as Tung Tau Cottage Area East, is often outsourced to professional logistics companies. Professional logistics companies are responsible not only for loading, fastening, and unloading prefabricated building components but also for customs clearance. The information flow can be obtained by analyzing the contracts between the plant and logistic companies, as well as their working files for custom clearance. Therefore, maintaining real-time information visibility and traceability of the precreation components is critical to ensuring the smooth delivery of logistics and supplies to the sites.

The third focus is on the information flow from factory to on-site assembly. Compact sites in Hong Kong necessitate that prefabricated components must reach construction sites efficiently to fit into the on-going job on site. Therefore, not only is real-time information visibility and traceability critical but the sequence and positions of the prefabricated components should also be well organized. This part of information flow can be obtained by analyzing the working files, drawings, and field notes, as well as through non-participant observation and semi-structured interviews with site managers. The information obtained will be significant HKHA in formulating high-level decision-making after providing feedback to BIM or HOMES.

Step 3: Develop a Web portal based on service-oriented architecture

A Web portal should be developed and operated following a standard service-oriented architecture to enhance information interoperability among EIS of various stakeholders. A complete service-oriented architecture process involves three main phases, namely, publish, search, and invoke. Service providers/developers set up Web services at sites of selected servers and publish the particulars, including but not limited to interfacial description capability and location. The required Web services can be searched and selected by service consumers from the published database. Prior to the solicitation of services, values must be defined clearly and delivered over a detailed application process.

The three typical phases involve three fundamental Web services tools, including universal description, discovery and integration (UDDI); Web services description language (WSDL); and simple object access protocol (SOAP). UDDI is a platform-independent, XML-based registry for distributed services to list themselves on the Internet. The WSDL standard provides a uniform method for describing the abstract interface and protocol bindings of these services. This tool further describes what a Web service can do, where it resides, and how to invoke it. SOAP is a platform-independent protocol for invoking the distributed Web services through the exchange of XML-based messages (Pang et al. 2014).

The concept of service in service-oriented architecture (SOA) is extended in the proposed platform. Various related application systems or information sources are defined as services, which can be classified into three categories. The first category includes standard optimization software where scheduling and planning algorithms are devised and deployed. Under the cloud computing concept, this category belongs to software as a service. The second category includes third-party native enterprise information/application platform. Examples of this platform include various BIM and HOMES modules. This category considers platform as a service. The third category includes data sources obtained directly from different types of native database systems. Adaptation is provided to convert information sources into standard Web services with standard output. This category presents the database concept as a service in cloud computing.

The proposed Web portal is a hybrid service-oriented architecture where software, platform, and database as services are combined innovatively to ensure the efficient working of different functions required by various stakeholders engaged in prefabrication construction

Step 4: Integrate Auto-ID technologies to improve information interoperability as well as real-time information visibility and traceability of the offshore prefabrication construction

The objective of enhancing housing production through re-engineering of offshore prefabrication processes requires all parties, particularly HKHA and its associated entities, to align the processes based on available information to form better decisions. Information is recognized as a core element of successful management and mapping the offshore prefabrication processes enables the information flow to be obtained throughout these processes. DFD should be adopted to ensure ease in obtaining the information flow. DFD refers to an illustration that explains the course or movement of information in a process. The information identified in DFD will be structured, stored, retrieved, visualized, and traced in real-time to support various decision-making processes within HKHA. This process will be accomplished by adopting Auto-ID technologies, such as barcode, quick response code, RFID, and magnetic strip. Among these Auto-ID technologies, RFID is the most promising in terms of obtaining real-time information among prefabrication manufacturing, logistics, and on-site constructions.

RFID tags can be used to store information, while RFID writers with USB connection to computers can assist in encoding information into the tags. Previous studies have suggested that as a rule of thumb, the information in the tags should be brief. For example, a serial code, with its complex structure as stated in the data flow diagram, should be placed in a backend system; the rationale for this step is for security reasons and to use the processing power provided by the backend system. RFID readers (e.g., handshaking devices) will be used to retrieve information from both the tags and the backend system. Programming based on the APIs of RFID will be necessary to complete the functions.

