SMART WORK PACKAGING FOR CONSTRAINTS MANAGEMENT IN PREFABRICATION HOUSING PRODUCTION

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Smart Work Packaging for Constraints Management in Prefabrication Housing Production

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CERTIFICATE OF ORIGINALITY

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Abstract

The situation in the shortage of public residential housing (PRH) becomes more and more stringent in Hong Kong. According to the Housing Authority of Hong Kong statistics, there were more than 153,300 general applicants for PRH and the average waiting time for them was 5.5 years (at its highest in last two decades) at the end of December 2018. To expedite the supply of PRH, the PRH in Hong Kong has benefited and will continue to benefit significantly from prefabrication housing production (PHP). However, the supply of PRH is still plagued by the pathological schedule delay of PHP. For example, the government planned to construct 13300 flat units of PHP in the financial year of 2016-2017. However, the actual amount is 11276 units, and 15.22% delay occurred. The constraints (e.g., limited space, lack of collision-free path planning, skillful workers shortage) in the fragmented PHP process have been proved to be the primary drivers. The constraints are also the apparent bottlenecks and thus are more predictable than the uncertainties to be improved in the task executions. As such, reliable constraint-free workflows are vital for achieving an industrialized construction environment across design, manufacturing, logistics, and on-site assembly so as to reduce schedule delays and cost overruns. However, the current constraints management approaches are limited to offer smart solutions for achieving adaptivity, autonomy, and sociability in the workflows. e.g., automatic identification and analysis

of constraints and their interrelationships, optimal constraints improvement planning in a dynamic manner, and real-time sensing and tracking constraints status.

The primary aim of this research is to investigate the smart solutions and approaches for constraints management in PHP process to equip the workers with the capacity of modeling, optimizing, and monitoring in the task executions. The specific objectives of this research are as follows: (1) To define the concept and properties of smart work packaging (SWP), specify its functions and paradigm for constraints management (CM), develop its prototype representation and propose the framework for SWP-CM; (2) To develop the constraints modeling module in SWP for enhancing the sociability in the constraints identifying, mapping, and analyzing process; (3) To develop the constraints optimizing module in SWP for improving the adaptivity in the constraints improvement process; (4) To develop the constraints monitoring module in SWP for achieving the autonomy in the constraints tracking, updating and predicting process; (5) To develop a simulation game for disseminating the concepts of SWP-CM in the industry and education.

This research first reviewed previous studies regarding constraints management and smartness in PHP to summarize the current challenges and opportunities in this field. The constraints in the on-site assembly process of PHP and the opportunities of smartness for constraints improvement in workflows were identified by literature review and interviews. The SWP was defined with the smartness properties, and a conceptual framework was established to demonstrate the functions of SWP for constraints management in the task executions. On the basis of this framework, three scenarios were developed to detailedly present the functions of SWP in constraints modeling, optimizing, and monitoring. The validations were also conducted in these separate demonstrations. Finally, a simulation game is proposed as a hand-on learning tool to disseminate the "SWP for constraints management (SWP-CM)" in the education and the industry.

The key findings concluded from this research are from five perspectives. Firstly, a conceptual framework outlined the skeleton and elements for SWP-CM with three core characteristics and three primary functions. Secondly, the social network analysis and the hybrid system dynamic (SD)-discrete event simulation (DES) model were incorporated into the constraints modeling service to simulate and pick out the most critical constraint "Lack of collision-free crane path planning" in the on-site assembly process of PHP. Thirdly, the constraints optimization service was proposed to improve dynamic constraints in the crane path planning by prioritizing their importance and embedding decision-making mechanism. It is proved to be an adaptive approach of conducting the crane path re-planning by considering its necessity. Fourthly, the constraints monitoring service focused on tracking and updating the status of crane operator fatigue, which is an internal constraint of "Lack of collision-free crane path planning." The service performance showed excellent accuracy. Finally, the simulation game was developed, and it indicated an excellent learning effect on the concepts of SWP-CM.

This research made original contributions to the constraints management in the on-site assembly process of PHP from both theoretical and practical perspectives. From the theoretical perspective, this study extended the body of knowledge in the project management of PHP by enriching the constraints management with the smartness and lean principles. Additionally, it is also innovative thinking from the theory of constraints perspective to reconsider the goal of PHP by transferring separated project-level targets (e.g., schedule, safety, quality) into the integrated task-level executions. From a practical perspective, this study developed three services to demonstrate the functions of constraints modeling, optimizing, and monitoring. It could not only help workers to execute the task in a more autonomous, adaptive, and sociable manner but also it made the workflow more smooth and reliable. Additionally, a simulation game was a practical learning tool to help students and practitioners know well about SWP-CM.

Publications

1. **Xiao Li**, Hung-lin Chi, Geoffrey Qiping Shen. Smart Work Packaging-enabled Constraint-free Path Re-planning for Tower Crane in Prefabricated Products Assembly Process. *Advanced Engineering Informatics,* ***Under Review***

2. **Li, X.,** Wu, C., Wu, P, Xiang, L, Shen, G.Q., Vick, S, Li, CZ. (2019). SWP-enabled constraintsmodeling for on-site assembly process of prefabrication housing production, *Journal of Cleaner Production*

3. **Li, X.,** Shen, G. Q., Wu, P., Xue, F., Chi, H. L., & Li, C. Z. (2019). Developing a conceptual framework of smart work packaging for constraints management in prefabrication housing production. *Advanced Engineering Informatics*, *42*, 100938.

4. **Li, X.,** Shen, G. Q., Wu, P., & Teng, Y. (2019). Integrating Building Information Modeling and Prefabrication Housing Production. *Automation in Construction, 100,* 46-60.

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Abbreviations

AR	Augmented Reality
AWP	Advanced Work Package
BIM	Building Information Modeling
CIC	Construction Industry Council
CM	Constraints Management
CNN	Convolutional Neural Network
CPS	Cyber-Physical System
CWP	Construction Work Package
DB-LSTM	Deep Bidirectional Long Short-term Memory
DES	Discrete Event Simulation
DfX	Design for X
EWP	Engineering Work Package
HKHA	Hong Kong Housing Authority
HKHS	Hong Kong Housing Society
IoT	Internet of Things
IWP	Installation Work Package
JIT	Just-in-time
LOD	Level of Detail
LPS	Last Planner System
PBS	Product Breakdown Structure
PHP	Prefabrication Housing Production
PRH	Public Residential Housing
PRM	Probabilistic Roadmap
RBL	RFID/BIM/Lean Construction
RFID	Radio Frequency Identification
SBP	Smart BIM Platform
SD	System Dynamics
SNA	Social Network Analysis
SCO	Smart Construction Object
SCM	Supply Chain Management
SOA	Service-oriented Architecture
SPO	Smart PHP Object
SWP	Smart Work Packaging
TOC	Theory of Constraints
WBS	Work Breakdown Structure
WFP	Workface Planning

Glossary

Building Information Modeling (BIM): It is to provide users with the ability to integrate, analyze, simulate, and visualize the geometric or non-geometric information of a facility.

Construction Work Package (CWP): It is an executable construction deliverable with the well-defined (e.g., budget and schedule) work scope which cannot overlap with another construction work package.

Engineering Work Package (EWP): It is an engineering deliverable with preparation-oriented work scope, which includes drawings, procurement deliverables, specifications, and vendor support to be consistent with the sequence and schedule of CWPs.

Installation Work Package (IWP): It is a detailed work plan that ensures all necessary elements under the scope of the IWP are well organized and delivered before executions, which enable workers to execute quality tasks in a safer, more effective and efficient manner.

Prefabrication Housing Production (PHP): It is a practice of manufacturing or fabricating the material, components, modules, and units of high-rise housing building efficiently at different locations and then converging at the site for installation.

Product Breakdown Structure (PBS): It is a product-oriented planning approach to analyze, document, and communicate the outcomes of a project, which offers a comprehensive understanding of the physical deliverables.

Smart BIM Platform (SBP): It is a digital platform to extend BIM to a multi-dimensional application with service-oriented architecture by integrating central database and data brokering function so that decisions and performance evaluation in PHP planning and control could be more feasible, accurate, and systematic.

Smart PHP objects (SPOs): SPOs are PHP objects, such as prefabricated materials, components, modules, units, machinery, and devices, which are equipped with supporting technologies to achieve inbuilt autonomy and awareness.

Smart Work Packaging (SWP): It is an approach to decompose the PHP workflows by PBS of building systems that are made smart with augmented capacities of visualizing, tracking, sensing, processing, networking, and reasoning so that they can be executed autonomously, adapt to changes in their physical context, and interact with the surroundings to enable more resilient process.

Work Breakdown Structure (WBS): It is a deliverable-oriented planning tool to hierarchically decompose the entire scope of work into the combination of product, data, and service that are required in a project.

CHAPTER 1 Introduction

1.1 Introduction

This chapter delineates the fundamental blueprint of this study, which starts with an overview of the research background and raises the research questions. Then it defines the research scope and determines the aim and specific objectives. Accordingly, the research design is conducted, which is followed by highlighting the significance of this study. Finally, the overall structure of this thesis is outlined.

1.2 Research Background

1.2.1 The Practice of Prefabrication Housing Production in Hong Kong

The situation of unbalanced public residential housing (PRH) supply and demand becomes more and more stringent in Hong Kong. According to the Housing Authority of Hong Kong (2019), there were more than 153,300 general applicants for PRH and the average waiting time for them was 5.5 years (at its highest in last two decades). In order to expedite the supply of PRH, the PRH in Hong Kong has benefited and will continue to benefit significantly from prefabrication housing production (PHP), which is an innovative solution that the prefabricated materials, components, modules, and units are manufactured efficiently at different locations in Great Bay Area (GBA) of Mainland China and then converge at the site for installation (Li et al., 2017a). The popularity of PHP, also known as modular construction or prefabricated construction, is productively boosting in the construction industry of Hong Kong as it meets market demand for improving industry-wide performance in the aspects including fast-track process, alleviating the on-site labor shortage, more sustainable and safer working environment (Li et al., 2017b). However, the supply of PRH is still plagued by the pathological schedule delay of PHP. For example, the government planned to construct 13300 flat units of public housing in the financial year of 2016-2017. However, the actual amount of public housing production is 11276 units, and 15.22% delay occurred (Housing Authority, 2018). The uncertainties and constraints in the fragmented PHP process have been proven to be the dominant drivers (Li et al., 2016b). Uncertainty refers to something that may occur, whereas constraint (e.g., limited space and buffers) is something that will happen (Li et al., 2016a). For example, adequate space on-site for storing prefabricated products is usually a factor that needs to be considered. In Mainland China, this is a risk because it rarely has limited space but may happen; however, in Hong Kong, this is a constraint because it always has limited space on-site, which requiring stakeholders to make a Just-in-time (JIT) delivery action to reduce the impact. The constraints are the obvious bottlenecks and thus are more predictable than the uncertainties to be removed in the task executions. As such, the reliable schedules with constraint-free are vital for achieving an industrialized construction environment across the fragmented stages including design, manufacturing, logistics, and on-site assembly so as to avoid schedule delay and cost overrun (Wang et al., 2016a).

The reliability of PHP schedules can be enhanced via proactive constraints management, which is the process of identifying, optimizing and monitoring of bottlenecks (e.g., unavailable drawings and specifications, shortage of workforce and materials, limited workspace, uncompleted preceding works, lack of work permits, quality, and safety issues) to ensure that work package-level tasks assigned to workers can be successfully executed (Blackmon et al., 2011). Managing constraints in PHP processes means preparing more (e.g., on detailed and dynamic planning with lean solutions) and acting fast (e.g., on decision-making and collaborative working) using available information and knowledge. As such, the principal objective of constraints management is to continually improve the reliability of workflow by guaranteeing that precise information is always available at the right time in the right format to the right person.

1.2.2 The Practice of Smart Construction in Hong Kong

As stated by Hong Kong government in the latest policy address "We have established $1 billion Construction Innovation and Technology Fund to encourage wider adoption of innovative technologies and stimulate the provision of cutting-edge solutions in the construction industry" (Policy Address, 2018), prefabrication housing production (PHP) as the modern construction method should stand at the forefront to adopt and integrate the advanced information technologies and industrialization principles such as mechanization, automation, robotics, standardization, modularization, and information-driven construction in the life cycle of construction projects, including design, manufacturing, logistics, and on-site assembly stages. Although PHP performs well in current practice due to its time-saving and less labor needed on-site, and quality is also enhanced via the trial and testing of products under factory conditions using consistent standards (Li et al., 2014), it should be noted that many PHP projects involve various stakeholders who store, retrieve and manage information on their own isolated systems (Persson et al., 2009), so the efficiency of collaborative working and decision making could be negatively affected by the fragmented information during design, manufacturing, logistics, on-site assembly stages. In Hong Kong, the problem of information fragmentation is amplified when the manufacturing work of PHP has been completely shifted offshore, e.g., to the Great Bay Area (GBA) of Mainland China. Furthermore, as reported by the Construction Industry Council of Hong Kong, there will be a shortage of 5,000 to 10,000 skilled construction workers over the year from 2019 to 2023 (CIC, 2019). Thus, a more advanced smart construction environment is needed to improve productivity from the perspectives of stakeholders (e.g., decision-makers, workers). There have been several smart construction practices focusing on how to support decision-makers and collaborative workers with precise, timely, and well-formatted information for project execution in Hong Kong (Zhong et al., 2017; Li et al., 2017c). For example, an internet of things (IoT)-enabled Building Information Modeling (BIM) platform is developed with the support of smart construction objects (SCOs) by equipping objects with information and communication technologies such as radio frequency identification (RFID), augmented reality (AR), and other sensing and tracking technologies (Li et al., 2018b; Li et al., 2018c; Niu et al., 2016). It can truly improve the visibility and traceability of prefabricated products for achieving just-in-time (JIT) coordination (Zhong et al., 2017). If the level of detail (LOD) in schedule can be classified into LOD 100 (master schedule), LOD 200 (phase schedule), LOD 300 (weekly schedule), and LOD 400 (daily work plan), previous outcome works in mitigating the uncertainties to improve the phase schedule which is a LOD 200 covering each PHP phase. However, there are still massive constraints have not been improved and removed in the more detailed schedule (e.g., LOD 300 and LOD 400). For example, the detailed task or activity still beset some missing or incomplete prerequisites including design (drawings and BIM models), prefabricated products, space, buffer, labor, equipment, permits, specifications, plans, prerequisite work, which prevent the reliability of PHP workflow, particularly in the on-site assembly process (Li et al., 2018a).

1.3 Research Problem Statement

Inefficient constraints management is one of the core issues in PHP planning and control due to the assignment of constraint-free tasks to the workers is not always the case. The constraints in the PHP process do not lend themselves to be managed well by the traditional approaches (e.g., critical path methodology (CPM), last planner system (LPS), workface planning (WFP), advanced work package (AWP)), which have several significant limitations including: (1) the sluggish process for identification and analysis of constraints and their interrelationships; (2) static constraints improvement without the dynamic re-planning ability; (3) cannot track and predict constraints status in a real-time manner. These limitations can be explained by the fact that traditional approaches may not completely understand the nature of issues in PHP. These key characteristics of issues in PHP include:

(1) Product-oriented PHP with discrete informational components could not be well managed to generate value-added information. The information technologies could help turn the PHP products into smart PHP objects (SPOs) with the ability of awareness, autonomy, and communicativeness. However, the stakeholders need to receive well-defined information and executable work plans based on compiling plenty of data from SPOs. Without them, the resources could not be efficiently gathering, time is wasted due to searching resources, and the progress is slowed down. Furthermore, when the

schedule delayed, workers may become rushed, probably with multiple trades stacked together, then quality defects and safety accidents more readily occur. Thus, the smart work packaging (SWP) with adaptivity, sociability, and autonomy seems to be adequate to address this issue by helping manage the massive constraints that exist by processing the information from SPOs.

(2) Interdependent PHP activities involving miscellaneous tasks increase the complexity of collaborative working. Manually identifying, optimizing, and monitoring constraints on one crew-level work package is a difficult task. Moreover, there are numerous interdependent work packages in various activities. However, identifying, optimizing, and monitoring constraints on crew-level work packages is the basic decision-making support for stakeholders. Without raised intelligence, constraint management is typically brute force, left up to experienced site workers through instinctive collaborative working. Thus, the SWP could work as a multi-agent system to collectively identifying, optimizing, and monitoring constraints through interacting with SPOs and smart BIM platform (SBP).

(3) Fragmented PHP stages involving various stakeholders reduce the efficiency of the decision-making. There are many critical constraints need to be confirmed and monitored by stakeholders. Thus, an integrated platform, smart BIM platform (SBP), is needed to cover the services across different stages including design, manufacturing,

logistics, on-site assembly, maintenance, and deconstruction, which to support the execution of SWP. SBP provides the platform to allow flexibility in the definition of SWP scope so as to keep increased agility in handling the constraints.

1.4 Research Scope

This study is motivated by the rising adoption of PHP and the urgency of PHP processes to be reliable. Although it attempts to develop an approach "smart work packaging" for managing constraints through modeling, optimizing, and monitoring, it should first clarify the specific boundaries. PHP has a large scope involving the life cycle of construction projects, from design, manufacturing, logistics, and on-site assembly. In addition, it should be noted that the constraints management has its genesis in the manufacturing industry, and there will be more constraints in the construction industry due to the more stages/processes/activities in PHP. Thus, two specific boundaries are identified below:

(1) This study concentrates on the constraints management mainly in the on-site assembly process of PHP due to it is the driving center for delivering the final product and the most value-added process (See Figure 1.1). The contractors in Hong Kong usually adopt four-day assembly cycle or six-day assembly cycle as their repetitive schedule units on the basis of project scale. The case study in this research focuses on the four-day assembly cycle that the trades in this process normally include site

superintendent, expeditor, quality inspector, tower crane operator, tower foreman, crane banksman, buffer foreman, prefabricated products installer, general labor, and safety supervisor.

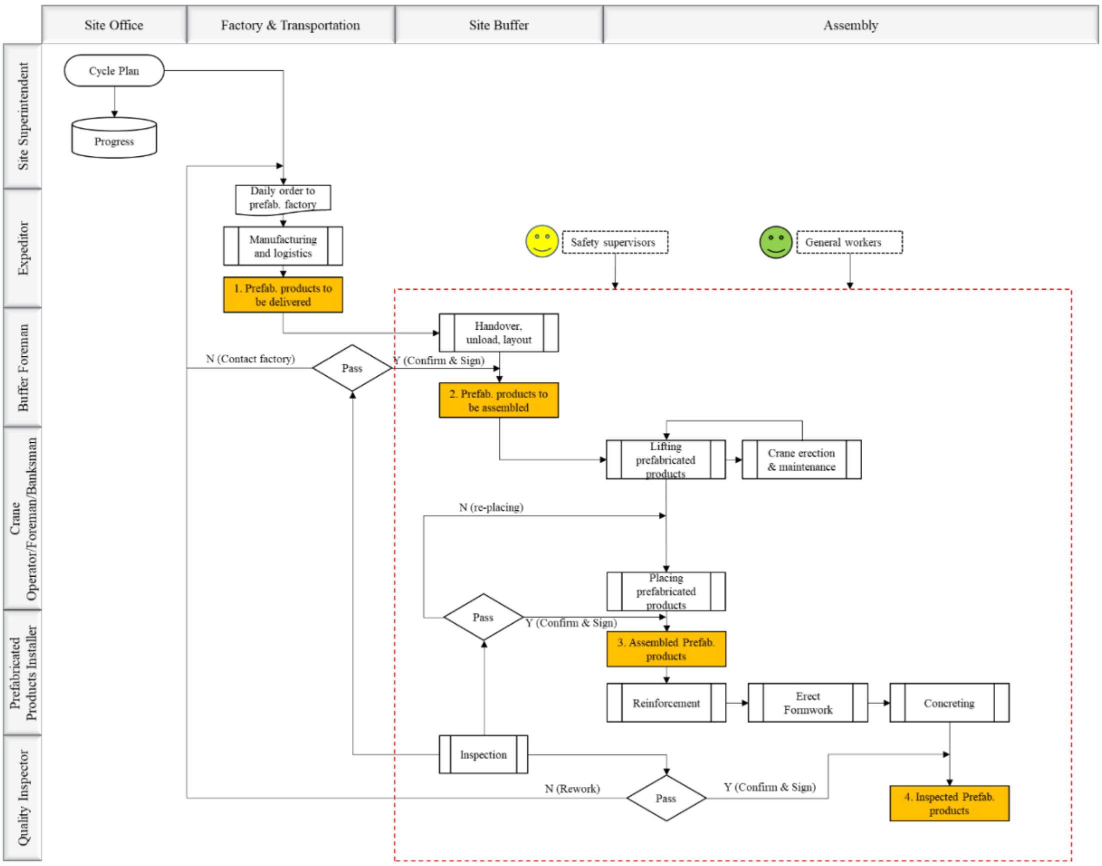


Figure 1.1 On-site assembly process

(2) The constraints considered in this study mainly from two categories, including physical constraints and informational constraints. These constraints could be characterized as any bottlenecks, such as technical sequencing, temporal/spatial limitations, and safety/quality concerns, which keep work plans assigned to PHP crews from being successfully executed in the PHP processes. Examples of these constraints include incomplete BIM models, drawings and specifications, unavailability of

workforce, materials, prefabricated products, equipment and tools, shortage of temporary structures, limited workspace, lack of work permits, unidentified safety and hazard issues, uncontrolled environmental conditions (e.g., severe weather), untimely and inaccurate transportation, and uncompleted quality control hold-points.