Step 5: Integrate people, offshore prefabrication processes, information flow, and technologies in a BIM-centered system

The task of integrating people, offshore prefabrication processes, information flow, and technologies in a BIM-centered system can be understood as an actual example of the IoT (Internet of Things). Figure 8.2 shows the BIM-centered system prototype. In the prototype, a gateway will be developed to connect the RFID subsystem with the BIM subsystem. Graphically, this connection can be considered as a gateway between BIM and the backend system. A data exchange protocol will be developed at a lower level and an API at a higher level; these two elements will enable information synchronization between the two subsystems. One proposal suggested that the data exchange protocol be based on the Industry Foundation Classes (IFC) standards because of the interoperability of the gateway subsystem. IFC is published by the International Alliance for Interoperability and as a major data standard for BIM, IFC plays an important role in the process because IFC is a standard for globally sharing data throughout the project life cycle across disciplines and technical applications in the construction industry. The information collected and mapped in DFD will be incorporated into the BIM subsystem. Various APIs have been developed to facilitate further developments on the BIM software (e.g., ArchiCAD, AutoCAD, Revit, and NavisWork) and enable users to connect to the Auto-ID subsystem. Of particular interest in this case is enabling the BIM subsystem to "talk" to the building components through Auto-ID technologies and respond to the intervention of users when necessary. Microsoft Visual Studio is the ideal programming environment for developing gateway.

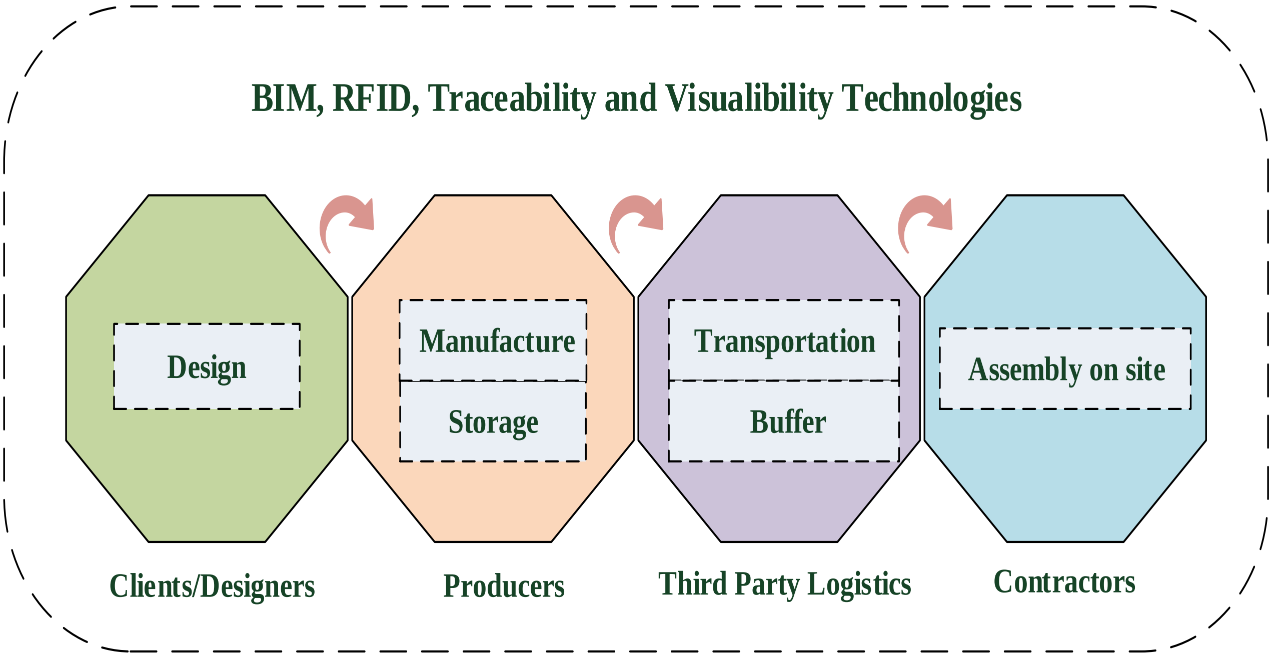


Figure 8.2 Prototype of the proposed RFID-enabled BIM platform for prefabrication housing production

Once the Auto-ID subsystem and gateway are developed, the next step is to encapsulate their functionalities for industrial users. Computer technologies, such as Google Sketch Up and Microsoft Visual Studio, will be used to develop the operable system. All these technologies, including SCOs, RFID, wireless, and BIM, have been discussed and tested considerably in the construction industry. Hence, in this case, the innovative action is to organize these technologies cohesively to improve current offshore prefabricated construction processes. Not all of the aforementioned technologies are completely available and are still subject to further development. The integration will transfer and upgrade the managerial level of HKHA and the construction industry in both Hong Kong and PRD in a real-time, interoperable, and closed-loop manner.