1.5 Research Aim and Objectives

The primary aim of this study is to investigate an intelligent approach to manage the constraints of PHP in the on-site assembly process. This approach is developed under the context of product-oriented PHP and object-oriented BIM to help model, optimize, and monitor the constraints at a more detailed level for achieving value-added workflow. The specific objectives of this study are presented below:

(1) To define the concept and properties of smart work packaging (SWP), specify its functions and paradigm for constraints management (CM), develop its prototype representation and propose the framework for SWP-CM；

(2) To develop the constraints modeling module in SWP for enhancing the sociability in the constraints identifying, interrelationships mapping, and analyzing process;

(3) To develop the constraints optimizing module in SWP for improving the adaptivity in the constraints improvement process;

(4) To develop the constraints monitoring module in SWP for achieving the autonomy in the constraints tracking, updating and predicting process;

(5) To establish a simulation game for disseminating the concepts of SWP-CM in the industry and education.

1.6 Research Design

To satisfy the aim and objectives, the research path is designed and illustrated below, see Figure 1.2.

(1) The first stage of this study makes efforts to raise the “what kind of approach can improve the constraints management of PHP in a smart manner?”. Through literature reviews on the traditional constraints management (CM) approaches (e.g., work packaging (WP) method), the existing limitations can be found. Meanwhile, the potential opportunities for CM can be apperceived by content analysis of the advanced information technologies (e.g., BIM) related studies under the context of PHP planning and control. Then the new approach should be established with its definition, properties, functions for CM, and system architecture. These finally can be grouped into a framework and validated by a simulation game and interviewing experts who have rich experiences in PHP projects. This stage will lead to Chapter 2 and 4 of the thesis.

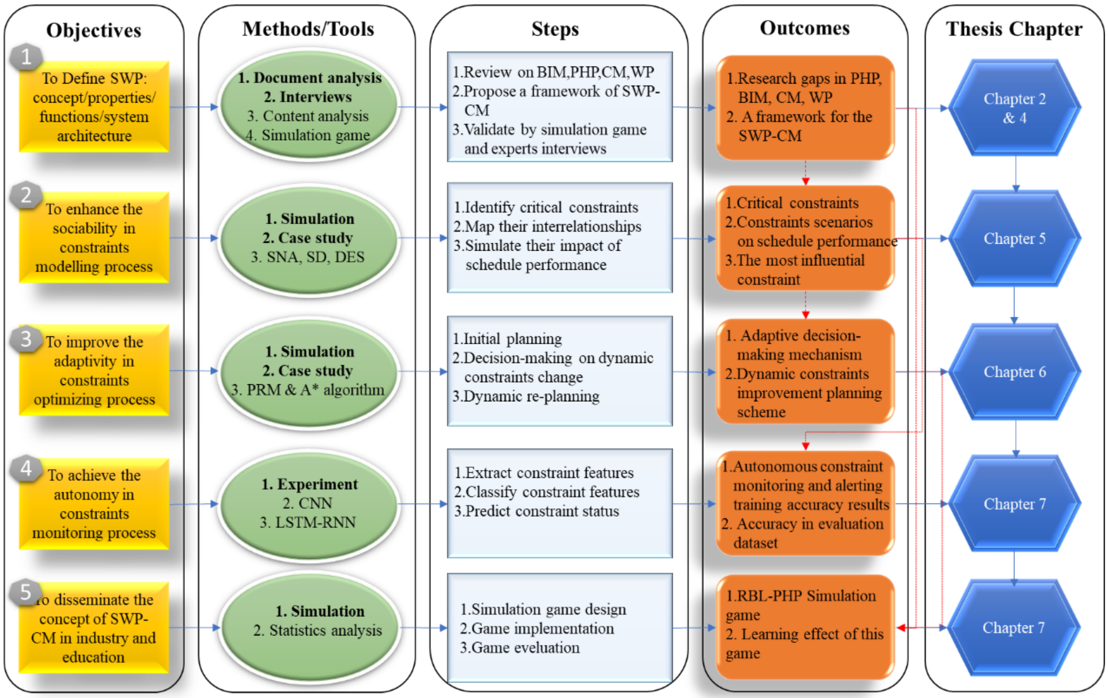


Figure 1.2 The overall research path

(2) The second stage of this study tries to clarify, “How this new approach work on constraints management?” Firstly, the activity-level critical constraints of the on-site assembly process will be identified. Their interrelationships and impacts on schedule performance will be simulated to investigate the most influential constraint. Secondly, the constraints optimization module will be developed to optimize the internal constraints (task-level constraints) in the most influential activity-level constraint. Lastly, the constraints monitoring module will be designed to monitoring one of the task-level constraints. These processes will lead to Chapters 5 to 7 of the thesis.

(3) The last stage is to explain, “How this approach disseminate to industry and education?” The role-play simulation game will be developed to facilitate the practitioners and students to learn the process and concepts of this new approach. This

can lead to Chapter 8 of this thesis.

1.7 Significance and Contribution of the Research

The significance and contribution of this research could be reflected in the following three aspects:

(1) The development of the smart work packaging approach in the PHP process is considered as the significant contribution of this research. In the previous studies, there is a lack of sound crew-level task execution approach to interacting with the product-level smart PHP objects and decision maker-level smart BIM platform. This approach considering the characteristics of product-oriented PHP and object-oriented BIM to integrate virtual tools into the physical environment in an efficient and real-time manner.

(2) The empirically consolidating the theory of constraints and Lean philosophy for improving constraints in the on-site assembly process of PHP is considered as another contribution of this research. The previous studies pay few attentions to the constraints management, particular in PHP. The Lean thinking of constraints management could facilitate the SWP to execute constraint-free tasks. Meanwhile, the modules and tools developed into SWP help to explore the nature and internal logic of constraints in the management process.

(3) The integrated methodologies developed in three modules, including constraints modeling, constraints optimization, constraints monitoring are also of significance.

These three functional scenarios raise the paradigm of the constraints management in SWP, which has not been investigated in the previous studies. From a practical perspective, this study also provides a training module for the industry and education to train their practitioners or students to use this approach in the construction industry.

1.8 Structure of the Thesis

This thesis includes nine chapters.

Chapter 1 introduces the critical context of this study, including the research background, research problem statement, research scope, research aim and objectives, research design, significance and contribution, and thesis structure.

Chapter 2 conducts a comprehensive review of the literature regarding constraints management and advanced information technologies in PHP. The content analysis is conducted in two aspects: (1) the current challenges of constraints management in PHP and the opportunities investigated from the manufacturing industry; (2) the knowledge domains and opportunities of integrating BIM into PHP for constraints management.

Chapter 3 presents the methodology of this study. Firstly, the framework of the methodology is established. Then, the detailed methods employed in this study are explained, such as literature review, interview, case study, simulation, and experiment. Additionally, the data analysis techniques adopted in this study are also illustrated, including content analysis, social network analysis (SNA), system dynamics (SD), discrete event simulation (DES), probabilistic roadmap (PRM), A* algorithm, convolutional neural network (CNN), deep bidirectional long short-term memory (DB-LSTM), and statistical analysis.

Chapter 4 illustrates the framework of smart work packaging (SWP) for constraints management (CM). Firstly, the concept and characteristics of SWP are well-defined. Then the paradigm, functions, functional structure of SWP for constraints management are built in the framework. In addition, a layered system model of SWP for constraints management is developed as the system architecture to explain its working mechanism. The simulation game developed in this study is also used to validate this framework.

Chapter 5 demonstrates the SWP-enabled constraints modeling service in the on-site assembly process. And three sub-services are designed for achieving constraints modeling. Firstly, the identification of critical constraints is embedded in the social network analysis (SNA) sub-service. Secondly, the sub-service of hybrid SD-DES model for assessing and simulating the potential effect of the identified critical constraints on the schedule performance of PHP is developed. Thirdly, the most influential constraint can be identified by constraints scenario analysis sub-service.

Chapter 6 demonstrates the SWP-enabled constraints optimization service in the crane path planning. The lack of collision-free path planning is the most influential constraint in Chapter 5. Then the more specific constraints at the task level in the crane path planning process can be optimized. This process can comprise three sub-services: task-level constraints identification and classification sub-service, initial path planning sub-service, and adaptive path re-planning sub-service.

Chapter 7 demonstrates the SWP-enabled constraints monitoring service for alerting crane operator's fatigue. The same as Chapter 6, the task-level constraints in the crane path planning process should be monitored. And one of the constraints (crane operator's fatigue) is selected as the monitoring target. Also, three sub-services are incorporated into it. Namely, spatial fatigue features extraction sub-service, temporal fatigue features extraction sub-service and fatigue alert sub-service.

Chapter 8 displays the simulation game for SWP-CM named RBL-PHP. The overall elements for the RBL-PHP contain the study groups, general outline, learned concepts in RBL-PHP, detailed design, process, and evaluation.

Chapter 9 summarizes the significant findings of this study, which have also been examined by satisfying the aim and objectives of this study. The theoretical and practical contribution to both the body of knowledge and industry have also been highlighted. Finally, the limitations and future studies are discussed.

1.9 Chapter Summary

This chapter raises the research questions from the current issues in both practices of PHP and smart construction, such as schedule delay of PHP (constraints and uncertainties), inefficient decision making (information fragmented), and unskilled collaborative working (skilled labor shortage). These issues are well connected in the problem statement. To narrow the proposed solution in a specific field, the research scope is locked in the on-site assembly process of PHP. Then the aim and objectives are nominated. Furthermore, the research design is conducted to achieve them. Additionally, significance and contribution are highlighted. Finally, the structure of the thesis is also established.

CHAPTER 2 Literature Review

2.1 Introduction

This chapter conducts a comprehensive review of the literature regarding constraints management and smartness in PHP. The content analysis is conducted in two aspects: (1) the challenges of the current approaches for constraints management in PHP and the opportunities investigated from the manufacturing industry; (2) the knowledge domains and the opportunities of integrating BIM into PHP for smartness in constraints management.

2.2 Constraints Management (CM)

2.2.1 Theory of Constraints and Lean Construction

The constraints management (CM) has been proposed more than 30 years in the manufacturing industry by consultants and practitioners but has seldom been aware by the researchers and professionals in the construction industry (Rahman, 1998). The CM is originated from developing a production scheduling software named Optimized Production Technology (OPT) in the late 1970s (Jeziorek, 1994). From then on, the practice of CM in the production scheduling process has been gradually evolved into a management philosophy that helps explore and improve the performance of intricate systems. Goldratt and Cox (1984) first used the Theory of Constraints (TOC) to improve processes to achieve their goals continually. Although the assumptions and thinking processes of TOC have been clarified (Goldratt, 1990) and it has also been adopted to the field of project management, the comprehensive constructs of TOC have not been exhaustively defined (Goldratt, 2017). Gupta (2003) claimed that if TOC is to be widely accepted and generalized, then this theory should be empirically developed and validated.

The Theory of Constraints (TOC) is a methodology for identifying the most critical bottleneck that prevents achieving the goal and then systematically improving the constraint until it is no longer the bottleneck (Goldratt, 1990). It assumes that each intricate system may comprise multi-connected activities, and there is at least one activity serves as a constraint in the fully connected system (i.e., the constraint is the "weakest link in the chain"). And the entire process throughput can only be maximized when the constraint is improved. A corresponding deduction is that spending more time on improving non-constraints activities cannot generate significant benefits, and only improvements to the constraint will reach the goal. As such, TOC aims to offer an accurate and continuous focus on improving the current constraint until it no longer confines the goal, when the focus changes to the next constraint. From this perspective, TOC, to some extent, has similar philosophies as the Lean Construction. The TOC and Lean Construction can both serve as systematic methods for improving productivity in PHP processes. However, they apply similar thinking into different focuses: The TOC concentrates on identifying and improving constraints that restrict throughput. Thus, successful implementation can increase PHP capacity. While Lean Construction concentrates on eliminating waste in the PHP process, and the best practice aims to reduce PHP costs. Both of them target on the workflow and can help upgrade PHP processes to be more reliable and agiler (Nave, 2002).

Lean Construction for PHP refers to the utilization of lean production principles into the whole construction project delivery system to achieve lean manufacturing, lean supply chain and lean site assembly (Salem et al., 2006). It facilitates to manage and improve PHP processes with minimum waste and maximum value by meeting customer demands (Sacks and Goldin, 2007). To this end, the PHP processes have been considered separately in two parts: conversion activities and flow activities (Koskela, 1992). The conversion activities could add value to the material or information which both are transformed to productions, while, flow activities are tied together with conversion activities, bring constraints and uncertainty such as inspection, moving and waiting (Wu, 2014). The Lean Construction tools such as Just in time (JIT) and standardized work have proved to be the primary method to help people identify constraints or uncertainty that lead to abnormal situations (Yu et al., 2011). JIT refers to a production system where materials are utilized immediately when they are delivered to avoid overproduction (Wu and Low, 2011). JIT construction adopts a pull-driven method that aims to minimize the buffers and inventories (Wu and Low, 2010). Accordingly, the upstream outcomes should only be available when required by downstream activities (Sacks et al., 2010b). Standardized work is executed through a work package that consists of work sequence, workforce requirements, and clarified work scope for which a worker is responsible. For each task, a standardized worksheet provides step-by-step instructions to ensure workers follow the best practice. For each step, the work element sheet provides detailed specifications on safety and quality (Hassan and Kajiwara, 2013). Improving the efficiency of conversion activities, through the use of new information technologies to enhance the transparency, automation, and traceability of construction process is also critical to achieving Lean Construction (Senaratne and Ekanayake, 2011).

TOC uses its laser-like focus to improve the constraint, while Lean Construction uses the broad-spectrum tools. In real practice, as all PHP projects have finite resources, it often needs to compromise. It means that not each constraint is really worth optimizing, and not all waste can be eliminated. In this instance, the TOC can work as an efficient mechanism in prioritizing improvements for constraints, while Lean Construction can offer a rich toolbox of improvement techniques. Thus, the combination of TOC and Lean Construction may generate synergy on constraints management. These constraints in PHP could be defined as any limiting factors, such as technical sequencing, temporal/spatial limitations, and safety/quality concerns, which prevent tasks assigned to PHP crews from being successfully executed in the PHP processes (Blackmon et al., 2011). Examples of such constraints in on-site assembly process (See Table 2.1) include incomplete models, drawings and specifications, unavailability of workforce, materials, prefabricated products, equipment and tools, shortage of temporary structures, limited workspace, lack of work permits, unidentified safety and hazard issues, uncontrolled environmental conditions (e.g., severe weather), untimely and inaccurate transportation, and uncompleted quality control hold-points.

Table 2.1 Constraints Summarized in the on-site assembly process

ID	Constraints	Description	Reference										
			1	2	3	4	5	6	7	8	9	10	11
C1	Incomplete shop drawings and BIM models	It determines the constructability	√		√						√		√
C2	Incomplete specifications	Specifications are detailed descriptions of the materials, workmanship, and standard.	√	√								√	
C3	Lack of permits	The official approvals issued to the construction activities.	√		√				√		√	√	
C4	Unavailable and unassigned labor resources	The skilled workers are recruited and ready for task executions	√		√	√		√	√			√	
C5	Bad weather conditions	Adverse weather causes delay and shutdown, e.g., heat-stress, typhoon.							√	√	√		√
C6	Unavailable production and transportation schedule	To guarantee the just-in-time (JIT) deliveries of products.			√			√	√	√			
C7	Lack of traceable status of prefabricated products	The ability to track information of location, quality, etc.	√						√	√			
C8	Bad conditions of transportation vehicle and route	The height and weight limit on the road for the vehicles, and traffic congestion.	√						√	√			
C9	Unavailable quality control hold-points	It determines where to conduct quality inspection and testing.					√		√		√	√	√
C10	Unavailable connection points for handling	It determines where to assembly or installs the prefabricated products.									√	√	√
C11	Lack of inspection and testing instructions	It determines how to conduct quality inspection and testing.			√						√		√
C12	Incomplete identification of installation items	It determines the efficiency and accuracy to recognize the prefabricated products							√	√			
C13	Lack of lifting load capacity	It determines the number of prefabricated products can be transported each time	√	√								√	
C14	Lack of collision-free path planning	It determines the efficiency and safety of the lifting task	√	√								√	
C15	Unavailable lift and place location in the assembly process	It determines the accuracy and efficiency to transport the prefabricated products								√		√	
C16	Incomplete plan for movements and location of the crane	It determines the efficiency of the whole assembly process	√									√	
C17	Unavailable equipment, tools, and devices	It determines the efficiency of task executions for workers			√	√					√	√	√
C18	Lack of crane maintenance plan and instruction	It determines the safety of crane operations	√	√								√	
C19	Lack of blind zone operation procedure/instruction	It determines the safety of crane operations	√	√								√	
C20	Lack of visible and audible communication mechanism	It determines the efficiency of collaborative working between different trades.			√					√			√
C21	Inadequate buffer space	It limits the storage capacity for prefabricated products				√	√			√		√	
C22	Lack of optimal buffer layout	It affects both the storage capacity and the installation sequence				√	√			√		√	
C23	Lack of optimal installation sequence	The inadequate installation sequence leads to the rework.	√	√				√					
C24	Unavailable prefabricated products	It is caused by delay delivery and leads to assembly delay		√		√				√			
C25	Unavailable necessary rigging	It determines the efficiency of lifting task execution		√		√						√	

C26	Inadequate workforce/work space	It prevents enough space for workers from executing tasks		√					√		√		
C27	Unavailable installation instructions	It can guide the workers to install the prefabricated products properly.	√		√					√			
C28	Unavailable temporary structures	It can reduce the workface, e.g., the scaffold, and lead to potential safety hazards.		√	√				√		√		
C29	Inadequate safety training and hazards identification	It reduces the ability of hazards prevention, identification and alerting.	√				√				√		
C30	Unavailable safety checkpoints	It determines the accuracy of hazards identification	√						√		√		
C31	Incomplete special personal protection equipment (PPE) instructions	It determines the efficiency and safety of safe task executions	√								√		

Notes: 1.(Blismas et al., 2005; Blismas and Wakefield, 2009); 2. (Azhar et al., 2016); 3. (Abuwarda and Hegazy, 2016); 4. (Liu et al., 2015); 5. (Hwang et al., 2018); 6. (Arashpour et al., 2016); 7. (Gibb and Isack, 2003); 8. (Li et al., 2016a); 9. (Blackmon et al., 2011); 10. (Hamdi, 2013). 11. (Wang et al., 2016)

2.2.2 Challenges of CM in the Construction Industry

Constraints management is one of the critical strategies for production control and planning. The concept of constraint was firstly introduced in 1984 as the theory of constraints, which is a comprehensive management philosophy (Goldratt and Cox, 1984). Constraints management systems have proven to be more effective when compared to the reorder-point (ROP) systems and material requirements planning (MRP) systems in the aspects of capacity management, inventory management and process improvement in the manufacturing industry. It is also argued that constraints management can outperform the Just-in-time (JIT) system owe to the more targeted nature of improvement efforts in constraints (Boyd and Gupta, 2004). The significance of performing detailed control and planning with constraints management to issue executable work plans has also been widely recognized by the construction industry. For example, the Last Planner ® System (LPS) uses the principles of Lean Construction (e.g., pull-driven method) to generate the planned workflow within a collaborative team environment. It includes master scheduling, phase scheduling, lookahead planning, and weekly work plan (Ballard, 2000). Constraints identification and commitments to remove constraints are conducted in the lookahead planning to determine what must be done for making tasks ready. However, the current process of constraints management within LPS is often criticized for the slow fulfillment of constraints analysis and short preparation for constraints removal (Hamzeh, 2009). It should also be noted that the LPS adopts weekly work planning instead of real-time planning, leading to a poor foresight capacity. The weekly feedback time may be too long for some tasks whose constraints can only be removed within a short duration of time before their execution (Sacks et al. 2010b). In addition, manual (e.g., paper-based and meeting-based) constraints analysis, constraints status updating, and coordination are still the dominant approaches to constraints management (Wang et al., 2016a).