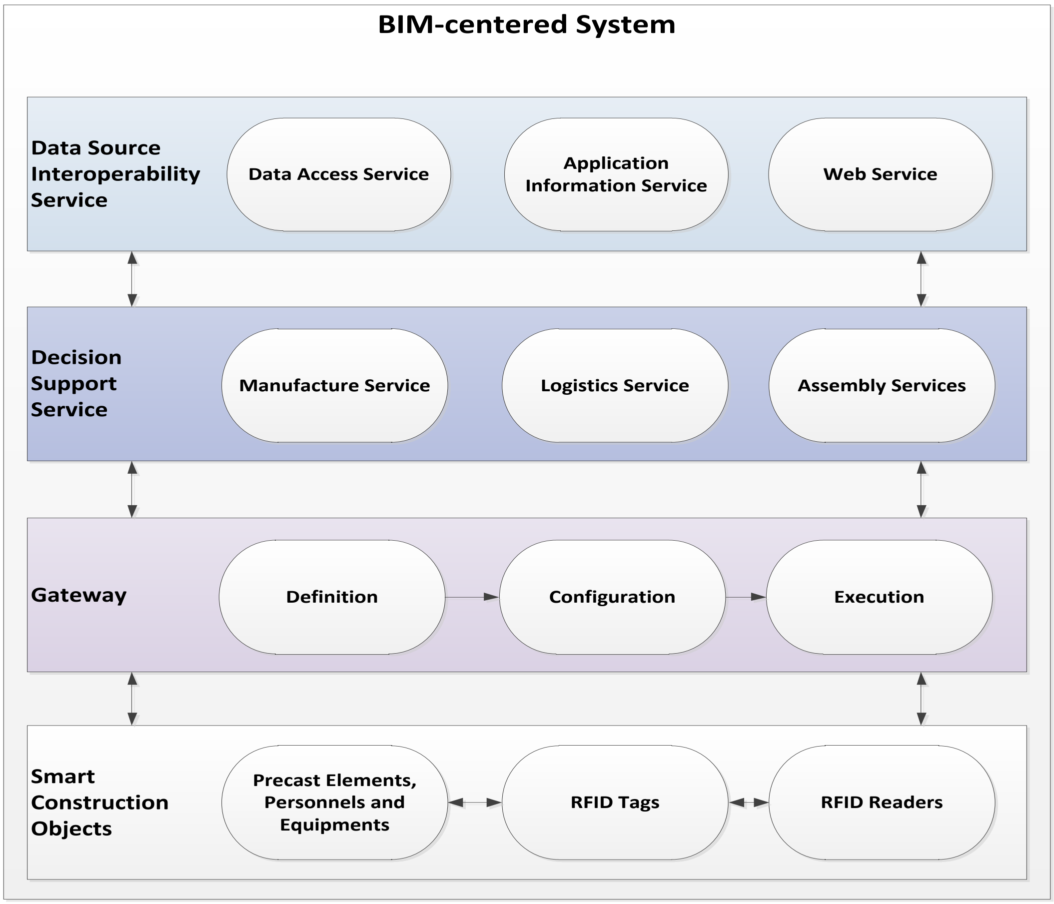


Figure 8.3 Overview of the BIM-centered system

Figure 8.3 shows that the BIM-centered system can be developed further into four key components, namely, the SCOs, gateway, decision support service, and data source interoperability service. Through the development of the RFID-enabled platform, the identified critical schedule risks would be minimized and mitigated and the management level of PHP would be generally enhanced. The abundant paper-based records can be subsequently freed for many processes and only reserved for verification in key processes, which will help enhance efficiency of installation management, information storage and transportation. The usage of BIM technique can also be henceforth extended to construction phase. If the histories of building components and the project progress are kept for future operation and maintenance phase, the BIM of built works can also be utilized, which will help fill the information gaps among stakeholders, technologies, and processes and enhance interoperability between various stakeholders and their heterogeneous. It should be noticed that the platform is in fact not changing the core processes of the current business processes. Instead, some real-time data gathering is attached to the processes in convenient ways for the operators. For example, an inspector in the production factory can scan the component object for a confirmation of original design. The disseminations of the real-time data and the status of the virtual models are also suggested in multiple ways, while App and SMS notification can be used to guide the relevant workers, greatly improving real-time information visibility and traceability.