Compared with LPS, work packaging is a planned, executable process to strategically decompose the PHP scope into distinct and manageable pieces with proper sizing and criteria. Each work package should be assigned to an individual supervisory unit that is able to handle all its constraints. Therefore, the tasks should be separated into smaller pieces (e.g., 500-2000 man-hours of work) as long as the benefits outweigh the additional administrative burden (Isaac et al., 2017). In addition, the most frequently used criteria in work packaging design include the type of prefabricated product, the workface in which the prefabricated product is located, the specific physical location of the prefabricated product, and the workflows (Ibrahim et al., 2009). The dependencies between tasks/activities included in various work packages should also be considered. Whereas the PHP can be broken down into a group of building systems (e.g., structure, envelope, partitions, services, and equipment) with a hierarchical product structure (e.g., material, component, module, unit) in the design, the work packaging in PHP can be defined by considering both product breakdown structure (PBS) and work breakdown structure (WBS). One of the practical examples is advanced work packaging (AWP), which was developed through the collaboration between the construction owners association of Alberta (COAA) and Construction Industry Institute (CII) (Hamdi, 2013). AWP uses a hierarchy of engineering work packages (EWPs), construction work packages (CWPs), and installation work packages (IWPs) to allow engineering and procurement planning to be driven by construction sequencing. It breaks down the project processes into CWPs aligned with WBS. CWPs, in turn, contain one or more IWPs. It works well in handling the complex mega project (e.g., oil and gas project), but its organizational structure with CWP, EWP, and IWP is hierarchical and not flattened enough for PHP to improve the efficiency of decision making and collaborative working (Li et al., 2019a). Moreover, there are also several significant limitations in the current work packaging methods for efficiently managing constraints in PHP. Firstly, the process for identification and analysis of constraints and their interrelationships is sluggish because the constraints are only discussed in look-ahead meetings rather than in real-time manner (Hamdi, 2013; Isaac et al. 2017). In addition, constraints status is untraceable and non-transparent due to the lack of sensing and tracking technologies for monitoring (Liu et al. 2015). Constraints improvement planning is usually static without the dynamic replanning ability (Abuwarda and Hegazy, 2016). Enlightened by the smartness of smart construction object (SCO) (Niu et al., 2016), a more collaborative, autonomous, and adaptive approach for constraints management through constraints modeling, monitoring, and optimization may be possible.

2.2.3 Opportunities of CM Learned from Manufacturing Industry

Much effort has been made in using cutting-edge information technologies to make work packages smart (Ibrahim et al., 2009; Abuwarda and Hegazy, 2016). For example, Isaac et al. (2017) developed algorithms for BIM which can be integrated with design structure matrix (DSM) and domain mapping matrix (DMM) to automatically label relationships between prefabricated products and their following sequence in which the prefabricated products should be assembled. Table 2.2 demonstrates a summary of the studies related to the development of smart work packaging. As can be seen from Table 2.2, the development of smart work packaging (SWP) has focused on the various aspects of constraints management, including modeling, monitoring, and optimization. Some studies, although not directly using the name “smart work packaging” or “SWP”, address the interaction between humans, resources (e.g., machines and products) and environment with smartness using emerging technologies such as IoTs, wireless sensor networks, big data, cloud computing, or other enabling technology to facilitate task execution.

Compared with traditional task execution process, SWP has many unique characteristics, including interoperability, traceability, value-added, awareness, security, accessibility, accuracy, and consistency. However, information communication, adaptive to changes, autonomous actions during task executions have been identified as the necessary requirements of SWP in previous studies (Lu et al.2017; Wang et al. 2016b; Ren et al. 2017; Lee et al., 2009). For example, Based on using simulated or historical data, SWP could achieve autonomy by executing particular tasks when specific requirements are met (Lu et al., 2017). In addition, each SWP can gain sociability by communicating with its internal elements, as well as others to work as a distributed multi-agent system for collaborative working (Ren et al., 2017). Most importantly, the SWP must be adaptive and can react flexibly to changes by learning from its own experiences, environment, and interaction with others (Wang et al. 2016b; Lee et al., 2009). Thus, it is believed that the three critical characteristics of the SWP are autonomy, adaptivity, and sociability. The potential functions of SWP have also been introduced and assessed in different scenarios including modeling (i.e. the understanding of the interconnections among tasks), monitoring (i.e. the tracking and updating of real-time status), and optimization (i.e. the planning and scheduling of tasks) (Luo et al. 2018; Wan et al. 2018; Zhang et al. 2018).

However, it should be noted that SWP and its definition, characteristics, functions , applications, and prospects in the PHP field have yet been systematically explored for constraints management. Although individual SWP studies have been investigated, they do not stand on a systematic view to explore the full potential of SWP. It is a necessity in driving toward a sweeping and interconnected smartness in next-generation PHP practice, particularly in the field of constraints management in PHP. This requires an investigation of the unique and inborn characteristics of SWP from the manufacturing industry and the incorporation of PHP characteristics.

Table 2.2 Studies related to SWP in the manufacturing industry

Research	Function	Interpretations	Characteristics		
			Autonomy	Adaptivity	sociability
Zhang et al. (2018)	Monitoring	IoT-enabled active sensing system to assist operators in monitoring the real-time manufacturing process	√		
Wan et al. (2018)	Optimization	Cyber-physical production system (CPPS)-enabled dynamic resource allocation for operators		√	
Luo et al. (2018)	Modeling	Using mobile intelligence to handle low-priority data to improve data delivery efficiency			√
Kim (2018)	Optimization	Predefined jobs can be processed concurrently in different machines		√	
Blanco-Novoa et al.(2018)	Modeling	AR-based interface to assign tasks to the operators and assist them in interacting with surroundings			√
Longo et al. (2017)	Optimization/Modeling	Smart operators have been proposed for complex human-machine-product interactions by integrating AR contents and intelligent tutoring systems		√	√
Wang et al. (2017)	Monitoring/Modeling	Cloud-assisted industrial robots perform tasks with the capacity of interaction and negotiation.	√		√
Peruzzini and Pellicciari (2017)	Optimization	Cyber-physical system (CPS) and pervasive technologies are applied to improve the adaptivity of the machine behavior to the working conditions and the specific workers' skills, tasks, and cognitive-physical abilities are improved for aging workers		√	
Lu et al. (2017)	Monitoring	An RFID-enabled positioning system in an automated guided vehicle for logistics automation	√		
Ren et al. (2017)	Modeling	A method on the perspective of both macro and micro level is developed for correctness analysis of cooperative behaviors among industrial devices			√
Wang et al. (2016b)	Optimization	An approach of facilitating the large-scale online multitask learning and decision-making is developed for operators to perform flexible tasks		√	
Wang et al. (2016c)	Optimization/Modeling/Monitoring	A multi-agent system with autonomy can achieve big data-based feedback and coordination to assist the central coordinator	√	√	√
Ivanov et al. (2016)	Optimization	A dynamic model for supply chain scheduling to solve simultaneous consideration of both machine structure selection and job assignments		√	
Seiger et al. (2015)	Optimization/Modeling/Monitoring	An object-oriented workflow language is developed for formalizing processes with the heterogeneous and dynamic environment in CPS	√	√	√
Giner et al. (2012)	Modeling	The smart workflow is developed by the adoption of automatic identification technologies which can modeling and reengineering business processes			√

2.3 Smartness in Prefabrication Housing Production (PHP)

Recently, there have been many studies on how to improve smartness in PHP by providing the right formatted information at the right time to the right location, through the integration of Building Information Modeling (BIM) and sensing and tracking technologies (Chen et al.2015; Chi et al. 2015; Li et al. 2018b). The U.S. National BIM Standard (NIBS, 2012) defined BIM as a term with three linked functions, including Building Information Modeling, Building Information Model, and Building Information Management. Building Information Modeling refers to the business process of generating and using building data in the lifecycle of buildings. Building Information Model refers to the digital representation of the physical and functional characteristics of a facility, and Building Information Management is the process of utilizing digital building information for effective sharing. Previous studies related to the use of BIM in PHP include modeling the information of prefabricated components for efficient data exchange management (Lee et al., 2016), modular and parametric design optimization for reusable modules (Isaac et al., 2016), information retrieval and matching for automated quality assessment of prefabricated products in manufacturing (Kim et al., 2016), information sharing and communication for supply chain planning and control of prefabricated products with real-time visibility and traceability (Zhong et al., 2017), documenting the progress of the as-built status for the accurate site assembly (Bosché et al., 2013), and the management of prefabricated products related resources and constraints for a reliable workflow (Wang et al., 2016a).

It should be noted that with the rapid development on practical implementations of BIM and PHP, the theoretical perspectives of their integration (hereinafter referred to as BIM-PHP), which aims to bridge the object-oriented BIM models with the production-oriented PHP for improving working efficiency, should not be overlooked. The objectives of this review are to (1) analyze the current body of knowledge relevant to BIM-PHP; (2) investigate the opportunities of integrating BIM with PHP.

2.3.1 Current Knowledge Domains of Integrating BIM with PHP

This review analyzes 65 publications, and Figure 2.1 presents the distribution of these publications by the country/region and the prefabrication production structures of these publications. United States, Hong Kong, United Kingdom, and Israel are the top four countries or regions, in terms of publications on BIM-PHP. 63% of all studies related to BIM-PHP are conducted in these four countries or regions. In the United States, there is a lack of integrated frameworks, tools, and technologies for facilitating the transformation of the conventional design/construction approach to one that is based on manufacturing to improve the productivity (Ramaji et al., 2016). In addition, information fragmentation and uncollaborative working environment have been recognized as significant barriers to achieving an efficient supply of public housing project in Hong Kong (Li et al., 2017b). Miscommunication among different PHP stakeholders, especially the lack of agreement among different participants in terms of operations, expectations, and motivations, is considered as a negative factor affecting the adoption of PHP in the UK (Goulding et al., 2015). Figure 2.1 also presents the production structures that are investigated in these studies. A total of 50 articles (77%) investigate prefabricated components (e.g., precast concrete floors, walls, mechanical, electrical, and plumbing (MEP) services) and the use of BIM to enhance the information exchange in these components. For example, Niu et al. (2016) developed the smart construction objects (SCOs) for prefabricated façade by enhancing the façade with tracking, sensing, processing, storage, and communication capability in a BIM platform so that SCOs have inbuilt autonomy and awareness. Compared to the component, other production structures, such as material, module, and unit, have attracted relatively low research interest. This is partly because the component is the foundation in BIM and is comfortable to be identified and investigated in BIM.

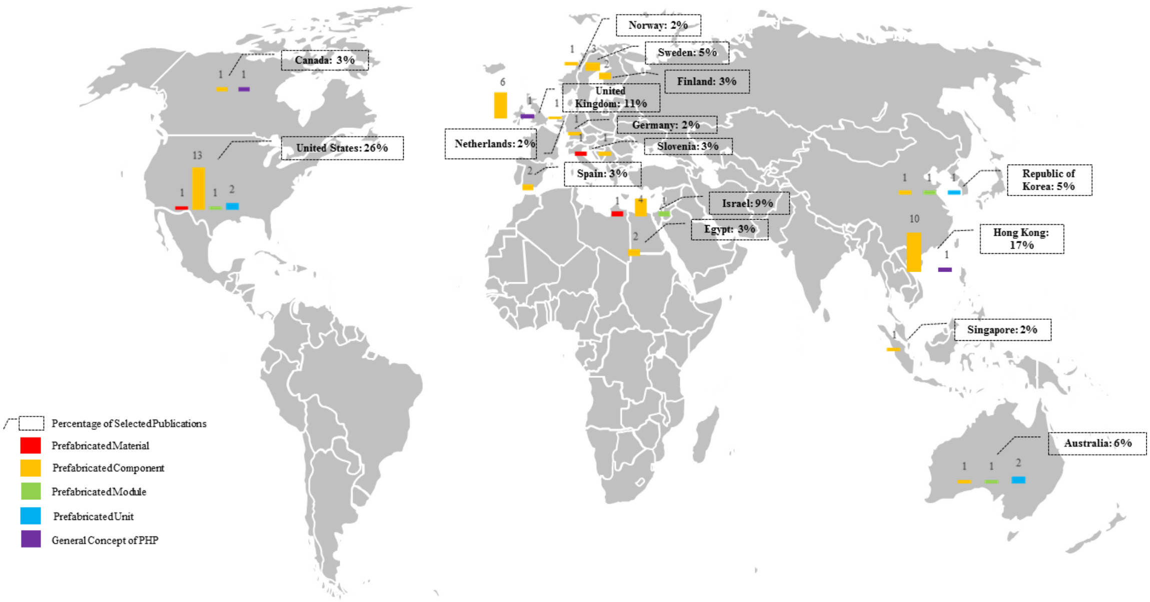


Figure 2.1 The country/region distribution of selected publications with the different complexity of prefabricated structures

(1) BIM-PHP stages

BIM has been extensively adopted in PHP in various stages of a project lifecycle, including a feasibility study, design, manufacturing, transportation, construction, and maintenance. Feasibility study and strategy development in the pre-design stage play a critical role in identifying the strengths and challenges of BIM-PHP. Some of the most notable examples in the pre-design stage are SWOT analysis of Internet of Things-enabled BIM platform for PHP (Li et al., 2016b), best practices for electrical prefabrication (Said, 2015), business models in new offsite productions (Goulding et al., 2015), and the impact of BIM on PHP labor productivity (Poirier et al., 2015). The design is the project lifecycle stage, which receives a lot of attention. The design stage covers interoperability, 3D parametric and geometric modeling, and visualization. In interoperability-related applications, some prominent examples are related to specifying information requirements (Lee et al., 2016), enhancing the semantic representation of information (Belsky et al.,2016) and information exchange (Sacks et al., 2010a). In 3D parametric and geometric modeling applications, some noteworthy examples are functional information modeling from different domain knowledge (Lee et al., 2006) and physical information modeling for products modularity and flexibility (Farr et al. 2014; Moya et al. 2014; Wikberg et al. 2014). Of all the BIM applications in the design stage, interoperability is the most important one at the technical level due to its significance in facilitating the information exchange among BIM platforms, (e.g., Revit®, Tekla, Inventor, IDAT Precast, CATIA™, Autodesk Fabrication), enterprise systems, and smart prefabricated components. It can accredit this issue to off-the-shelf software/platforms cannot well define the information for the professionals in different domain knowledge, and various software use different methods to model the geometric and non-geometric data. However, the standard data schema, Industry Foundation Classification (IFC) based interoperability tools can be used to improve the information exchange. For example, the Autodesk® has developed several tools including Classification Manager, Model Checker, COBie Extention for Revit® to facilitate different professionals in information classification, compliance checking, and information filtering. 3D parametric and geometric modeling is also a critical one at the functional level because it is the foundation to implement the strategy of design for X (DfX) (Bock and Linner, 2015) that programs the details of products and models the information in order to offer an optimal level of PHP in the lifecycle of construction projects including manufacturing, transportation, assembly, maintenance, deconstruction, and recycling. The BIM applications in construction stage mainly concentrate on information sharing and communication, and visualization. In information sharing and communication applications, some notable examples are related information storage, retrieval, and documentation. For example, Niu et al. (2016) investigated how the information delivered from the previous stages could be synchronized in the assembly stage, and the real-time as-built information (e.g., location and progress status) would be documented in a timely manner. As can be seen from these studies, BIM has commonly been adopted in separate lifecycle stages in PHP. For achieving integrated industrialization, there seems to be a lack of an integrated platform for setting up a continuous interaction between all the stakeholders in order to maintain effective delivery of prefabricated products with customer-oriented performance criteria at the cradle-to-grave level (Richard, 2017).

(2) BIM-PHP areas

Building information modeling is the most significant area, and it is mainly related to modeling components information and modeling process information. For example, Costa and Madrazo (2015) adopted the linked data approach to connect the BIM models with a catalog of prefabricated products. The linked information obtained from multiple sources can create semantic descriptions of the prefabricated products. Similarly, Sacks et al. (2010a) established the information delivery manuals (IDM), which can capture the use cases and the precise information to be exchanged in the workflow. Resource management is also an important research area in BIM-PHP, partly due to the high cost of PHP components (Bosché et al., 2013). As such, enhancing the traceability and intelligence of PHP components have received much attention. Supply chain management (SCM) is always plagued with the fragmentation, discontinuity, and heterogeneity in BIM-PHP (Niu et al., 2017). Thus, the coordination strategy and the concurrence of process and information become necessary for improving the interconnection of SCM. Production engineering management, including modularity and flexibility, and clash detection, schedule management, including schedule risk control and progress monitoring, have also received much attention. Balancing the modularity and the flexibility of prefabricated products is an essential area of research in product engineering management of BIM-PHP (Wikberg et al., 2014). For example, the customized and BIM supported design could be decomposed into non-repetitive assemblies of components with standardized interfaces that can be preassembled off-site (Isaac et al., 2016). This application area is necessary because it is the foundation to achieve mass customization of building products (Farr et al., 2014). Similarly, due to the fragmentation and discontinuity of information in the lifecycle stages of construction projects, the reliability and stability of workflow should be improved through satisfying all potential constraints (e.g., rough design drawings, limited workspace, shortage of manpower and materials.) prior to execution (Azhar et al., 2013). Thus, constraints management is another vital process in BIM-PHP. As can be seen from these studies, BIM has not provided manageable and structured workflows in PHP. For achieving executable industrialization, there seems to be a lack of an advanced work breakdown approach with interfacing rules of products for simplifying the PHP process and avoiding repetitive linear sequences between all the crews in order to maintain a resilient execution for mass production (Richard, 2017).

(3) BIM-PHP products

The building system of PHP could be a set of modular products and coordinated information where the details are resolved before actual buildings are planned. The building system of PHP usually comprises five functional sub-systems: structure, envelope, partitions, services, and equipment (Richard, 2007). Each sub-system of PHP could gather a series of prefabricated products (i.e., material, components, modules, and units). An open system can swap prefabricated products to offer more options to both the customers and manufacturers in a larger market by following the principles in terms of performance criteria (PHP stakeholders), interfacing rules (PHP crews), and modular coordination (PHP products) (Richard, 2017). However, the coordinated rules or information are not well organized and connected to each modular product. Thus, adopting supporting technologies with a hierarchical PHP product structure could facilitate the integration of BIM and PHP. The supporting technologies can be categorized into two groups in current BIM-PHP studies, which are sensing and tracking (e.g., RFID, GPS, 3D camera), and 3D model creation and comparison (e.g., 3D laser scanning, photogrammetry, augmented reality (AR)). These supporting technologies can directly contribute to the aforementioned BIM-PHP workflow, such as prefabricated products traceability, progress monitoring, documentation, and quality inspection. Sensing and tracking technologies are necessary for activities in manufacturing, transportation, on-site assembly, and maintenance. Some of the useful applications include identifying and searching the prefabricated products in the factory, accurately positioning the prefabricated products in the assembly process, and timely detecting defective products or systems in the maintenance stage. As one of sensing and tracking technologies, RFID is not entirely new in PHP. It is commonly used for identifying and tracking the resources (e.g., personnel, components, equipment) which can then be visualized in BIM (Ikonen et al., 2013). GPS is also a powerful tool for providing the exact positions of prefabricated products in BIM through 2-way, differential GPS, and kinematic GPS, which has higher accuracy (Vähä et al., 2013). As for the 3D camera, it can be integrated with mobile robotics manipulator, which is used to rapidly detect and track the prefabricated components by computer-vision-based pose estimation for assembling the components into pre-designed modular structures (Feng et al., 2015). For 3D model creation, 3D laser scanning is particularly applicable in quality management due to its efficiency in capturing the existing condition of the prefabricated products, which has been adopted to measure the deviations between 'as-built' and 'as-designed' models for quality control (Wang et al., 2016 c). Although data acquisition is relatively fast when using 3D laser scanning, post-processing tasks still take a long time to reach a high level of BIM details (Kim et al., 2016). Thus, photogrammetry and AR can be used as alternatives for the 3D model creation and comparison. As can be seen from these studies, these technologies have contributed to capturing, generating, and analyzing the data from the physical environment. However, it is still disenabling physical objects (e.g., prefabricated products, machinery, equipment) to be smart in terms of awareness, autonomy, and communicativeness for improving the efficiency of modular coordination.

2.3.2 Current Issues of PHP

Schedule delay continually impedes the success of PHP due to the lack of required coordination to prevent work starvations between prefabrication factories, logistics, and on-site construction (Li et al., 2018a). The issue of fragmentation is amplified when the manufacturing work of PHP in Hong Kong has been completely shifted offshore, e.g., to the Great Bay Area (GBA) of Mainland China, which results in all uncertainties and constraints prior to tasks execution could not be timely satisfied to enhance and improve the reliability of PHP processes (Li et al., 2016). Previous studies investigated the stakeholder-associated risks in the whole PHP processes, such as low interoperability between different enterprise resource planning systems (ERPs), logistics information inconsistency, delivery delay of prefabricated products to the site (Li et al., 2016). To help reduce these risks, the internet of things (IoT)-enabled BIM platform, including the services of production, logistics, and on-site assembly, was developed to improve the visibility and traceability of prefabricated products for achieving just-in-time (JIT) coordination (Zhong et al., 2017; Li et al., 2018b). Meanwhile, data analytics methods, e.g., the hybrid simulation model, are also developed to facilitate risk identification and interrelationships mapping in the PHP processes (Li et al., 2018a). If the level of detail (LOD) in schedule can be classified into LOD 100 (master schedule), LOD 200 (phase schedule), LOD 300 (weekly schedule), and LOD 400 (daily work plan), previous outcome truly works in mitigating the risks to improve the phase schedule which is a LOD 200 covering each PHP phase. However, risks and constraints are different and must be identified and treated differently. Constraints can usually be identified, improved, and removed in a more detailed schedule (e.g., LOD 300 and LOD 400) (Wang et al., 2016a). For example, the detailed task or activity still beset some missing or incomplete prerequisites including design (drawings and BIM models), prefabricated products, space, buffer, labor, equipment, permits, specifications, prerequisite work, which prevent the reliability of PHP workflow, particularly in the on-site assembly process (Li et al., 2018b).

2.4 Research Gaps and Industry Needs

Through the critical review of the literature for the last two decades, a broad scope of research themes in the area of constraints management, and BIM-PHP have been investigated and summarized. Their research outcomes have contributed significantly to the body of knowledge in constraints management and BIM-PHP, providing valuable and constructive information for scholars and practitioners in BIM-PHP. Although acknowledging their contribution, one significant research gap of previous literature should be addressed: a lack of study on devising a smart approach to manage constraints in PHP. The research gap is evidenced as follow:

(1) Although the traditional methods for constraints management have generated synergy by combining the Theory of Constraints and Lean philosophy, there are still several limitations including a. the sluggish process for identification and analysis of constraints and their interrelationships; b. static constraints improvement without the dynamic re-planning ability; c. can not track and predict constraints status in a real-time manner.

(2) Although the smartness in PHP at stakeholder-level and product-level have been enhanced by introducing BIM platform and smart objects in previous studies, there is still a lack of approach in delivering value-added information for more efficient task executions at the crew level. This approach should be capable of managing both the physical objects and informational components in a real-time manner.

(3) Few studies have been dedicated to constraints management of PHP with

consideration of crew-level smart task executions approach. The constraints management is also seldom paid close attention in previous studies of the PHP field. However, the fragmented-oriented PHP processes are really needed to improve collaborative working and decision making by releasing constraints-free work prior to tasks execution.

(4) Apart from the research gaps, the industry need is highlighted as a lack of a tool for identifying and modeling, optimizing and removing, monitoring and predicting the constraints, which may lead to the schedule delay, cost overrun, quality and safety issues in PHP projects of Hong Kong.

2.5 Chapter Summary

This chapter first reviews the Theory of Constraints (TOC) and Lean Philosophy to highlight their common grounds and differences as the theoretical supports for constraints management. Then, the challenges of traditional approaches for constraints management in the construction industry have been explored, and the opportunities learned from manufacturing industry are also illustrated. Additionally, the literature review regarding smartness in PHP is conducted on integrating BIM related information technologies with PHP to identify a possible advanced approach for constraints management. The knowledge domains of BIM-PHP are investigated, and a conceptual framework including smart BIM platform, smart work packaging, and smart PHP objects as the opportunity is proposed to achieve efficient crew-level constraint-free task executions. Finally, research gaps and industry need are well discussed.

CHAPTER 3 Research Methodology

3.1 Introduction

This chapter aims to illustrate the methods and analytical tools used in this study for developing smart work packaging to manage constraints in prefabrication housing production. Firstly, the framework of the methodology is established. Then, survey, simulation, case study, and experiment as the methods in this research are illustrated. Finally, the analysis techniques grouped to achieve the functions of modeling, optimization, monitoring, and simulation game are interpreted in detail.

3.2 The Framework of Methodology

To achieve the research objectives, the detailed research methods and analysis techniques are summarized in Table 3.1 to form the framework of methodology. The methods and techniques are adopted from both qualitative and quantitative perspectives.

Table 3.1 The framework of methogology

No.	Research Objectives	Research Methods	Analysis Techniques
1	To define the concept and properties of smart work packaging (SWP), specify its functions and paradigm for constraints management (CM), and propose the system architecture for SWP-CM.	1. Survey	1. Content analysis 2. Expert interview 3. Gemba Walks
2	To develop the constraints modeling module in SWP for enhancing the sociability in the constraints identification and mapping process;	1. Survey 2. Simulation 3. Case Study	1. Content analysis 2. Expert interview 3. Gemba Walks 4. Social network analysis 5. System dynamics 6. Discrete event simulation

3	To develop the constraints optimizing module in SWP for improving the adaptivity in the constraints improvement process;	1. Survey 2. Simulation 3. Case Study	1. Content analysis 2. Probabilistic roadmap 3. A* algorithm
4	To develop the constraints monitoring module in SWP for achieving the autonomy in the constraints tracking and updating process;	1.Experiment	1.Convolutional neural networks 2. Long short-term memory
5	To develop a simulation game for SWP-CM to disseminate this approach into the industry and education.	1. Simulation 2. Experiment	1. Statistical analysis

3.3 Research Methods

3.3.1 Survey

In this study, the survey is used to collect and analyze data with the techniques include expert interviews, Gemba walks, and content analysis.

(1) Content analysis, as a structured literature review technique for making replicable and valid inferences from large bodies of literature, is adopted to seek the new approach for constraints management and identify the initial list of constraints in the on-site assembly process of PHP (Klaus, 1980). This technique has been widely used to help researchers extract textual information from the literature (Liang et al. 2016; Mok et al. 2015). Takes the content analysis of "integrating BIM with PHP" as an example. A five-step procedure is applied and shown in Figure 3.1:

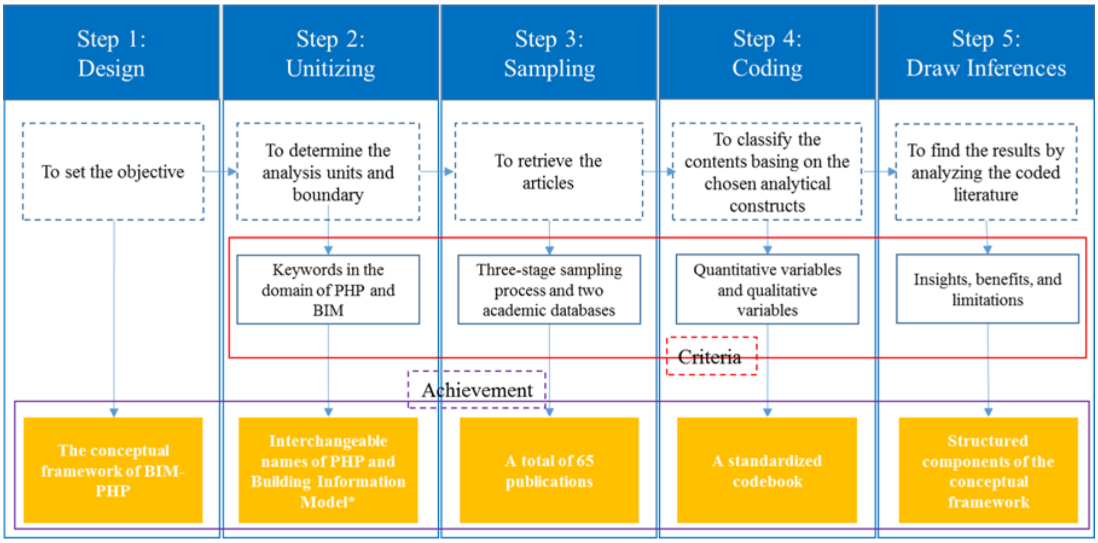


Figure 3.1 Process to review the BIM-PHP

- Step 1: Setting up the objective. This objective is to critically analyze all articles that are related to the development and implementation of BIM-PHP.
- Step 2: Determining the analysis boundary. The analysis boundary of this study is related to the development of BIM and its relevant implementations in PHP, including its interchangeable representations in the housing field, such as prefabricated construction, prefabrication, modular construction, off-site construction, precast construction, manufactured construction, industrialized building system, and pre-assembly construction.
- Step 3: Identifying sample articles. A three-stage sampling process, which is previously adopted by Mok et al. (2015), and Li et al. (2018c) , is also adopted to identify articles from two databases, including Scopus and ISI Web of Science. The three-stage process includes: (1) a scope definition stage which restricts the sample articles within academic journals (articles and reviews), because of their relatively high research impact. Book reviews, editorials, and papers in conference proceedings are not included. (2) a searching stage which identifies articles that contain the keywords in the Title/Abstract/Keywords. A total of 96 publications are identified. (3) a relevance checking stage which

excludes irrelevant papers through a brief and manual examination of the content of all articles. A total of 65 publications are selected for further analysis.

- Step 4: Coding and analyzing selected articles. The selected articles are coded and analyzed through quantitative variables and qualitative variables (which are shown in Table 3.2). These variables are adapted from Mok et al. (2015). In these codes, the production structure refers to a hierarchical structure of prefabrication products from low to high, including material, component, module, and unit (Li et al., 2017c). According to Li et al. (2017c), components (e.g., floor slabs) are produced from materials and assembled into modules (e.g., prefabricated bathrooms), which will then be integrated into a unit (e.g., prefabricated rooms). This taxonomy classifies the PHP from the point of the physical product, which can be planned and controlled (manufactured, transported, assembled) to evaluate the working efficiency. There are also other taxonomies. For example, the sub-systems of a building include structure, envelope, partitions, equipment, and services, which classifies the PHP from the perspective of functions. However, it is not very applicable to evaluate the work efficiency, and the trend in the development of PHP is to integrate both of them into a pre-finished level. For example, Hong Kong government has tried to manufacture the 3D factory-finished units (precast concrete or prefabricated steel), which can act as a sole vertical load-bearing structure and integrate all the envelope/partitions/spaces as well as all the equipment and services. In this situation, the material, components, and modules of the unit then can be manufactured efficiently by the specialized manufacturers and then converge at the main factory.

Table 3.2 Codebook for the content analysis of this review

Code	Definitions of Code
Quantitative variables coded	
Year	The publication year, from 2005 to 2017
Author	List of authors
Article title	Title of the article
Journal	The journals where the article is published
Institution	The institution of the first author
Country/Region	Country/Region where the study is conducted
Production structure	From high-level to low-level, including units, modules, components and materials
Information requirement	Information requirements for information modeling and exchange
BIM-PHP stages	Specific BIM applications in the lifecycle of a project
BIM-PHP areas	Specific research and application areas in BIM-PHP
Supporting technologies	Supporting technologies adopted in BIM-PHP to facilitate the implementation
Methodology	Qualitative, quantitative, or mixed methods
Data collection methods	The survey, interview, case study, experiment or others
Qualitative variables coded	
Research Questions	Research issues and gaps explicitly stated in the article
Contribution	Contribution to the body of knowledge
Major Findings	Key findings explicitly stated in the article
Future Needs	Future studies or limitations explicitly stated in the article

- Step 5: Summarizing the insights, benefits, and limitations. The above codes of BIM-PHP are critically analyzed and re-structured as the basis of the conceptual framework. A case is used to demonstrate the use of the framework, and the feedback is used to strengthen the conceptual framework.

(2) The expert interview is an efficient technique to collect professional information and comments in a specific field. In this study, the proposed conceptual framework of smart work packaging for constraints management was validated by 14 PHP industry professionals, who were the primary stakeholders of PHP in Hong Kong. All the 14 experts validated the conceptual framework and provided their comments on the potential application scenarios and functions based on their expertise. As shown in Table 3.3, the invited professionals included major stakeholders in PHP projects, including client, contractor, manufacturer, transportation company, and consultancy. All industry professionals had more than 10 years of experience in the development, operation, and management of PHP projects and related technologies. It is therefore expected that these PHP professionals can provide an unbiased and constructive assessment of the proposed conceptual framework.

Table 3.3 The background of the 14 interviewees and their contribution

No.	Organization (Stakeholder)	Expertise	Years of Experience	Main Contribution
1	Housing Authority (Client)	Construction Management	20+	Constraints Identification
2		Supply Chain Management	20+	Applications of Functions
3	Housing Society (Client)	Lean Construction	20+	Example Scenarios
4		Production Management	20+	Constraints Monitoring
5	Gammon Construction (Contractor)	Construction Management	15+	Constraints Modeling in On-site Assembly Process
6		BIM	10+	The system model of SWP
7	Aggressive (Contractor)	Construction Management	15+	Constraints Optimization in On-site Assembly

				Process
8	WHS (Manufacturer)	BIM	10+	The function model of SWP
9		Prefabrication Production	10+	Production Breakdown System
10		Process Operations	10+	Constraints Optimization in Production Process
11	MDM (Logistics)	Supply Chain Management	15+	Constraints Modeling in Supply Chain Process
12		Logistics and Positioning Technologies	10+	Constraints Monitoring in the Logistics Process
13	CIC (Consultancy)	Lean Construction	20+	Paradigm of Constraints Management
14	TSL (IT Consultancy)	IoTs Solutions	15+	Properties of SWP

(3) Gemba walks (Womack, 2010) is a Lean Construction technique that believes the issues/data can be understood/collected through a direct site experience. It may be a set of actions, such as see the actual workflow, understand the task requirements, ask questions, and learn. The Gemba Walk is an opportunity for the researchers to walk the floor of the workplace to identify activities with constraints. For example, the detailed task or activity still beset some missing or incomplete prerequisites including design (drawings and BIM models), prefabricated products, space, buffer, labor, equipment, permits, specifications, prerequisite work, which prevent the reliability of PHP workflow, particularly in the on-site assembly process (Li et al., 2018b). This study used Gemba walks to concentrate on the four-day assembly cycle (FDAC) process, which means the typical floor can be assembled and finished by the four-day plan, as shown in Fig.3.2 and Fig.3.3.