Changes can be brought to the prefabrication manufactory in four aspects. Firstly, the data required by the factory and those exchanged with other stakeholders becomes more accurate and reliable. Secondly, the ability of responding to design changes and job plan changes are much stronger. The management of the factory goes a bit more efficient. Lastly, the construction resources can be less wasted henceforth. Cross-border logistics can also be improved. Firstly, the logistics service provider can adapt better to the factory and the main contractor's business processes. Secondly, as a proportion of management users, coordinators in logistics companies can have a dynamic tracking and control function for their own. Information sharing, which is usually a shortcoming in small business, can attract attention and positive response from their partners. Lastly, the cross-border logistic and supply chain management can therefore become more efficient and time-saving. The main contractor can be benefitted from knowing the real-time information of prefabrication components. The data collection on site becomes effective, reliable and more value-added. Therefore, the whole on-site team of the main contractor can be more resilient when facing changes, such as design changes, order changes, changes due to repairing defective components, etc. The housing production related departments, can be benefited from obtaining real-time information from the prefabrication production to the on-site assembly. The visibility and traceability tools provide useful tools for monitoring and checking the status and quality problems. The multi-dimensional information of cost and progress provided by the platform, can help the client to manage the progress and arrange payment accordingly. Historical information of the stakeholder's performance stored in the platform can even be used for facilitating contractor and sub-contractor selection.

8.4 Simulated Evaluation of the Effectiveness of the BIM-centered Platform

Built on the theoretical assumption that network complexity can be decreased by removing key nodes and links, several BIM-centered strategies were suggested to improve stakeholder coordination in PHP, which would ultimately help to address stakeholder risks and eliminate risk relationships highly interconnected with other risks. Network density and cohesion were recalculated to simulate the effectiveness of the suggested strategies.