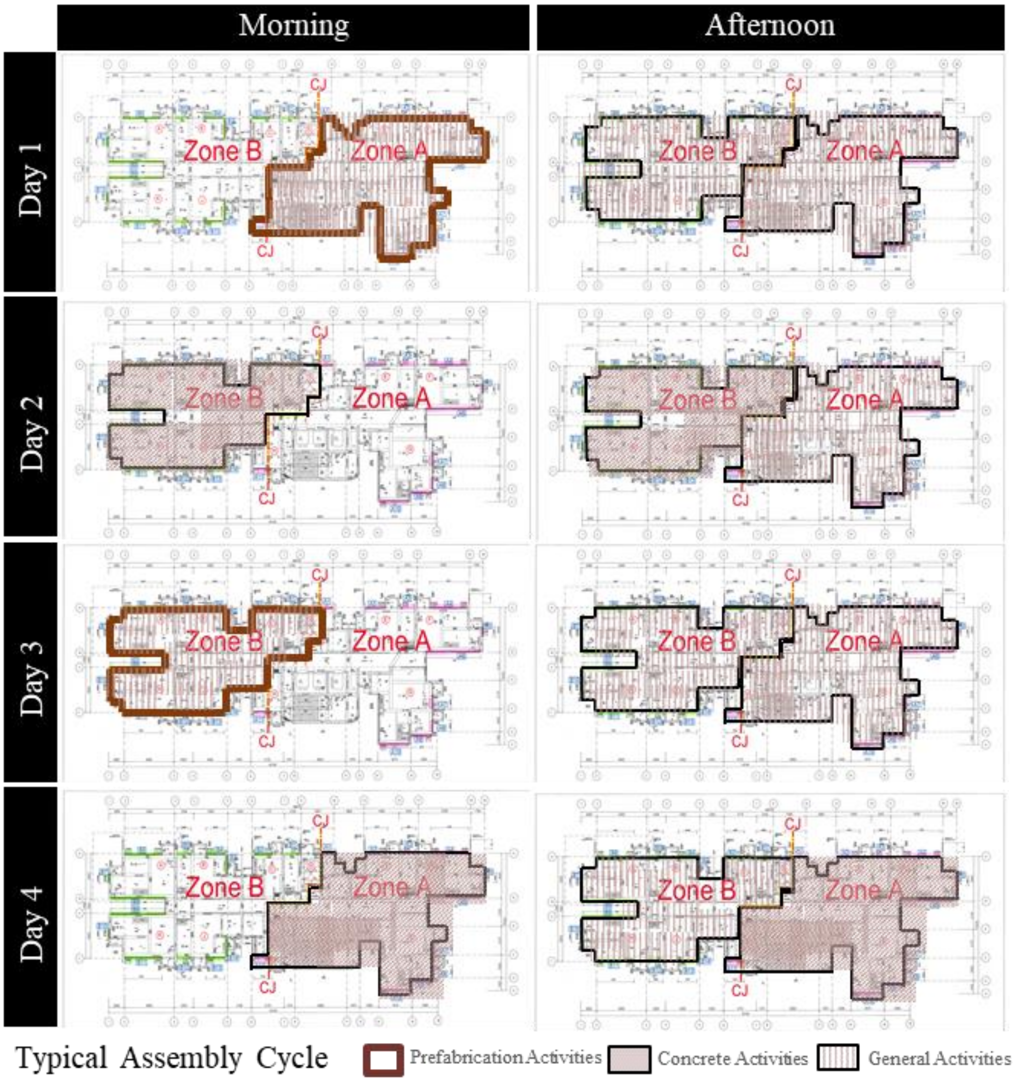


Figure 3.2 Four-day assembly cycle

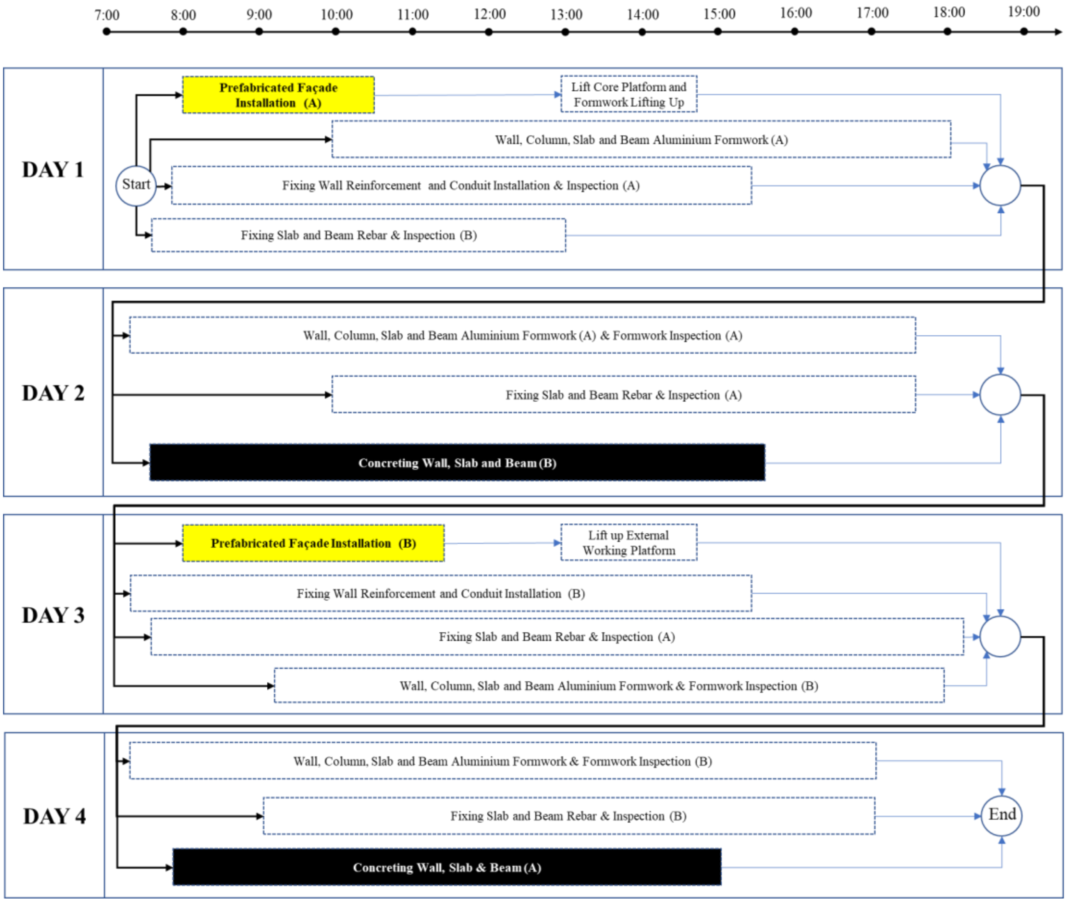


Figure 3.3 The process of FDAC

3.2.2 Simulation

In many situations, it can not afford to conduct an experiment in the real world. Simulation is a method to explore the issue and find its solutions through a risk-free way, which can allow to make mistakes, undo actions, and repetitive starts. In this study, simulation is applied into three aspects: (1) Modeling the constraints for evaluating how and to what extent the model can function as an experiment platform to assess the impacts of different constraints on the schedule performance of the PHP project. Simulation results considering mixtures of various constraints scenarios under the different timeline of the PHP project are generated. (2) The constraints optimization schemes under different decision-making results can be simulated in the 3D virtual environment (BIM environment). (3) Simulation game, as an experience-based learning approach, has increasingly gained popularity in the construction management field for school education and industrial training (González et al., 2015; Sacks et al., 2007; Wang et al., 2016a). The core merit of a simulation game is that it integrates characteristics of simulation (about a real-life situation, event or activity) and games (players, rules, competition, co-operation) to transfer the knowledge of technologies and theories among practitioners and students (Rusca et al., 2012).

3.2.3 Case Study

In this research, case study runs through the whole study to have an up-close, in-depth, and detailed investigation of the smart work packaging approach for constraints management in a specific project case "Subsidized Sale Flats Project at Tseung Kwan O Area 73A". It is a residential tower of 33 stories, which provides 330 flats (1 to 3 bedroom) with 1020 units, including one basement (car park, plant room), a 4-level podium for the commercial shop, car park, landscape area, plant room, podium garden, and multi-function room. The only prefabricated facade is adopted in this project, which incorporates nine different kinds of modules to form 26 different types of facades. This case is well investigated through three aspects: (1) The information of constraints, trades interrelationship, assembly processes, schedule, and labor quantity are analyzed in constraints modeling service; (2) The information of BIM models, crane operations, dynamic constraints, and environment are used in the constraints optimization service; (3) The information from crane operators are examined in the constraints monitoring service.

3.2.4 Experiment

The experiment is the process to support or contradict a hypothesis by testing it. In this study, the experiment is conducted in two areas: (1) For the constraints monitoring service, the crane operator fatigue monitoring model is trained on the training dataset and tested on the validation dataset to evaluate its accuracy. (2) For the simulation game, it designs the experiment with two groups. The first group uses traditional learning method of computer-based multimedia presentation. The second group adopts the smart work packaging approach.

3.4 Analytical Tools

Before selecting the primary analysis techniques to achieve the functions of modeling, optimization, and monitoring in smart work packaging for constraints management, a variety of tools have been summarized and compared to see which methods are suitable for dealing with the core characteristics of PHP, which includes interdependent trades and activities involved into PHP, dynamic constraints occurred on the site, real-time tracking and updating the constraints are needed.

3.4.1 Techniques for Constraints Modeling Service

This study has proposed a service-oriented architecture (SOA) to encapsulate smart work packaging (SWP) into the Infrastructure as a Service (IaaS) layer Section 4.2. Constraints modeling thus can work as a service in SWP to include the sub-services for critical constraints identification, hybrid model development, and critical constraints analysis. This service should work as a function in the overall smart work packaging (SWP). The authors have proposed a service-oriented architecture (SOA) to encapsulate SWP into the Infrastructure as a Service (IaaS) layer in the previous study (Li et al., 2019a). Based on this conceptual study, in order to provide practical and useful tools for workers to automatically identify critical constraints, dynamically explore interactional and interdependent relationships of these constraints, and understand the impact of these constraints on schedule performance, we further embed a few practical techniques and analytics methods into the SWP. The identification of critical constraints and their interrelationships, as the first step in constraints modeling service, is supported by social network analysis (SNA) technique, which applies social network theory to help explore the complex system that contains miscellaneous relationships. The on-site assembly process can be considered as an intricate network involving different workers. The integration of SNA can, therefore, help facilitate the identification of critical trades associated constraints and their cause-and-effect relationships in the on-site assembly process of PHP. The use of SNA can be found in various research fields, such as schedule risk (Li et al.,2016), urban renewal (Yu et al., 2017), and social responsibility (Lin et al., 2018). The authors have also investigated the use of SNA for constraints identification in a static manner (Gong et al., 2019). However, the adoption of automatic and dynamic SNA has not been investigated. Therefore, in this study, the SNA sub-service is proposed. It has three major steps: (1) The workers of different trades register or log-in the SNA service of their own SWP and get the constraints template; (2) they score and evaluate the constraints interrelationships; (3) they visualize the network and identify the critical constraints and interactions in an automatic manner. Secondly, assessing and simulating the potential effect of the identified critical constraints on the schedule performance of PHP should be considered in SWP to facilitate the decision making of the workers. Computer simulation has been widely adopted in diverse decision-making in construction processes by enabling 'what-if' scenarios (Lee, 2017). Discrete Event Simulation (DES) has been a primary means for such simulation, representing sequential operation details (Alvanchi et al., 2011). As DES models can offer detailed information for execution, they have been primarily used to solve operational issues (e.g., physical constraints) such as shop-floor fabrication and on-site assembly which can replicate the PHP processes for helping different trades to analyze their constraints. However, DES is deficient in the dynamic analysis of system interaction. For example, DES models can analyze on-site assembly process with an event-oriented view but cannot organize feedback structures between process performance (e.g., schedule performance) and its project contexts (Hwang et al., 2016). Instead, the control theory-based system dynamics (SD) models can be applied to analyze the interactions (e.g., causal loop) and structures (e.g., stock and flow) of the project environments due to their perfect demonstration of feedback effects. Also, SD models are efficient to integrate management actions. Unlike the DES models which target operational details, SD models focus on handling strategic issues (e.g., informational constraints) (Li et al. 2018a). Thus, by considering the advantages of DES and SD, a hybrid SD-DES dynamic model can be embedded into SWP to help workers of different trades conduct a more comprehensive constraints evaluation in both operational and strategic levels. In this research, a customized SD-DES hybrid dynamic model sub-service is developed to encapsulate the SD models into each event in the DES model. DES model primarily facilitates to measure the operation level of the on-site assembly system, including the capacity and number of project resources, the duration of on-site assembly tasks, and the lifting distance of the crane tower. SD models are primarily linked to strategic level context, such as the satisfaction level of the tasks, level of worker fatigue, level of worker skill. The development of SD-DES hybrid dynamic model sub-service has three significant steps: (1) Define the system boundaries of the SD-DES hybrid dynamic model service; (2) Encapsulate the SD models and their associated attributes into the DES model for simulating the variations in the schedule performance of PHP; (3) Validate the developed model through conducting structure and behavior tests. This validation process can build up the confidence of the simulation results. Thirdly, constraints scenario analysis is conducted for both project managers and workers to understand different simulation results so that the influence of different critical constraints on schedule performance can be understood.

3.4.2 Techniques for Constraints Optimization Service

In prefabricated construction, manufacturers perform continuous efforts to upgrade the design of prefabricated products, with the evolution from components (light-weight, e.g., facade) and modules (large and heavy, e.g., volumetric precast bathroom) to pre-acceptance integrated units (larger and heavier, e.g., completed with finishes, fixtures, and fittings) (Han et al., 2014). Given this course of prefabricated products evolution, cranes, with their great transportation capacity, perform a decisive role in the assembly of prefabricated products by lifting them vertically and horizontally (Han et al., 2014). As such, the constraint-free path of the crane will be a crucial factor for safety and productivity, particularly in the PHP construction site of Hong Kong due to the high level of congestion. Presently, cranes operators execute lift tasks based on their knowledge and limited site perception. This intuitive manipulation can usually lead to inefficient and unsafe operations (Kang et al., 2009). Although the duration of inefficient operations in one assembly cycle may be short, it can gather to a compelling amount of time when the hundreds or thousands of assembly cycles conducted in a PHP project (Kang and Miranda, 2008). The robotic motion planning methods are still the mainstream approaches for developing crane path-planning algorithms to achieve collision-free travel, where cranes can be generally considered as multiple-degree-of-freedom (DoF) (e.g., 3 DoF for tower crane) robotic manipulators (Lei et al., 2013b). The studies to date for crane path planning (See table 3.4) has concentrated primarily on developing algorithms and computer-aided tools to generate feasible or optimal paths in the offline (pre-processed) or online (real-time) manner. Although some studies have also made efforts to enhance the dynamic path re-planning of the crane through reducing the computational time and improving path quality when certain unpredictable constraints occur (AlBahnassi and Hammad, 2011; Zhang and Hammad, 2012; Chi et al. 2014), they did not draw attention to whether the path should be re-planned or remain unchanged when the constraints change dynamically in the construction site. Thus, an innovative decision-making approach for path re-planning in a dynamic construction site by computing path cost values according to the importance and implications of these constraints is imperative. Inspired by the methods in Han and Hasan (2018), and Chi et al. (2014), a resilient decision-making approach in SWP of crane operator can be developed for crane path re-planning in a dynamic construction environment through using path cost values that diffused from a specific group of constraints. Accordingly, two techniques are adopted in the following: (1) probabilistic roadmap (PRM) is a path planning technique to help determine a path between the start and the goal by sampling and connecting the points in the configuration space (C-space). The process of PRM can be usually shown in Figure 3.4 (Chi et al., 2014). Then, a graph search algorithm such as A* is usually used to search an optimal path. (2) Compared with Dijkstra's algorithm that is time-consuming to assess all sides of the grid to find an optimal solution, A* search algorithm with a partial heuristic function can help balance efficiency and performance for evaluating the quality of current solutions and removing impossible paths during search processes (Chi et al., 2014).

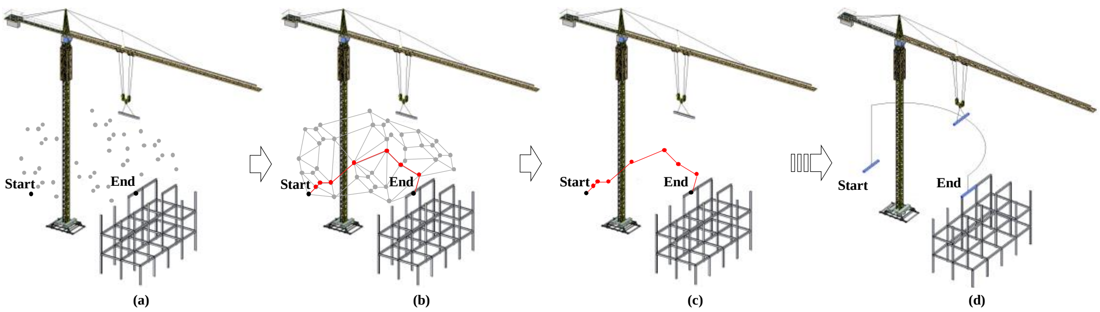


Figure 3.4 The process of PRM in Cartesian space: (a) sampling; (b) graphing; (c) solution finding; and (d) refining phases

Table 3.4 Summary of previous studies in crane path planning

Research	Concerns	Interpretations	Constraint Detection
Reddy and Varghese (2002)	Efficiency	Development of automatic path planning for mobile cranes using the configuration space (C-Space) method	Offline_Static
Sivakumar et al. (2003)	Solution quality	Development of automatic path planning for multi-crane operations by employing A* and hill-climbing	Offline_Static
Ali et al. (2005)	Solution quality	Automated path planning of multi-crane by using genetic algorithms (GA)	Offline_Static
Kang and Miranda (2006)	Solution quality/efficiency	Integration of three different path planning methods (path generation, operations coordination, and collision detection) to generate and visualize the feasible paths	Offline_Static
Kang and Miranda (2008)	Solution quality	Development of a coordination method for crane motions can make multiple cranes work collaboratively to avoid a collision on a confined and changing construction environment	Offline_Semi-dynamic
Kang et al. (2009)	Solution quality/efficiency	Simulation and visualization of physical-based on-site assembly processes in a dynamic virtual environment (predictable changes)	Offline_Semi-dynamic
Chi and Kang (2010)	Solution quality	To develop a simulation system that generates paths with both visual presentation and physical information (e.g., force feedback, cable sways, and collision behaviors)	Offline_Semi-dynamic
Chang et al. (2012)	Efficiency	To make use of probabilistic roadmap methods (PRM) for path planning in a near real-time manner.	Offline_Static
AlBahnassi and Hammad (2011)	Solution quality	A framework is developed for real-time crane path planning by considering the dynamic properties of known and unknown obstacles with sensing and tracking technologies.	Online-dynamic
Zhang and Hammad (2011, 2012)	Solution quality	Integration of real-time location systems with rapidly-exploring random trees (RRTs) to create safe and efficient crane paths while handling the constraints in a dynamic environment	Online-dynamic
Lei et al.(2013a,2013b)	Solution quality	A generic and automatic approach to achieve binary (Y/N) path checking for mobile crane lifting with construction site changes over time	Offline-static
Olearczyk et al. (2014)	Efficiency	To propose a path that the sequence of simple rotations and translation in which smoothness in minimized	Offline-static
Lin et al. (2015)	Solution quality	Development of path planning method by considering the movement nature, size and shape of a crane	Offline-static
Hung et al. (2016)	Efficiency	To provide four strategies in a collision-free pathfinding approach and an approach of path refinement for reducing the processing time of configuration space	Offline-static
Cai et al. (2016, 2018)	Solution quality/efficiency	To develop a path planner considering the kinetic structure of crane and perform crane lifting tasks under multiple constraints that show the fast generation of optimized paths in virtual environments.	Online-dynamic
An et al. (2018)	Solution quality/efficiency	To provide an optimized path through optimizing operations of a lift task for a truck crane by considering the characteristics of the crane	Offline-static

3.4.3 Techniques for Constraints Monitoring Service

Crane operator executes the repetitive lift tasks under the fatigue state in a complex construction environment may lead to catastrophic casualties as same as the vehicle drivers. There are apparent signs that indicate an operator/driver is fatigue, e.g., repeatedly yawning, failure to keep eyes open, swing the head forward, face complexion changes due to blood flow (Ngxande et al., 2017). As the facial features of operator/driver in a fatigued state are significantly different from that of the conscious state, the real-time monitoring the operator/driver's face by the camera can be an efficient, non-invasive and practical approach to alert the drowsiness and avoid the accidents (Shi et al., 2017). PERCLOS (percentage of eyelid closure over the pupil over time) is a reliable measure to monitor the fatigue (Zhang et al., 2017). In addition, numerous machine learning-based approaches have also been applied to fatigue monitoring. For instance, Mbouna et al. (2013) proposed a model to extract the visual features from the eyes and head pose of the drivers, and then support vector machines (SVMs) was used to classify the fatigue levels. Choi et al. (2016a) trained the hidden Markov models (HMMs) to learn the temporal behaviors of head pose and eye-blinking for identifying whether the driver is drowsy or not. However, these approaches relied on hand-crafted features which have been proved to be inefficacy in real-time monitoring and can be inaccurate when driver/operator wears the sunglasses or under considerable variation of illumination conditions (Park et al., 2016). Concurrently, features learned from unlabelled data by using the deep neural networks such as the convolutional neural network (CNN) have been proved to have a significant advantage over hand-crafted features in real-time monitoring of fatigue (Zhang et al., 2017).

CNN is the class of deep and feed-forward neural networks that involves three main elements, including local receptive fields, shared weights, and spatial or temporal pooling (Lecun and Bengio, 1995). The process of fatigue monitoring and alerting by CNN is the same as other machine learning-based methods that can be shown in Figure 3.5. The previous studies regarding fatigue monitoring and alerting by using CNN related models have also been summarized in Table 3.5. CNN was first applied to fatigue monitoring as the features extractor of static facial fatigue images by Dwivedi et al. (2014). Then, Zhang et al. (2015) used the CNNs as both face and nose detectors to show their performances that are quite better than the conventional face detectors such as AdaBoost and WaldBoost with Haar-like features. To achieve the real-time fatigue monitoring, Reddy et al. (2017) utilized multi-task cascaded CNN with the compression technique to achieve a faster fatigue recognition than existing models of VGG-16 and AlexNet at a reasonable accuracy rate. As the fatigue states are dynamic (e.g., yawning, nodding) and it is difficult to distinguish whether the driver/operator is yawning or talking when only capturing their open mouths, a 3D CNN was proposed to capture the motion information of numerous adjoining frames from videos, and 3D filters (kernel) were adopted to extract spatiotemporal features (Huyng et al., 2016). Furthermore, Part et al. (2016) integrated three existing CNN-based models including AlexNet, VGG-FaceNet, and FlowImageNet in terms of their efficiency in the extraction of image features, facial features, and temporal features. However, these methods can only extract features with fixed temporal length, and the 3D convolution processes may spend numerous resources and time to impede the real-time monitoring. Long Short-Term Memory networks (LSTMs) has been proved to be effective in learning long-term temporal dependencies by solving the exploding and vanishing gradient problems that is a Gordian knot for the traditional recurrent neural network (RNN) (Hochreiter and Schmidhuber, 1997). And an LSTM comprises typically a cell and three gates (input,output, and forget). The cell can remember values over arbitrary time intervals, and the gates control the information flow out and into the cell. Thus, the integration of CNN and LSTM can be an alternative in fatigue monitoring and alerting. Several studies have adopted CNN to extract frame-level features and then feed them into LSTM to extract the temporal features for determining whether fatigue or not. And several refinement techniques help them achieve the high accuracy such as reducing the hidden layer of LSTM (Guo and Markoni, 2018), noisy smoothing in post-processing (Shih and Hsu, 2016), and alignment technology to learn the most critical fatigue information (Lyu et al., 2018). However, to improve the accuracy, all information included in time series data should be entirely employed. The frames of video are sequentially fed into an LSTM that lead to an information flow with positive direction from time step t-1 to t along with the chain-like structure. Therefore, the LSTM can only utilize the forward dependencies, and it is very likely that valuable information is filtered out or not efficiently passed through the chain-like gated structure (Cui et al., 2018). Thus, it may enrich the temporal features by considering the backward dependencies. Moreover, the facial expressions of fatigue can be periodical and regular, and even short-term periodicity such as nodding can be detected. Learning the periodicity of time series data, particularly for recurring fatigue patterns, from both forward and backward temporal information, can improve the performance of fatigue monitoring and alerting. However, to the authors' knowledge, few studies on crane operator fatigue monitoring considered the backward dependencies. To fill this gap, a deep bidirectional LSTM (DB-LSTM) is integrated into the CNN to form the architecture of fatigue monitoring and alerting system.