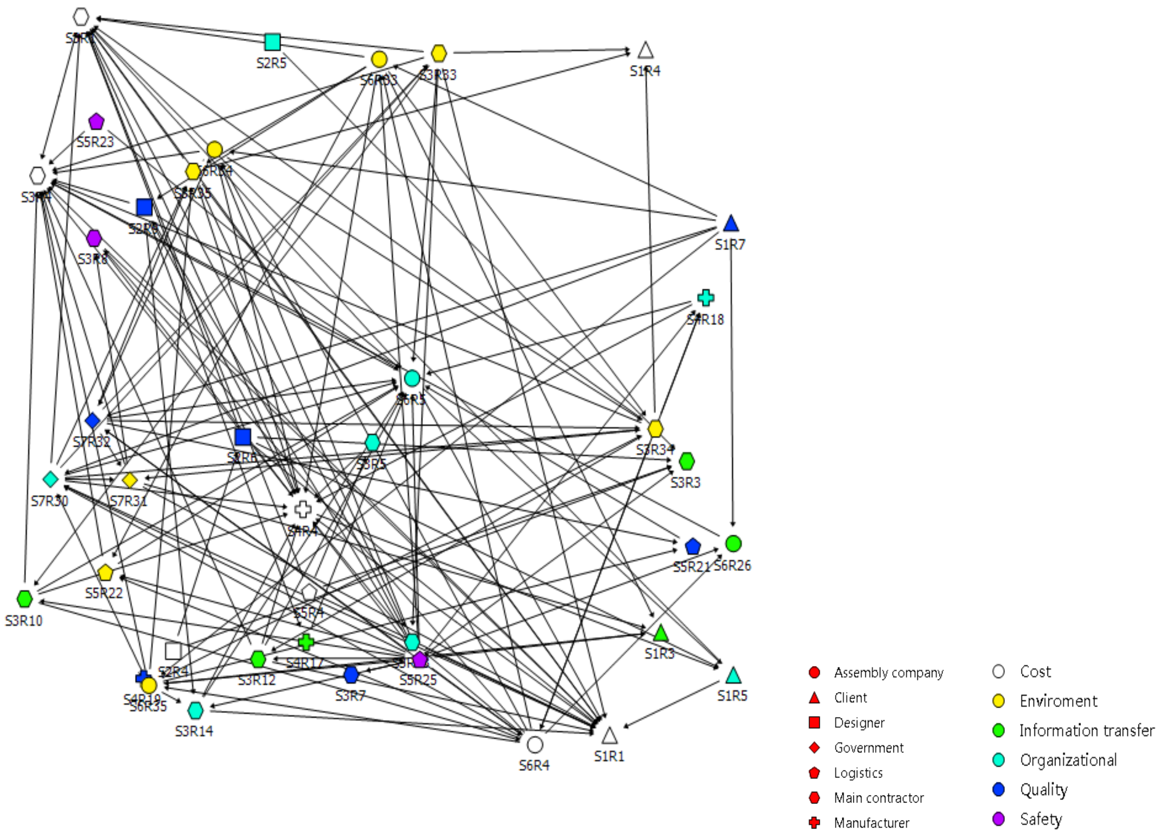


Figure 8.4 Risk network after mitigating critical risks and interactions

By recalculating the key SNA indicators, this section illustrates an immediate simulation of the stakeholder issue network after the implementation of the proposed strategies in the above section. An important assumption here is that all of the proposed strategies are effectively implemented, and corresponding critical risks and interactions are eliminated. The simulation serves as a reference tool to test the effectiveness of the suggested strategies and to predict the potential of network complexity reduction. After the suggested risk mitigation solutions are performed mainly by resolving the critical risks and links in Table 5, the network in the case study is reduced to a structure of 40 nodes and 151 interactions, as shown in Figure 8.4. In comparing this network to the initial network in Figure 3, three observations can be made: (1) The network is less condensed by reducing the links considerably. (2) The number of isolates increases, implying that more stakeholder risks can be handled individually without propagating effects. (3) The dyadic interactions increase where they are easier to be managed through the consideration of the particular 151 cause-and-effect relations. The reduced network complexity is also reflected by the values of network properties. The density and cohesion of the network in Figure 8.4 are 0.097 and 0.071, respectively. Compared with the original network density and cohesion of 0.225 and 0.962, respectively, these values are reduced by 90.3% and 92.9%, respectively. The betweenness centrality values for both risks and links are largely reduced compared to the values in Table 8.3. According to the simulation results, the suggested risk mitigation solutions are useful to decrease the network complexity and therefore improve the effectiveness of the stakeholder management process. In evaluating their usefulness from a more practical perspective, continuous monitoring and assessment of the network dynamics is deemed necessary. The performance of the mitigation actions should be reviewed and monitored periodically in the future.

Table 8.3 Top risks and interactions after risks mitigation

Rank	**Node Betweenness Centrality**			**Link Betweenness Centrality**		
	Original	After	Change	Original	After	Change
1	0.127	0.082	-35.6%	51.5	49.0	-4.9%
2	0.080	0.054	-33.4%	51.2	43.0	-16.0%
3	0.069	0.039	-43.0%	51.1	29.9	-41.5%
4	0.061	0.022	-63.4%	38.5	25.5	-33.8%
5	0.054	0.020	-62.1%	36.4	21.0	-42.3%
6	0.049	0.018	-62.8%	34.8	20.8	-40.2%
7	0.047	0.017	-64.6%	34.6	20.8	-39.9%
8	0.046	0.016	-65.7%	32.4	20.2	-37.7%
9	0.041	0.015	-63.3%	32.1	19.7	-38.6%
10	0.041	0.013	-68.4%	29.5	18.8	-36.3%

8.5 Chapter Summary

This chapter summarizes critical schedule risks and determines corresponding challenges to be handled in PHP. Required functions are identified and RFID-enabled platform deploying BIM to re-engineer offshore prefabricated construction processes are proposed to provide various technical and managerial solutions for mitigating potential schedule risks and improving schedule management level of PHP in Hong Kong. The effectiveness of the BIM-centered platform is validated through the use of SNA model from the network analysis perspective.

CHAPTER 9 Conclusions

9.1 Introduction

This chapter draws research conclusions. The three objectives of the research proposed at the beginning are reviewed to check whether all the objective are achieved. Key conclusions are summarized, and the research significance and contributions to the existing knowledge are concluded. Limitations and future research directions are discussed.

9.2 Review of Research Objectives

Disadvantages of fragmentation, discontinuity, and poor interoperability in prefabrication housing production (PHP) may cause a serial of risks that have significant adverse effects on the schedule performance of PHP in Hong Kong. Consequently, delay frequently occurs in PHP projects despite the promise of the government to meet the increased demand for housing. This study opines that effective management of schedule risks of PHP should envisage the key characteristics of prefabrication housing production to take dynamic interrelationships underlying various schedule risks in the PHP system for consideration from a dynamic point of view. However, established approaches by previous studies have not comprehensively understand the key characteristics of prefabrication housing production when conducting research on schedule risk management in PHP practices and failed to prevent frequent schedule delay problems in public prefabrication housing delivery in Hong Kong. Therefore, the research aim is to develop an effective model to manage schedule risks in prefabrication housing production in Hong Kong. Three specific objectives are needed to be achieved to fulfill the research aim, including:

(1) To identify and analyze critical schedule risks that affect the schedule of prefabrication housing production with consideration of involved stakeholders;

(2) To develop a hybrid dynamic model for assessing and simulating potential impacts of the identified major risks on the schedule performance of prefabrication housing production;

(3) To propose corresponding solutions for dealing with major schedule risks in prefabrication housing production.

9.3 Research Conclusions

This study proposes SNA and hybrid dynamic models for identifying, analyzing and evaluating schedule risks of PHP, facilitating the housing production industry to manage schedule risk in a more effective way. The three objectives of this research have been completed, including: (1) the identification and analyses of critical schedule risks that affect the schedule of prefabrication housing production with consideration of involved stakeholders; (2) the development of the hybrid dynamic model for evaluating and simulating potential impacts of the identified major risks on the schedule performance of prefabrication housing production; (3) corresponding managerial and technical solutions are put forwarded for dealing with major schedule risks in prefabrication housing production. Through achieving the three objectives, conclusions scattered throughout the thesis are summarized.

(1) Current management practices of schedule risks in prefabrication housing production project are needed to be further improved

Prior to improving the current practices and research, critical review has been conducted to examine the limitations of current practice and research. The review of literatures discloses prominent limitations of current practices and research, which includes: （a） processes of prefabrication housing production have been treated separately;（b） few research has been dedicated to risk management of PHP with consideration of involved stakeholders; （c） activities in different PHP processes and variables within the specific process are generally viewed as independent rather than interdependent; （d） most research on the risk management of PHP has been conducted from a static point of view. Nevertheless, it is stated by recent research that PHP is complex as a whole with various stakeholders involved, while activities in different PHP processes and variables within the specific process are largely interdependent. Also, schedule risks management of PHP is dynamic with the schedule performance of PHP varies all the time when the PHP project proceeds forward. As such, current practices of the management of schedule risks in prefabrication housing production project are needed to be further improved by envisaging the key characteristics of PHP.

(2) The SNA model is effective for identifying and understanding major schedule risks with consideration of stakeholders involved in PHP project

Previous research on the risks in prefabrication construction projects has been treated them as mutually isolated factors and confined to issues of completeness and accuracy from a static point of view without consideration of related stakeholders and their cause-and-effect relationships. However, in reality, most schedule risks in PHP project are closely interrelated with each other and associated with various stakeholders involved in the whole production process. This study applies social network analysis (SNA) to recognize and investigate the underlying network of stakeholder-associated risk factors in prefabrication housing production projects. The SNA model is approved to be an effective tool for identifying and understanding the major characteristics of schedule risks. Critical risks and relationships that have important roles in structuring the entire network of PHP are identified and analyzed. These identified critical risks and relationships not only provide more comprehensive understanding of the management of schedule performance of PHP and form a solid foundation for further modeling and simulation, but also serve as valuable references for future research with similar research objectives.

(3) The hybrid dynamic model is effective and applicable for evaluating the impact of schedule risks in PHP project

The hybrid dynamic model developed by integrating SD and DES can fill the research gaps of previous research on risk evaluation, serving as effective and applicable tool for evaluating the impact of schedule risks in PHP project. To be specific, with hybrid system dynamics and discrete event simulation approach, interrelationships underlying activities and variables within the PHP can be better depicted, modeled and simulated. Moreover, hybrid SD and DES method facilitates the examination of how the behavior of PHP system vary over time along with the change of various schedule variables from a dynamic perspective. DES specializes in modeling a complex system from detailed procedure to simulate behavior of individual components in dynamic manner, while SD approach focuses on developing model to handle stated characteristics because it can simplify a complex system into operable units through its special analytical tools. The hybrid DES and SD method provides effective tool for considering from both perspectives of detailed procedure and stated characteristics, enabling project managers to gain a deeper insight into schedule management and acquire a multidimensional understanding of schedule delay with consideration of both the short-term operational procedures and long term risk effect, and making the model to simulate how the schedule performance of the system of PHP dynamically change throughout the simulation period in a more effective way. Lastly, three types of variables are involved in the hybrid dynamic model, namely deterministic, and dependent, and uncertain, each type of variable are properly quantified based on different quantification method. The strict verification and validation process reveals that the model is strong and applicable for evaluating impacts of schedule risks in PHP project.