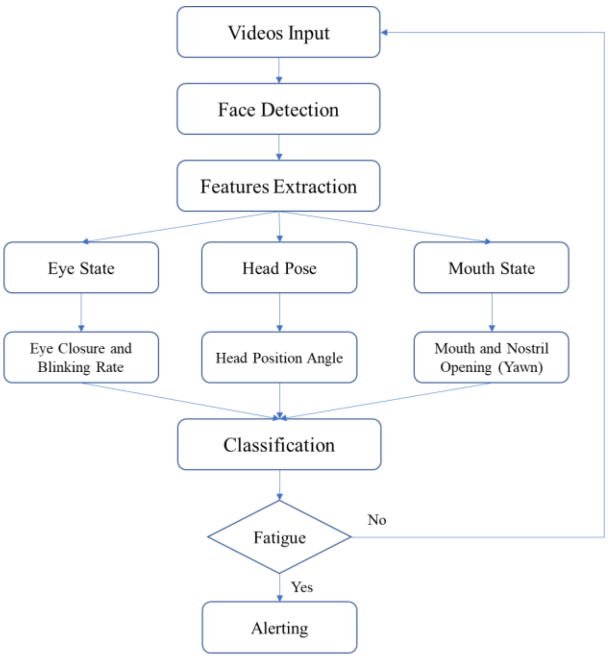


Figure 3.5 The machine learning-based process of facial fatigue monitoring and alerting

Table 3.5 The summarized studies using deep neural networks for fatigue monitoring

Research	Metric	Techniques	Database	Accuracy
Dwivedi et al.2014	Global face expressions	CNN, viola and Jones algorithm	Customized	78%
Zhang et al. 2015	Yawn (mouth and nose state)	CNN, Kalman filter with track-learning-detection	YawDD	92%

		(TLD)		
Huynh et al. 2016	Global face expressions	3D CNN, Gradient Boosting	NTHU	87.46%
Park et al. 2016	Global face expressions	AlexNet, VGG-FaceNet, FlowImageNet	NTHU	73.06%
Shih and Hsu, 2016	Global face expressions	VGG-16, LSTM	NTHU	85.52%
Reddy et al. 2017	Eye and mouth state	Multi-Task Cascaded CNN,	Customize d	89.50%
Guo&Markoni, 2018	Eye and mouth state	MTCNN,VGG-11,LSTM	NTHU	84.85%
Lyu et al. 2018	Global face expressions	Multi-granularity CNN, LSTM	NTHU	90.05%

3.4.3 Techniques for Simulation Game Evaluation

In order to validate whether there is a significant improvement between ex-ante and ex-post survey for the proposed SWP approach in the simulation game, meanwhile to verify whether the SWP approach has higher improvement than the traditional teaching method, the differences in responses between the two surveys in SWP and the differences in responses between two approaches (The data set of each approach is the differences in responses between the two surveys) could be analyzed by a paired samples t-test and an independent samples t-test, respectively, if the data is usually distributed. The paired samples t-test is adopted to compare the means of an ex-ante and ex-post survey on the same group of participants (SWP group), and the independent samples t-test is used to compare the means of two independent groups (SWP and traditional group). The non-parametric test will be adopted if the data is not normally distributed. The normality is checked by Shapiro-Wilk test at a 0.05 significance level. Additionally, the radar chart is adopted to evaluate the variations of each question.

3.5 Chapter Summary

This chapter presents the methodology of the research. The research methods adopted in the study contains survey, simulation, case study, and experiment. The analytical tools applied in this study can be divided into four groups: the first group includes social network analysis (SNA), system dynamics (SD), and discrete event simulation (DES) that is related to identify the constraints in PHP processes and model the interrelationships of these constraints; the second group comprises probabilistic roadmap (PRM) and A* algorithm that is relevant to optimize the most influential constraint (activity-level) and introduce a decision-making mechanism to improve its task-level constraints, and the techniques in the third group consists of convolutional neural networks and long short-term memory that is regarding monitoring one of the task-level constraints and predicting the variation of this constraint. The last group uses statistical tools such as paired samples t-test, independent samples t-test, and Shapiro-Wilk test to explore the significant difference between the SWP approach and the traditional approach in the simulation game.

CHAPTER 4 The Conceptual Framework of Smart Work Packaging for CM

4.1 Introduction

The development of smart work packaging (SWP) in recent years seems to be adequate to address the challenge. In PHP, there are a few studies which investigate the smart transformation of a group of tasks (e.g., the lowest level in the work breakdown structure) based on the building systems of product breakdown structure (PBS) by embedding the capabilities of visualizing, tracking, sensing, computing, networking, and reacting. The smart transformation centers upon autonomy, adaptivity, and sociability, which can facilitate better tasks execution by crews. For example, the PHP machinery (e.g., cranes) can be augmented with the autonomy to transport or hoist the prefabricated products independently and without direct intervention from the surroundings (Chi et al., 2012). In addition, the PHP planning approaches can be enhanced with adaptivity to be capable of reacting resiliently through dynamic re-planning when constraints are not removed (Abuwarda and Hegazy, 2016). SWP can also be strengthened with sociability to interact in a peer-to-peer manner with other work packages or resources to collectively model the constraints (Taghaddos et al., 2012).

This chapter, therefore, intends to develop the conceptual framework of SWP for constraints management in PHP, based on the established theories of work packaging and SCOs (Isaac et al. 2017; Niu et al. 2016). Work packaging can break down the PHP processes into manageable pieces to facilitate execution of activities or tasks. However, it is limited to help improve the constraints during task executions in an autonomous, adaptive, and optimal manner. e.g., automatic identification and analysis of constraints and their interrelationships (Hamdi, 2013; Isaac et al. 2017), real-time sensing and tracking constraints status (Liu et al. 2015), and optimal constraints improvement planning in a dynamic manner (Abuwarda and Hegazy, 2016). SCOs are construction resources augmented with smart characteristics of awareness, communicativeness, and autonomy using emerging information technologies. However, SCOs are usually defined on single construction objects, without considering construction project operations such as work packaging. Thus, the development of SWP, as the integration of work packaging and SCOs, seems necessary and imperative to improve constraints management in PHP. To improve the shortcomings in current practices of constraints management, this chapter aims to develop a conceptual framework of SWP-enabled constraints management (SWP-CM) in PHP. The specific objectives are: (1) to define the SWP; (2) to establish the framework of SWP-CM; (3) to propose a functional structure of SWP as a layered system model; and (4) to validate the SWP-CM by a simulation game. This chapter is demonstrated by the following structure. Section 4.2 explores the opportunities for integrating BIM and PHP. Section 4.3 defines SWP and proposes three core characteristics of SWP. Section 4.4 proposes the framework of SWP-CM with three main functions, including constraints modeling, constraints optimization, and constraints monitoring. Using a layered system model as a prototype, Section 4.5 offers details of the applications of SWP by exploring their design and development. Section 4.6 validates this conceptual framework by using a simulation game. Section 4.7 discusses the challenges and opportunities presented by SWP for constraints management, and Section 8 concludes this study.

4.2 The Opportunities for Integrating BIM with PHP

As can be seen from the Chapter 2.3, most studies focus on addressing isolated implementations of BIM, such as interoperability, and information sharing and communication, to address various issues in the design and construction stages of PHP. However, the rationality of individuals in decision making, collaborative working, and modular coordination is constrained by the information, their cognitive ability, and a limited amount of time they should execute (Niu et al., 2016). Such limitations are particularly amplified when other stages such as transportation, maintenance, deconstruction, and recycling are included. This limitation calls for the development of the smart BIM-PHP environment. In such environment, decision-making platform, collaborative working process, and modular/informational products are made smart by enhancing them be capable of tracking, sensing, networking, reacting and processing, which facilitate better decision making, collaborative working, and modular coordination. A conceptual framework of BIM-PHP, which is shown in Figure 4.1, is therefore developed to facilitate BIM-PHP. The proposed conceptual framework, based on the content analysis, has three pillars, namely the smart BIM platform (SBP), the smart work packaging (SWP), and the smart PHP objects (SPOs).

(1) Smart BIM Platform (SBP): Compared with the conventional BIM system, the smart BIM platform (SBP) involves not only a shared virtual 3D model developed in the design stage and updated in real-time, but also has the ability to provide service-oriented architecture (SOA) ranging from design to deconstruction and recycling. Each service requires more value-added information (e.g., cost, progress, safety, quality, lean solutions) to extend the original 3-dimensional platform to a multi-dimensional one, which then employs a more user-friendly (e.g., interactive and immersive) interface to facilitate the decision-making among different stakeholders at various stages of PHP. The performance for building systems of PHP in each service should not be simply measured from the perspectives of project management, but also evaluated by the customers' demands (Richard, 2017), such as adaptability (allowing for individualization and accommodating change without demolition), flexibility (the product is capable of geometrical variations, and the work processes could generate diversified products), multi-purpose framework (the sub-systems of PHP could accommodate different options through the addition of specialized products), and combinability (mass combinations from mass production). To achieve these, SBP will highly depend on well-formatted information/data sensed, processed, computed in the central database. As data systems are commonly geographically distributed, the data brokering function, considering the willingness of stakeholders for shared data management, needs to be embedded into the central database. In addition, only authorized stakeholders can access the information, ensuring information security.

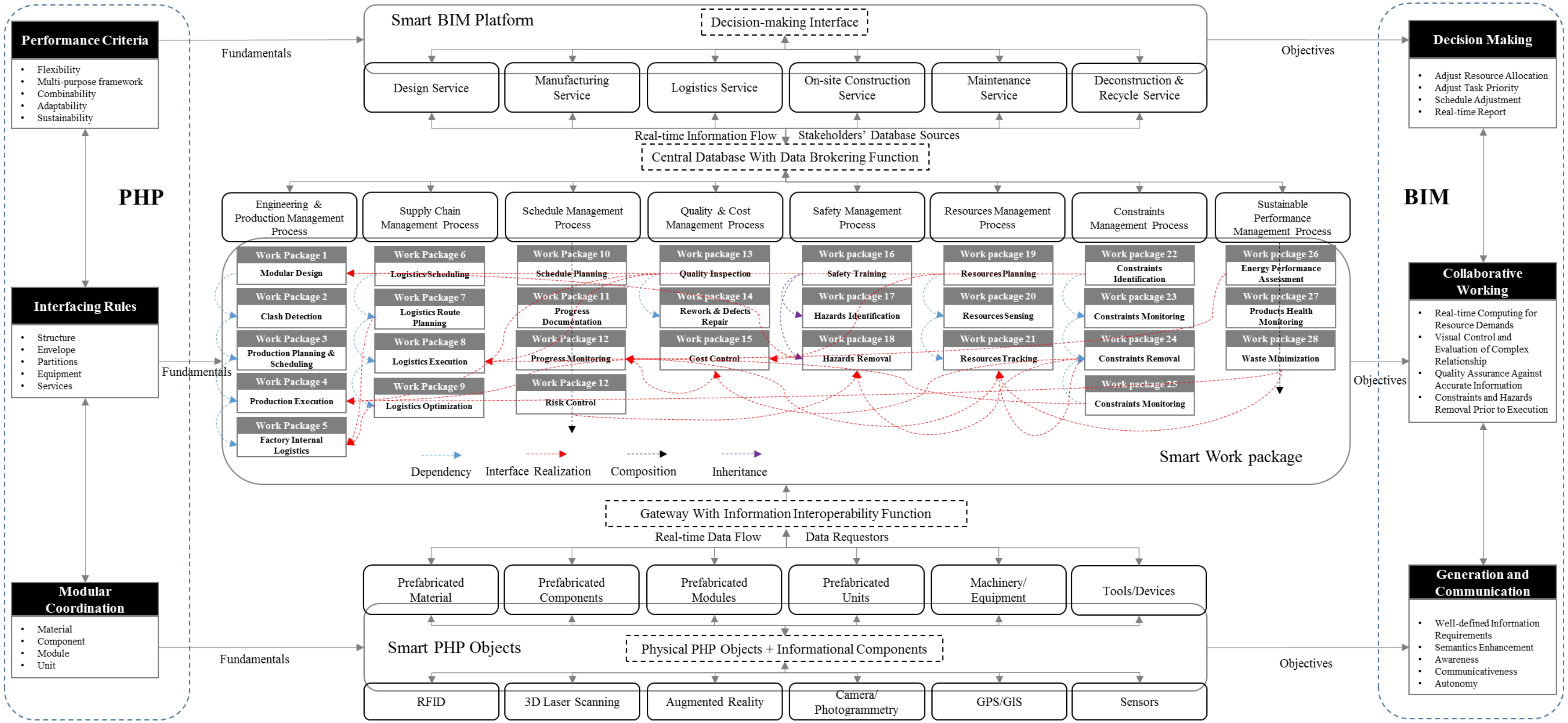


Figure 4.1 The conceptual framework for integrating BIM and PHP

(2) Smart Work Packaging (SWP): Each service will then be decomposed into collaborative and manageable processes (represented by the BIM-PHP areas in section 2.3.1), and each process includes relevant work packages. The work packaging method is to ensure activities which are highly interdependent could be decoupled into several separate packages for collaborative working (Isaac et al., 2017). Each work package delivered to each crew adopts product-oriented planning and control approach, which considers the interfacing rules of sub-systems of PHP (i.e., structure, envelope, partitions, equipment, services) to improve the reliability of workflow. The relationships among processes and work packages can be defined into four types: composition, interface realization, inheritance, and dependency.

- Composition: This relationship mostly exists between one process and its relevant work packages. For example, the schedule management process can be decomposed into several work packages, including schedule planning, progress documentation, progress monitoring, and risk control.
- Interface realization: This relationship is based on software engineering and refers to a group of work packages which support or rely on the behavior that is defined in an interface. For example, the work packages of constraints monitoring, energy performance assessment, cost control and resources tracking can be used to support the work package of progress monitoring, although these work packages have a composition relationship with constraint management process, sustainable performance management process, quality & cost

management process, and resources management process respectively.

- Inheritance: This type of relationship exists between a parent work package and its succeeding work packages. Both the parent and the succeeding work packages share some common characteristics while the succeeding work packages may have their own unique characteristics. For example, the safety training work packages generally include the approaches, tools, and specifications for hazards identification and hazards removal. However, on-the-job hazards identification and removal may be different from the general safety training work packages to reflect specific site characteristics.
- Dependency: This is the most popular relationship where the downstream work package is dependent on the upstream work package. The upstream activity provides the outputs which will be the inputs of the downstream activity, and any changes in the upstream outputs may affect the downstream activity. For example, the four work packages in the constraints management process, which are constraints identification, constraints optimization, constraint removal, and constraints monitoring, have a dependent relationship.

The relationships between processes and work packages can be used to achieve the intelligence of work packages. Automatic analysis of the topological relations between smart PHP objects can be conducted with the support of the aforementioned relationships in the smart BIM platform. In addition, visual guidance and interactive representation of the work sequence can be obtained by applying lean solutions by which the SPOs (e.g., prefabricated products) are assembled. The resource requirements, such as the quantity and location information, can also be evaluated in real-time. Based on the real-time information, evaluation of project success factors, such as productivity, safety, and quality, can be conducted. The results can then be used to adjust work packages for further improvement.

(3) Smart PHP Objects (SPOs): SPOs are PHP objects, such as prefabricated materials, components, modules, units, machinery, and devices, that are equipped with supporting technologies. For example, when PHP objects are enabled with tracking, sensing, processing, storage, and communication capability, SPOs have inbuilt autonomy and awareness (Niu et al., 2016). SPOs generate various types of information. Table 4.1 represents the information requirements in BIM-PHP and their relevant evaluation metrics. Specifying the requirement for these types of information could improve the modular coordination (i.e., dimension, space) of prefabricated products (i.e., material, component, module, unit) in a smart environment. The information requirements can be categorized into two groups: physical information requirements, such as dimension, weight, quantity, and functional information requirements, such as carbon emission, quality records, cost, energy consumption and the location (Belsky et al. 2016; Larsen et al. 2011; Wong et al. 2014). Correspondingly, many evaluation metrics have also been developed as benchmarks for assessing the information requirements (Niu et al. 2017; Demian et al. 2014), The most commonly adopted evaluation metrics include

accessibility, accuracy, appropriateness, consistency, interpretability, relevancy, security, timeliness, traceability, understandability, value-added and visibility.

In addition, it should be noted that understanding the information requirements within the specific knowledge domain has also been recognized as the fundamental needs for better information flow management (Nawari, 2012). In the design stage, the product-related information should be well defined. For example, Ramaji et al. (2016, 2017) integrated the PHP characteristics of both projects (e.g., site-built parts and on-site activities) and products (e.g., industrialized and object-oriented) into BIM to develop a product architecture model (PAM) which includes the information of functional elements (e.g., attributes, descriptions, specifications), physical objects (e.g., shape, dimension, weight, volume and quantity) and their interactions (e.g., relationships). In the manufacturing stage, the product performance-related information should be specified, such as the date of production, quality records, cost, location, and carbon emission. In the transportation stage, traceability related information is required, such as the information of the driver, tractor, and trailer, location, progress status, and transportation path. In the construction stage, the process performance-related information, including cost, safety, schedule, quality, carbon emission, constraints, position, and space are necessary. In the maintenance stage, the interaction between physical prefabricated products and functional information units can help monitor and predict the required information such as energy consumption, warranty expiration date, and defects. Hence, the bottom-up information requirements from objects and work packages to the platform could facilitate information delivery through the PHP lifecycle.

Table 4.1 Information requirements for BIM-PHP

Stage	Information Requirements (Physical & Functional)	Evaluation Metrics
Design	Shape & Dimension	***Accessibility:*** The information can be easily accessed when needed;
	Products Type & Layout	
	Material & Quantity	
	Weight & Volume	
	Structural Loads	***Accuracy:*** The information is free of error and complete;
	The specifications for coupling & decomposition	
	The relationships between products & interfaces	
	The relationships between parent & child components	
	The relationships between whole & part	***Appropriateness:*** There is neither too much nor too little information;
Manufacturing	Manufacturer & Material supplier	
	Work orders & Serial number	
	Date of Production	***Consistency:*** The information follows the same format throughout the PHP lifecycle;
	Standardized quality control records	
	Occupancy of Laydown yard	
	Location of prefabricated products	
	The specifications for assembly and maintenance	
	Progress Status	***Interpretability:*** The information is defined precisely and exchanged in appropriate format;
	Constraints and cost	
	Carbon emission	
Transportation	Transportation providers & transportation orders	
	Dispatched driver information	
	Dispatched tractor information	***Relevancy:*** The information is applicable to the tasks
	Dispatched trailer information	
	Real-time location of the vehicles	
	Progress Status	
	Transportation path	***Security:*** The information is protected against unauthorized access and editing
Construction	Occupancy of site, buffer, and workspace	
	The position of supporting equipment	
	The position of labor position	
	Quality inspection records	
	The position of prefabricated products	***Timeliness:*** The information is real-time and up-to-date
	Erection inspection records	
	Progress Status	
	Constraints and cost	***Traceability:*** The information flow is
	Carbon emission	
	Procedures and safety specification	

Maintenance	The warranty expiration date and contact Energy consumption Abandoned/removed/replaced products records Maintenance inventory	traceable, e.g., using RFID technologies; ***Understandability:*** The information is not hard to understand and manipulate; ***Value-added:*** The information offers benefits to downstream users ***Visibility:*** The information could be visualized for better sharing and communication

(4) The interactions between SBP, SWP, and SPOs: To support the implementation of the framework, an example service-oriented architecture (SOA) can be developed on the basis of cloud computing and Internet of Things (IoT) technologies (See Fig.4.2). The SOA includes three layers: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS).

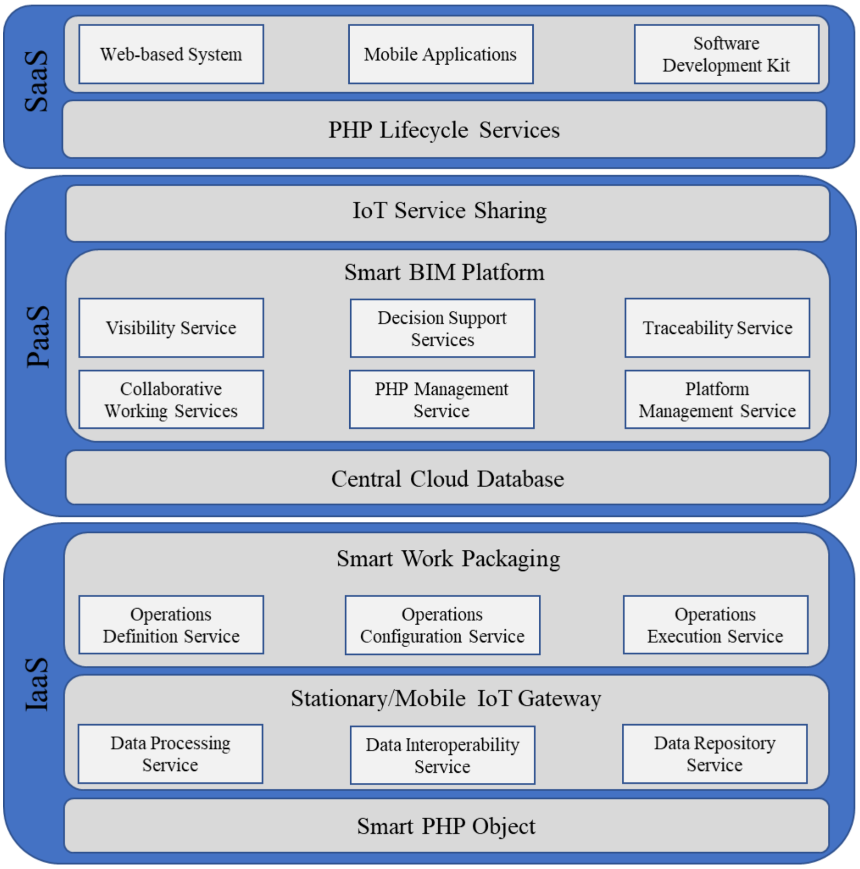


Figure 4.2 Example service-oriented architecture

The IaaS layer includes the SPOs and SWP. A gateway of data interoperability service is created between the SWP and SPOs. The gateway is an Internet of Things (IoT)-enabled industrial computer, which provides a communication link between the field (SPOs) and the central cloud database in PaaS. It could perform several critical functions in work packages to set up an information infrastructure, which can connect, manage and control the SPOs by defining, configuring, and executing the PHP tasks in a user-friendly manner. The data interoperability service could provide data query techniques for data requester to approach different SPOs for improving the interoperability issues in information sharing. To this end, the entitled APIs and drivers of different SPOs should be managed and referenced in a consistent manner. A consolidated query mechanism should also interpret requests to appropriate query languages that are required by SPOs. Additionally, fresh data retrieved from SPOs can be pre-processed and stored in a specific format by data process and data repository service. For example, the gateway to SWP can help pre-process the data collected from the SPOs and decipher the control commands sent from the upstream. To this end, the complex task processing technology could be applied to reorganize the heterogeneous data into a standardized scheme, which can be understood, shared, and used by SWP. The IoT Gateway in SWP can help SWP to link and handle a set of SPOs by wired or wireless communication. It can also facilitate SWP to communicate and interact with the central cloud database by uploading their outputs and downloading their inputs in a standardized format.

The PaaS layer offers several services for facilitating the implementation of SBP including platform management service, PHP management service, visibility and traceability service, decision support services (DSSs) and collaborative working services (CWSs). Here, DSSs and CWSs refer to sets of services that help SWP in modeling, planning, optimization, and monitoring of each task in PHP. All these services are issued and distributed through the IoT service-sharing module. The central cloud database within data source management could provide a self-service portal for managing SBP infrastructure and service provision, and the services across the SBP could reinforce SWP and host the smart PHP objects. The gateway to SWPs acts as an information bridge between the SPOs and SBP. Thus, decisions could be seamlessly synchronized into the work packages for their task executions.

The SaaS layer contains final applications for different users in different stages of PHP, which includes web-based system (e.g., for SBP which can be accessed easily through different ways), mobile applications (e.g., for SWP which can be used in mobile devices), and software development kit (which can connect with existing systems).

(5) An example of BIM-PHP: An exemplary study of a PHP public housing project in Hong Kong can be investigated to illustrate the applicability of the conceptual framework. The primary stakeholders in this project include the Hong Kong Housing Authority (HKHA) (the designer and client), the main contractor, an offshore prefabrication plant located in the Great Bay Area (GBA) of the Mainland China, and various transportation companies. The client aims to develop a new integrated approach to address the challenges identified in previous pilot cases of RFID-enabled BIM platform (RBIMP) (see Li et al. (2018a); Zhong et al. (2017)). For example, there was a lack of agile and lean management process to connect the informational components and BIM platform. This BIM-PHP conceptual framework extends previous studies and provides theoretical support for the integration by clarifying the information requirements, potential technical solutions, and proper evaluation.

a. Design Stage

In this PHP project, the project team does not adopt the traditional design process but using the BIM library of HKHA. In order to achieve the strategy of DfX, three principles are implemented in the design process, following the conceptual framework of BIM-PHP. A hierarchical structure of the prefabricated product, from units, modules, components, and materials, is adopted (see Figure 4.3). The physical and functional information flow in this hierarchical structure has two categories: whole and part, parent and child. For example, the properties of material and components can be part of the module or unit, but not the same as the module or unit. While the module can inherit some characteristics of the unit. In addition, each prefabricated product's physical and functional information, including dimension, weight, volume, quantity, material and its relationship with other products, is well defined to facilitate the process of computer-aided-manufacturing (CAM), transportation and on-site assembly. More importantly, Level of Development (LOD) 300 is adopted to ensure sufficient information can be obtained to meet the requirements of DfX strategy (Song et al., 2016). Higher LOD is not necessary because LOD 300 can meet the information requirements for BIM-PHP. Each design task (e.g., modular design and clash detection) has an SWP with relevant inputs and outputs, which can be downloaded and uploaded from the central database. For example, the SWP of modular design extracts the components, modules, and units from the BIM library of HKHA to conduct permutation and combination under the basic design codes. In addition, the information required in subsequent work packages is embedded in the products.

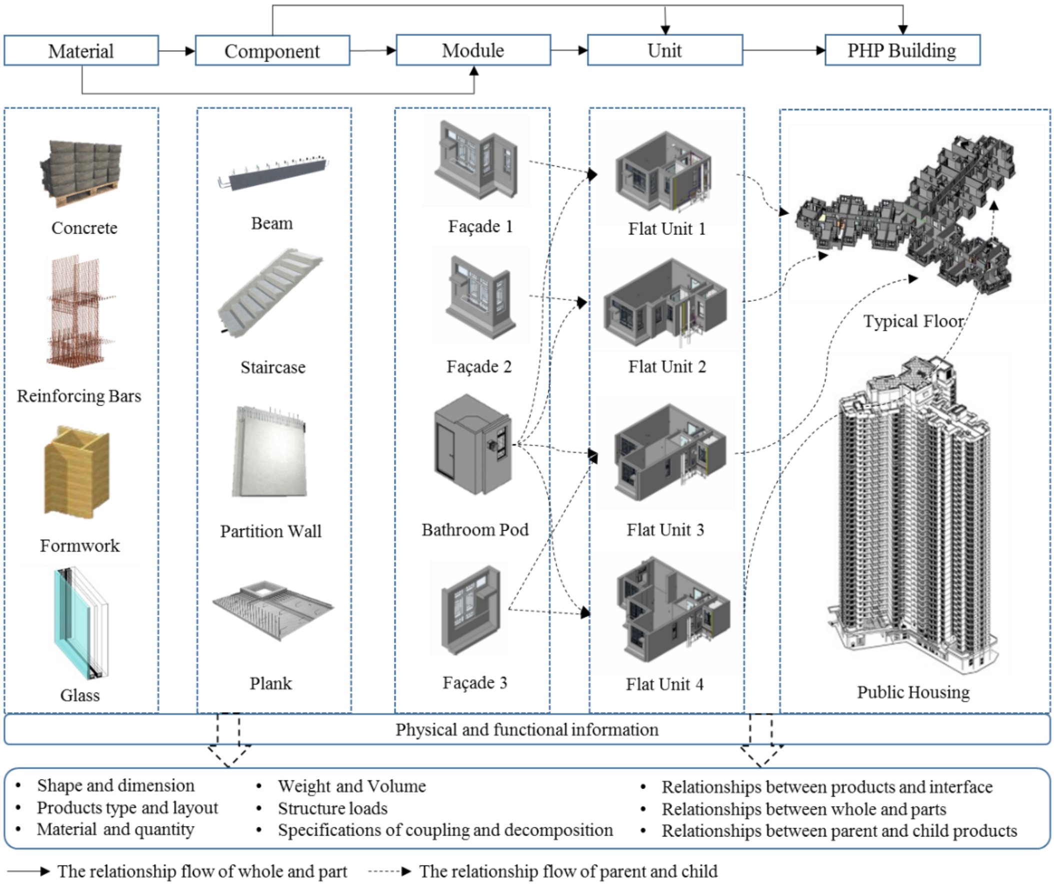


Figure 4.3 The hierarchical structure of prefabrication products with physical and functional information

The usual tasks fulfilled by BIM in a combination of various hierarchical products for different typical floor layouts include: (1) selecting the appropriate family template of cores (Flat unit 1-4); (2) layout reference planes to aid in drawing component/module geometry; (3) adding dimensions to specify parametric component/module geometry; (4) adding labels/attributes/materials to component/module to create type or instance parameters; (5) testing the new cores to verify correct component/module behavior; (6) integrating the cores with all other spaces, areas, structure, equipment and services in the typical floor.

b. Manufacturing Stage

In this case, the SWPs of production planning and scheduling, production execution, factory internal transportation are established. The SWP of production planning and scheduling help to decide what should be produced and the sequence of production. For example, the information of the prefabricated products is extracted from the BIM platform to a CAM system for manufacturers to generate production orders. The priority of these orders is determined by the urgency of actual demands on construction sites by the pull method. In the production execution SWP, RFID tags are embedded into the prefabricated products, and laser scanning is adopted for documenting the dimensions of prefabricated products and storing such information into the related SPOs. These SPOs facilitate the production execution SWP to provide updated progress for stakeholders to remove constraints and make necessary changes. The factory logistic SWP clarifies where the products should be delivered and how to search for them in the inventory yard when they are required. AR-based visual guidance and barcodes mounted in the SPOs can assist in inventory management.

c. Transportation Stage

The pull method is adopted to plan the transportation SWP, which are synchronized with the BIM platform. The SWP includes transportation planning and scheduling (e.g., driver, vehicle, route), transportation execution, and transportation optimization. In the transportation scheduling and planning SWP, the most urgent or expensive goods will be automatically assigned to the drivers with better driving track records. This process can be optimized by the dispatch algorithms in the SWP to better schedule and plan the transportation tasks. Lim et al. (2011) adopted the reroute-enabled dispatch optimization to improve the response time of urgent calls for ambulance fleet, and Truong et al. (2017) designed a patent of dispatch system that can receive requests from customers to run a match operation by selecting the qualified drivers from historical performance data. These studies are useful for the optimization of arranging transportation. Whenever a new order arrives, the ranking (priority or normal) of the importance of the order will be computed based on the historical data of lead time and goods value. The order that has a higher priority will be assigned to the driver that has demonstrated superior performance. Their performance will also be updated when the products arrive on time. The drivers can confirm their tasks and obtain relevant information about their assigned tractors and trailers by scanning their RFID staff cards through their personal digital assistants (PDAs). In the transportation execution SWP, drivers need to verify the matched vehicles by using their PDAs to scan the NFC (Near Field Communication) tags which are mounted in the tractors and trailers. They are also required to scan the RFID tags of the prefabricated products to ensure the right products are loaded in the right trailers. In addition, it is critical to achieving Just-in-time (JIT) delivery in the transportation execution SWP due to the constrained site space and buffer areas in Hong Kong. In order to achieve this, the location information of vehicles is also captured by GPS in PDAs and uploaded into the BIM platform, which then provides visible and traceable routes. As shown in Fig.4.4, both the status of vehicles (ID, location, tracking method, and status) and prefabricated products can be visible and traceable in one interface. Four logistic stages of the prefabricated products, including produced, arrived at the site, delivering and erected, are indicated by blue, yellow, green and purple respectively. In addition, in the transportation optimization SWP, the google map is also integrated into PDA for providing an optimized transport route (with minimum driving time) based on real-time traffic data.

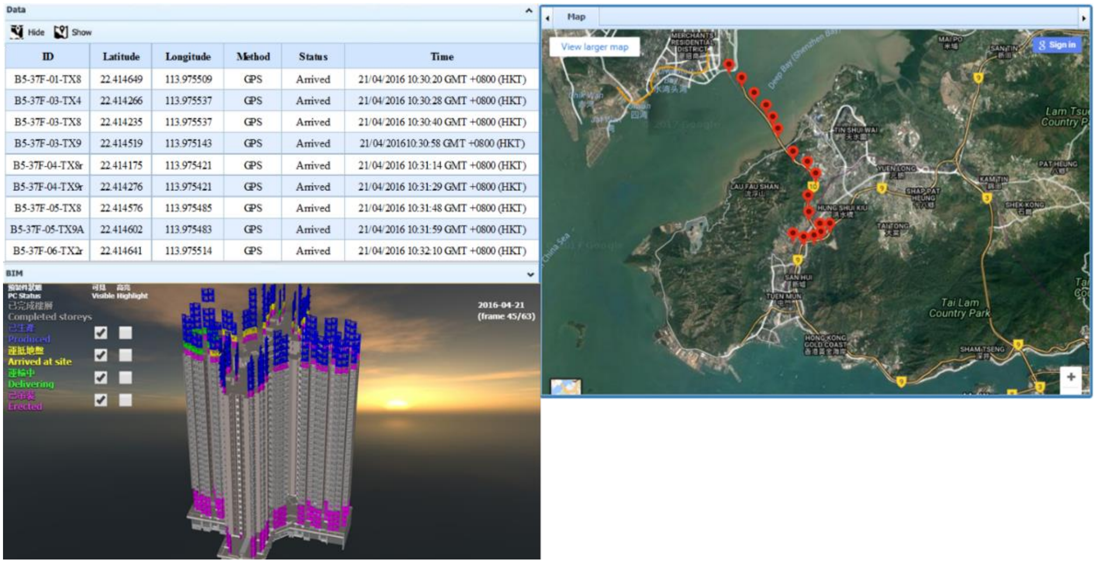


Figure 4.4 The user interfaces of location information tracking in transportation execution SWP

d. On-site Construction Stage

SWP is involved in this stage such as resource management related SWP (e.g., planning, sensing, and tracking), safety management related SWP (e.g., training, hazards identification and hazards removal), schedule, quality and cost control related SWP (e.g., schedule planning, progress documentation, progress monitoring, risk control, quality inspection, cost control, rework and defects repair). For example, progress monitoring SWP can provide real-time status information such as progress, on-site situation, and current assembly requirements with the support of RFID and laser scanning (Li et al., 2018a). In hazards identification SWP, AR can provide a step-by-step assembly instruction with hazards warning information which is extracted from the BIM platform and captured by RFID and other sensors (Li et al., 2018b).

e. Maintenance Stage

The case is an ongoing project which is in the construction stage. However, the case is designed to facilitate maintenance. In this PHP project, the modularity improves maintainability, because some prefabricated products with mechanical joints may allow safe, quick and easy replacement. All prefabricated products have RFID tags and other sensors for identifying, tracking and monitoring their location and status, which can then be used for health monitoring to provide early warning.

The conceptual framework does not require the integration of every individual PHP process such as deconstruction and recycling, given the long duration of the operational stage and the uncertainty of the deconstruction and recycling method after such a long operational stage. Deconstruction and recycling are not available for this case. For example, the prefabricated facades are bonded together at the construction site when concrete is cast over the semi-precast slab to thereby generate the equivalent of a monolithic structure modifiable only through a demolition sequence. Thus, design for deconstruction could be considered in a future project to minimize the waste and improve the sustainability performance by adopting an adaptability framework, which is based on a standard denominator called support structure and allows for variation to accommodate the individual needs through the permutation of detachable components (Akinade et al. 2015; Richard, 2005). Specifications related to the recycling and reuse of products can also be integrated into the SWP to support decision making (Ajayi et al., 2015). This case study, based on the current conceptual framework can offer an intuitive platform for mainstreaming the integration of BIM and PHP, which can be usefully improved with the support of other specific considerations. For example, a list of the evaluation indicators for the three stages of PHP are listed in Table 4.2. The list of indicators can be used to further validate the effectiveness of the proposed framework on project performance (e.g., productivity, quality, and cost).

Table 4.2 Evaluation indicators for the proposed framework in the stages of manufacturing, transportation, and on-site assembly

Stage	Evaluation Indicators
Manufacturing	Time to tag prefabricated products with RFID
	Number of prefabricated products to be tagged with RFID
	Time to locate prefabricated products in factory laydown yard for transportation
	Est. time saved locating and updating SBP
	Number of prefabricated products not been correctly selected
	level of streamlined access to engineering information from SBP or mobile device
	Time to update inventory
	Reduction in use of paper sheets to process inventory
	Total Man-Hrs saved
	Expected labor savings
	Number of prefabricated products not been prepared for pickup
Transportation	Time to generate prefabricated products manifest
	Total number of prefabricated products to be tagged with RFID
	Time to attach GPS/NFC
	The cost to attach GPS/NFC
	Average time to log SPOs information into the delivery manifest (time per SPO)
	Time to track vehicle registration on/off-site
	Est. time saved though auto vehicle registration per on/off event
	Total number of vehicles tracked
	Total Man-Hrs saved
	Expected labor savings
	The productivity of knowing exactly what has been transported/arrived on-site
	Time to locate SPOs per crew or per shift

	Time delays in delivery to expeditor who is waiting for the prefabricated products
	Est. time saved locating and updating SBP
	Efficiency to access cross-border permits documents
	Average entries/exits per day per vehicle
On-site Assembly	Time to update SPOs log when received on site
	Level of risk when assessing prefabricated products quality
	Reduction in use of paper sheets to process handover
	Time to locate prefabricated products on the buffer for the issue to crews
	Number of prefabricated products not been prepared for pickup
	Time delays in delivery to workers who are waiting for installation
	The productivity of knowing what has arrived on-site
	Average time spent locating a prefabricated product with RFID
	Worker crews' travel time/distance
	Time to locate supporting equipment
	Time to collect work-in-progress information by tracking the SPOs status
	Est. time saved progressing construction status of a key SPO
	Percentage of total SWPs progress that can be tracked at a detailed level
	Reduction in use of drawings to process installation
	Cost for misplaced prefabricated products
	Number of misplaced prefabricated products
	Time to identify misplaced prefabricated products
	Time to rectify misplaced prefabricated products
	Reduction in use of paper sheets to process installation
	Total Man-Hrs saved
	Expected labor savings
	Time saved per working shift (hrs)
	Est. time saved identifying SPOs in the field and locating in SBP

The need for a theoretical framework to re-engineer the BIM-PHP for better supporting stakeholders and workers with the capabilities of planning and control in an integrated environment has been highlighted by many studies. At the stakeholder level, Chen et al. (2015) proposed a framework for bridging the BIM and building by establishing three layers including BIM, central database and physical projects to improve project management performance. However, it does not involve the PHP context and considers the data sharing willingness or incentive mechanism from stakeholder perspectives. To address these, this section proposes an integrated platform, namely SBP, which considers customer-oriented PHP performance criteria (e.g., adaptability, flexibility, multi-purpose framework, combinability) and stakeholder-oriented BIM data brokering function to set up a continual and interactive decision-making mechanism to meet requirements of both stakeholders and customers in the lifecycle of BIM-PHP. This can reduce mistrust and ineffective communication among stakeholders to enhance the efficiency of decision making with well-formatted information sharing. At the task execution level, Zhong et al. (2017) developed several services (e.g., production scheduling, production execution, transport monitoring, on-site asset management) in the IoT-enabled BIM platform to achieve visibility and traceability in prefabricated construction, which various end-users can monitor a project's status, progress, and accumulative cost in a real-time manner. However, it does not propose a systematic planning and control approach at a more detailed level (e.g., look-ahead planning). This section introduces a smart workflow management approach, namely SWPs, which defines four relationship types (composition, interface realization, inheritance, and dependency) in workflows to facilitate coding the interface rules of products into SWPs. At the object level, Niu et al. (2016) developed smart construction objects equipped with properties of autonomy, awareness, and communicativeness. It does consider the information requirements for the PHP. This study introduces the smart objects concept to work as information generator with specific PHP information requirements, particularly the geometric information for modular coordination. It can reduce human interventions so as to raise the efficiency of collecting data with good quality with accessibility, accuracy, appropriateness, consistency, and traceability. In summary, the innovative contribution of this section is to integrate the object-oriented BIM and product-oriented PHP for specifying the services, processes and information under three manageable pillars, including SBP (used for decision making), SWPs (used for collaborative working) and SPOs (used for information generation and communication), in order to achieve a higher level performance in terms of decision-making and collaborative working in PHP.