(4) Simulation Scenario analysis functions as an experiment platform to simulate and analyze the effects of schedule risks and managerial and technical solutions

Though conducting simulation analyses for a series of devised scenarios, the SNA and the hybrid dynamic model demonstrate their capacity of serving as an experiment platform to model and simulate the impacts of various managerial and technical solutions on the overall schedule performance of PHP throughout the whole supply chain, such that the best implement can be identified in advance.

The simulation results demonstrate that (1) interaction exists among different risk mitigation solutions, and (2) the degree of the influence on schedule performance varies across the timeline of project. The later of the occurrence time of risks, the more significant influence the risks would have on the schedule performance of PHP; (3) the integrated impact of multiple mitigation solutions on the schedule performance of PHP is greater than the simple sum of the two solutions. The implication is that the PHP system is an organic whole running in a highly iterative manner such that one verified factor within the system may result in another enhancement in a blown-up feedback loop, leading to amplified effectiveness. A deeper understanding of this “systemic” behavior can provide a valuable perspective to managers, in which the combined effect of possible risk mitigation measures should be fully considered to achieve the expected performance. The process of devising scenarios of risk mitigation solution offers specific guides on proposing simulation scenarios for the hybrid dynamic model. The simulation results are informative for enlightening promising solutions to mitigate schedule risks and enhance schedule performance of PHP project.

(5) ***RFID- enabled managerial and technical solutions are effective for mitigating schedule risks of PHP***

Through the development of the RFID-enabled platform, the identified critical schedule risks would be effectively minimized and mitigated and the management level of PHP would be generally enhanced. The abundant paper-based records can be subsequently freed for many processes and only reserved for verification in key processes, which will help enhance efficiency of installation management, information storage and transportation. The usage of BIM technique can also be henceforth extended to construction phase. If the histories of building components and the project progress are kept for future operation and maintenance phase, the BIM of built works can also be utilized, which will help fill the information gaps among stakeholders, technologies, and processes and enhance interoperability between various stakeholders and their heterogeneous. The platform is in fact not changing the core processes of the current business processes. Instead, some real-time data gathering is attached to the processes in convenient ways for the operators. An inspector in the production factory can scan the component object for a confirmation of original design. The disseminations of the real-time data and the status of the virtual models are also suggested in multiple ways, while App and SMS notification can be used to guide the relevant workers, greatly improving real-time information visibility and traceability. According to the simulation results for assessing the effectiveness of the mitigation solutions, the managerial and technical solutions are useful to decrease the network complexity and therefore making the management of schedule risks more effective. In evaluating their usefulness from a more practical perspective, continuous monitoring and assessment of the network dynamics is deemed necessary. The performance of the mitigation actions should be reviewed and monitored periodically in the future.

9.4 Contributions of the Research

9.4.1 Contributions to Knowledge

(1) Identification of schedule risks and their interrelationships with consideration of involved stakeholders of PHP provides a new angle to examine the structure and patterning of schedule risks relationships in PHP system, such that the rationale behind of schedule delay and potential influences can be better understood.

The research pioneers to apply SNA model to identify, analyze critical schedule risks and risk interrelationships underlying various risk factors having influence on schedule performance of PHP project with consideration of various involved stakeholders from network perspective. Essential variables and affecting schedule performance of PHP are integrated into the models. All identified variables and their interrelationships provides a new angle to examine the structure and patterning of schedule risks relationships in PHP system, such that the rationale behind of schedule delay and potential influences can be better understood. This serves as a solid foundation for future studies on risk management of PHP, contributing to current knowledge.

(2) The model developed in this research forms an innovative tool for evaluating and simulating the schedule performance of PHP project from a dynamic point of view, with benefits of ease of modifying structure to reflect real situation, performing various sensitive analysis and communicating with simulation results more effectively.

Through applying the hybrid SD and DES approach, this research pioneers to encapsulates SD models into the DES model for simulating system behavior of PHP, forming an innovative research tool for evaluating and simulating the schedule performance underlying various risks of PHP project. Compared to traditional techniques, the strengths of the new research tool include: Firstly, the hybrid dynamic model considers macro and micro levels simultaneously, enabling project managers to gain a deeper insight into schedule management and acquire a multidimensional understanding of schedule delay.

Moreover, the hybrid dynamic model is in nature sufficiently flexible to be used to other PHP projects under other circumstances simply. As system dynamics model in this research is encapsulated into an event of the DES model to constitute a concrete "task module", an activity on node network can be built according to the network planning of other projects with the predefined "task module". The Hybrid SD and DES model has the benefits of ease of modifying structure to reflect real situation, performing various sensitive analysis and communicating with simulation results more effectively. One of the major advantages of the hybrid dynamic model is that the model is in nature sufficiently flexible to incorporate different schedule risk factors and to be used to other PHP projects under other circumstances simply. As system dynamics model in this research is encapsulated into an event of the DES model to constitute a concrete "task module", an activity on node network can be built according to the network planning of other projects with the predefined "task module". What is more, risk import channels that through which the influence of schedule risks flow in are devised by the model. The risk identification process, and influence mechanism are different. The identification process is to identify critical schedule risks for further evaluation and simulation, while influence mechanism is designed as the ports through which the schedule risks flow and ultimately impact the schedule performance of PHP. With the design of the influence mechanism in model, additional identified risks can be easily connected to the model for evaluation. As the hybrid SD and DES model has the benefits of ease of modifying structure and incorporating other schedule risks to reflect real situation, performing various sensitive analysis and communicating with simulation results more effectively, it is easy for the model to adapt and produce valid results.

Lastly, this research pioneers to investigate the management of schedule risks of prefabrication housing production with envisagement of key characteristics of prefabrication housing production, taking dynamic interrelationships underlying various schedule risks in the PHP system for consideration from a dynamic point of view. For this perspective, the study extends the application of hybrid SD and DES approach to the research area of the management of prefabrication construction and provides an experiment platform for debate and improvement in future research.

9.4.2 Contributions to Practice of PHP Industry

(1) This research assists involved stakeholders of PHP to gain insight on the complicated mechanism inherent in the system of PHP, result in better understanding of the cause and effect of schedule delay problems in PHP project from systematic point of view.

Through portrayal of the interrelationships underlying various identified variables, this research provides in-depth understanding on the system of PHP. The process and interrelationships of the activities of prefabrication housing production can be better understood and this research is useful for the involved stakeholders to gain insight on the complicated mechanism inherent in the system of PHP, contributing the practical knowledge of the industry of prefabrication housing production.

(2) This research provides a practical tool for involved stakeholders of PHP to identify, evaluate analyze and simulate schedule risks that might lead to schedule delay, such that corresponding schedule risks can be more effectively handled.

This research provides a practical tool for stakeholders involved in PHP to identify, evaluate and analyze potential schedule risks that might lead to schedule delay, and enable the test of effectiveness of risk mitigation measures prior to implementing them, such that any possible negative impacts can be identified and prevented in advance. Through the application of the developed model, various simulations can be run to figure out appropriate solutions prior to the implementation, such that corresponding schedule risks can be more effectively handled.

9.5 Limitations and Further Research

(1) Limitations

Despite the benefits, the limitations of the hybrid dynamic model developed in the research should be also outlined for its further development and broader application.

(1) Due to great number of interrelationships among the activities and identified variables having influence on schedule performance of PHP project, it is not realistic to comprehensively investigate and build all possible dynamic interactions into the model.

(2) Moreover, due to limited length and time, it is also not practical to devise, model and simulate all possible scenarios to analyze various schedule risks and evaluate all possible impacts of measures for mitigating risks. Due to the limitations of resource, this research only applies the developed model to only one practical project for verification and validation. But the validation case is representative enough as the case is from the public housing project, and in Hong Kong, almost half of houses are public houses that constructed by the public sector such as Hong Kong Housing Authority. Besides, as mentioned above, public housing production often encounter schedule delay problems despite the promise of the government to supply more houses, and for this studied case, the master program has been revised 7 times, it is the typical case that has serious schedule delay problems. For these two points of view, the surveyed case has representativeness.

(3) This research confines its boundary within the schedule performance, while other

performances such as cost, safety, quality and environment are also important for PHP project.

(2) Further research

Despite of the above outlined limitations, the research not only pioneers on managing schedule risks of PHP from a new perspective, but also serving as a solid basis for further research, which may include:

(1) Designing and simulating more scenarios for various schedule risks and risks mitigation measures to test their impacts on the schedule performance of PHP

(2) Improving and extending the applicability of the model to reflect practical project activities through adjusting incorporated variables according to data from more case studies.

(3) Extending the current research boundary to incorporate other performance indicators, such as cost, safety, quality and environment, into the model.

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