The conceptual framework also echoes the concept of industry 4.0 (Akanum and Anumba, 2015; Yuan et al., 2016) which is considered as an emerging trend for achieving a timely interaction between the virtual platform and the physical environment through information technologies such as cyber-physical systems (CPS), the internet of things (IoT), cloud computing and cognitive computing (Theorin et al. 2017; Li et al. 2017d). The proposed framework (SBP, SWPs, SPOs) could be the kernel of the concept of industry 4.0 and be extended by integrating more advanced technologies, sustainable material, flexible approach, and secure information. Although such systems have seldom been tested in a real-world situation in the construction industry, the future needs in the construction industry 4.0 ecosystem can be proposed using some insights from this section (See Figure 4.5). For example, sustainability is can important performance criterion in the proposed BIM-PHP conceptual framework.

The concept is also reflected in the design stage of construction industry 4.0 such as using renewable and energy-efficient materials or technologies (Wu et al., 2016). In addition, the customized building can be automatically decomposed into modular products and work packages through BIM in construction industry 4.0. which can be used to generate the smart PHP objects and smart work packages proposed in this study with the support from IoTs. The logistics (e.g., transportation) in construction industry 4.0 has already involved georeferencing on a GIS platform to trace the materials and prefabricated products and predict the delivery time based on the spatial routing network analysis (Liu et al., 2017). This is also the primary objective of smart BIM platform proposed in this study to achieve high-level decision making for integrated supply chain with coordination, traceability, and visibility. Robots and autonomous machines, the necessary elements of the construction industry 4.0, which are well connected to the new generation BIM platform, will be widely used in plants and on construction sites (Bock, 2015). These are also essential supporting technologies to achieve adaptivity, sociability, autonomy, and awareness of SPOs and SWPs in this study. In addition, mass customization which combines the flexibility, adaptivity, and personalization with low unit costs associated with mass production is one of the final objectives of construction industry 4.0. This is also a critical performance criterion in the proposed BIM-PHP conceptual framework.

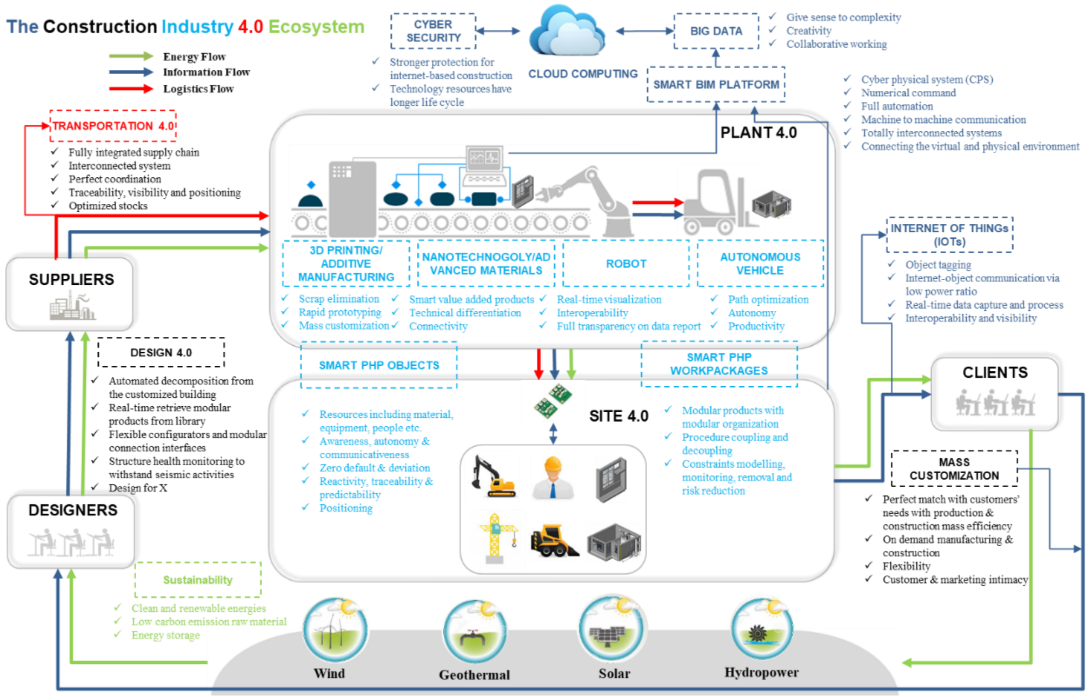


Figure 4.5 Future needs in BIM-PHP for establishing the construction industry 4.0 ecosystem

4.3 Definition of Smart Work Packaging (SWP)

In this chapter, SWP is defined as an approach to decompose the PHP workflows (e.g., technical process) by production breakdown structure (PBS) of building systems that are made *smart* with augmented capacities of visualizing, tracking, sensing, processing, networking, and reasoning so that they can be executed autonomously, adapt to changes in their physical context, and interact with the surroundings to enable more resilient process (Li et al., 2019b).

The core characteristics of SWP, namely, adaptivity, sociability, and autonomy, are shown in Figure 4.6. Physical or functional information, such as shape, dimension, products type, the layout of the work section, work procedure, and positions of aids and resources, are not included in Figure 4.6 because such information is also required in traditional work packaging method.

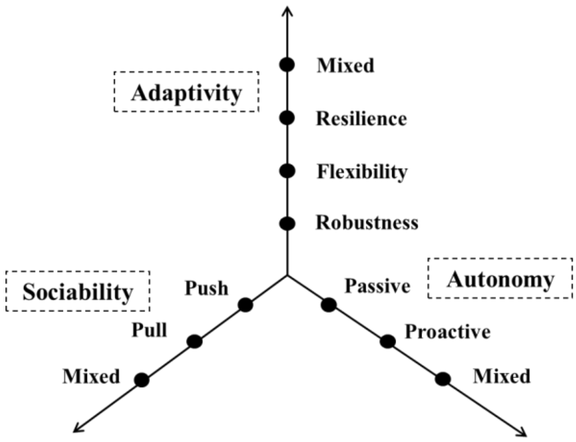


Figure 4.6 Three core characteristics of the SWP

4.3.1 Adaptivity

Adaptivity, the most distinct feature of SWP compared with traditional PHP work packaging method, denotes SWP's ability to have a positive response to change, and learn from their own experiences, environment, and interactions with others. This characteristic is based on the concepts of smart workflows proposed by Wieland et al. (2008), which includes three dimensions, i.e., robustness, flexibility, and resilience (Husdal, 2010). Robustness is the fundamental feature level that the SWP can process. With robustness, SWP can quickly regain stability by accepting goal-directed initiatives when encountering constraints. It can be mainly applied to plan and control primitive tasks, which refer to elemental motion with few steps or short durations. For example, the crane operator with the help of SWP can regain stable reaching, grasping, picking up, moving and eye travel in the lift operations when encountered static constraint (e.g., obstacles). Flexibility enables SWP to react to the foreseeable changes in a pre-planned manner. It is beneficial for guarding tasks execution against threshold-breaking or exceeding a pre-programmed tolerance range, and the SWP in this context primarily involves composite tasks such as to measure, connect, navigate, select, align, record, and report. For example, SWP can help crane operator measure the distance and report the parallax error when other tower cranes are approaching. Resilience is a high-level adaptivity that facilitates SWP to survive unforeseeable changes (that have severe and enduring impacts) in a dynamic replanning manner. The SWP tasks in this context include operation-specific tasks such as assembly, examining workflow, buffer layout, equipment path planning, and monitoring. For example, when an emergency occurs, SWP with resilience can offer assembly guidance and perform the optimized working path planning by cross-validating the real-time progress with as-planned workflow. Presently, SWP adaptivity can be achieved by advanced optimization approaches when making full use of the information collected from the sensing and tracking technologies.

4.3.2 Sociability

Sociability ensures that SWP can communicate with the surroundings (e.g., other smart work packages (SWPs), human/machine/products in SWPs). The communication can happen at pull, push or mixed modes. The pull mode occurs upon demand. For example, the deliverables/information (e.g., prefabricated products from the transportation driver) are delivered when requested by the SWP of the expeditor. In the push mode, SWP actively tracks and updates the information and issues alerts at regular intervals or when an emergency occurs. For example, the SWP of the project manager can obtain the traceability and visibility of the prefabricated products in a real-time manner to facilitate its Just-in-time delivery. The mixed mode combines the pull and push to request and deliver information in a peer-to-peer manner. Apart from the three interaction modes of SWP, there are four relationships between SWPs, namely, composition, interface realization, inheritance, and dependency, which can enhance the sociability of SWP in handling the modular products/processes in PHP (Ramaji et al., 2016). Composition refers to the relationship of one SWP and its relevant SWPs. For example, the work package of schedule management usually includes planning, progress checking, monitoring, and risk control. Interface realization refers to a group of work packages which support or rely on the behavior that is defined in an interface. Inheritance exists between a parent smart work package and its succeeding sub-SWPs. Dependency is the most popular relationship where the downstream SWPs are dependent on the upstream SWPs. To achieve the sociability of SWP, there are many communication and networking technologies to enhance the awareness of SWP such as active/passive RFID, ultrawideband (UWB), ZigBee, electromagnetic, Bluetooth, ultrasound, infrared (IR) proximity, Wi-Fi, near-field communication (NFC), laser, conventional radio frequency (RF) timing, wireless local area network (WLAN), received signal strength (RSS), and assisted GPS (A-GPS) (Niu et al. 2016; Zhang and Hammad, 2011).

4.3.3 Autonomy

Autonomy proposed in this chapter is based on the concept of SCOs (Niu et al., 2016). It refers to the capability of intelligent resources (e.g., machinery/tools/devices) in SWP to achieve autonomy through a pre-programmed method of decision making. There are three types of autonomy, including proactive autonomy, passive autonomy, and a mixed mode. Proactive autonomy aims to act in advance of a future situation. For example, the autonomous crane tower can generate a lift plan in accordance with the dynamic construction environment. It can sense and monitor the dynamic constraints in the environment to predict and execute the plan in advance, without human interventions. Passive autonomy, by contrast, can perform the instant reaction by triggering mechanism, particularly in an emergent situation due to the delays of personnel reactions. For example, the anti-heat stress uniform encapsulated in the SWP can issue an alert to the workers and help to reduce heat and humidity when they exceed a certain threshold (Yi et al., 2016). The mixed mode of autonomy may execute complex tasks involving multi-autonomy stages that can both control activities without intervention and act in a preset manner. For example, the path planning in SWP of a crane operator can firstly be pre-programmed with optimal paths and collisions can be detected in the operation process with the dynamic autonomy.

The three core characteristics of SWP are interrelated. Each subclass of the adaptivity, sociability, and autonomy is not a bijection. Instead, various subclasses of characteristics can be integrated to address specific constraints. In more complicated scenarios, it is also possible that the integration of characteristics that are more advanced than these three features is needed. However, this is currently beyond the scope of this study.

4.4 The Framework of SWP-enabled Constraints Management (SWP-CM)

The development of the conceptual framework started with the definition of the SWP after a comprehensive literature review of the work packaging method, constraints management, and the smartness concept (see Section 2.2). Afterward, a draft paradigm, as shown in Figure 4.7, was proposed as the backbone of the framework. The constraint modeling service is included in the SWP to facilitate the identification and interrelationship mapping of the constraints at the activity level (e.g., on-site assembly process). Then, the most influential constraint at the activity level to the goal (e.g., schedule performance) is isolated for further improvement, and this constraint often also contains many constraints at the task level. The constraints optimization service in SWP can help develop the optimal task executions by optimizing the constraints at the task level. Tracking, updating and predicting the statuses of the constraints at the task level are also included in the framework.

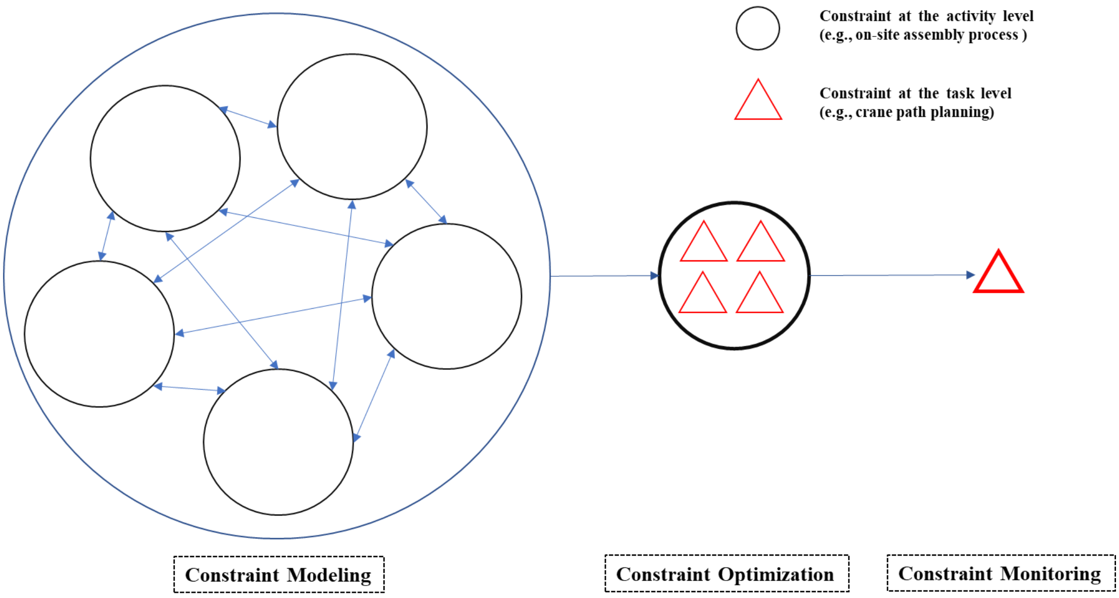


Figure 4.7 The paradigm of SWP-enabled constraints management

In addition, a layered system model, as the functional structure of SWP in PHP, was also proposed to instantiate the conceptual framework. Its development is based on previous studies on IoT-enabled BIM platforms for PHP (e.g., Li et al. 2017a; Li et al. 2018b), in order to take advantage of both smart BIM platforms and smart construction objects in PHP.

Subsequently, the proposed framework and the layered system model were examined and finalized by 14 PHP industry professionals, who were the primary stakeholders of PHP in Hong Kong. All 14 experts investigated the framework and provided their comments on the potential application scenarios and functions based on their expertise. As shown in Table 3.3, the invited professionals included the stakeholders from the client, contractor, manufacturer, transportation company, and consultancy. All industry professionals had more than 10 years of experience in the development, operation, and management of PHP projects and related technologies. It is therefore expected that these PHP professionals did provide an unbiased and constructive assessment of the framework. (detailed in Section 3.3.1)

In order to validate the proposed framework of SWP-CM, a laboratory test is conducted by using a simulation game (named RBL-PHP, RFID/BIM/Lean-PHP, a role-playing game) developed by the authors (Li et al., 2017a). The following questions are raised:

- Can the constraints in PHP workflow be intelligently identified, improved, and monitored?
- Can the framework reduce project duration to improve the reliability of PHP workflow?
- Can productivity be increased in the implementation of this framework?

The aim of the game is to simulate a real-world PHP environment by building Lego^{TM} houses. The task goals are to construct four buildings with the shortest duration, the highest accuracy, and the maximum percentage of the plan completion (PPC). Figure 4.8 shows the roles and the number of people needed in this simulation game. All the 32 volunteers are postgraduate students with limited knowledge of SWP and constraints management, and ten of them have more than three years of working experience in the construction industry. Such an arrangement can help collect comments, suggestions, and insights from the perspectives of both academic scholars and industry practitioners. The volunteers are averagely divided into two groups in two rounds. The first round is related to the use of traditional planning and control (without SWP techniques), and the second round is related to the implementation of SWP-CM. These two rounds are then comparatively analyzed to demonstrate the benefits and differences in implementing the proposed framework. In order to reduce the influence by learning curve issues, there is a briefing session for both rounds, and they are also instructed to play once before beginning the test.

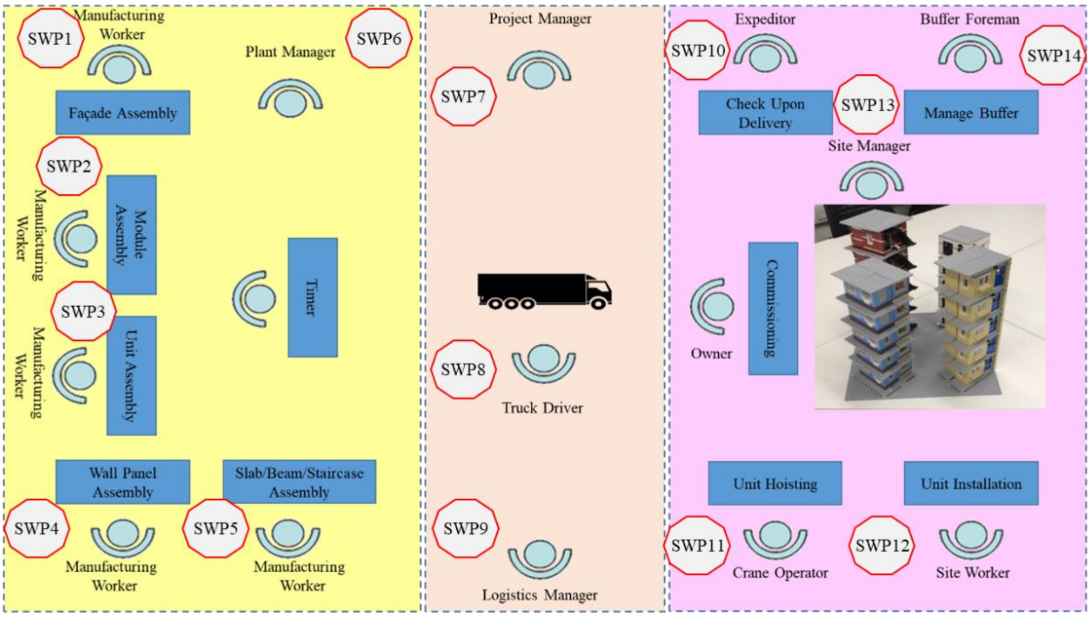


Figure 4.8 Roles and layout of the simulation game

After the review of this framework by the selected industry experts, the client of HK Housing Society with the background of Lean Construction agreed that there are two levels of constraints in the PHP process, namely activity-level and task-level constraints, but he pointed out that the framework should not only reflect the concurrent and continuous improvements of constraints from a perspective of Lean principles but also clarifies the process to the goal by picking out the critical chain of the constraints from the perspective of theory of constraints. An expert from the contractor emphasized the alignment of work packaging stage among activity-level planning, task-level planning, and task executions. In addition, the expert from CIC highlighted the implementation of the three constraints management steps in this framework could help analyze the constraints and their interrelationships systematically in the whole activity process, along with providing the executable plan to remove the constraint at a more detailed level. However, the three steps of the framework should be well-defined in SWP. The IT consultancy mentioned the capabilities of IoT and emerging technology solutions and the integration of these technologies into the framework. A project manager from the client emphasized that the fusion of SWP and constraints management under a clear application scenario should be well considered.

Figure 4.9 presents the final version of the SWP-CM framework. In the left part, the work packaging method with lean principles is designed as the basis to outline the workflow of the activity or task execution in PHP. The middle part shows the three core modules of constraints management. And the right part demonstrates the detailed process of SWP-CM. Based on the experts' comments, the following scenario can be used to illustrate the mechanism of the SWP-CM framework.

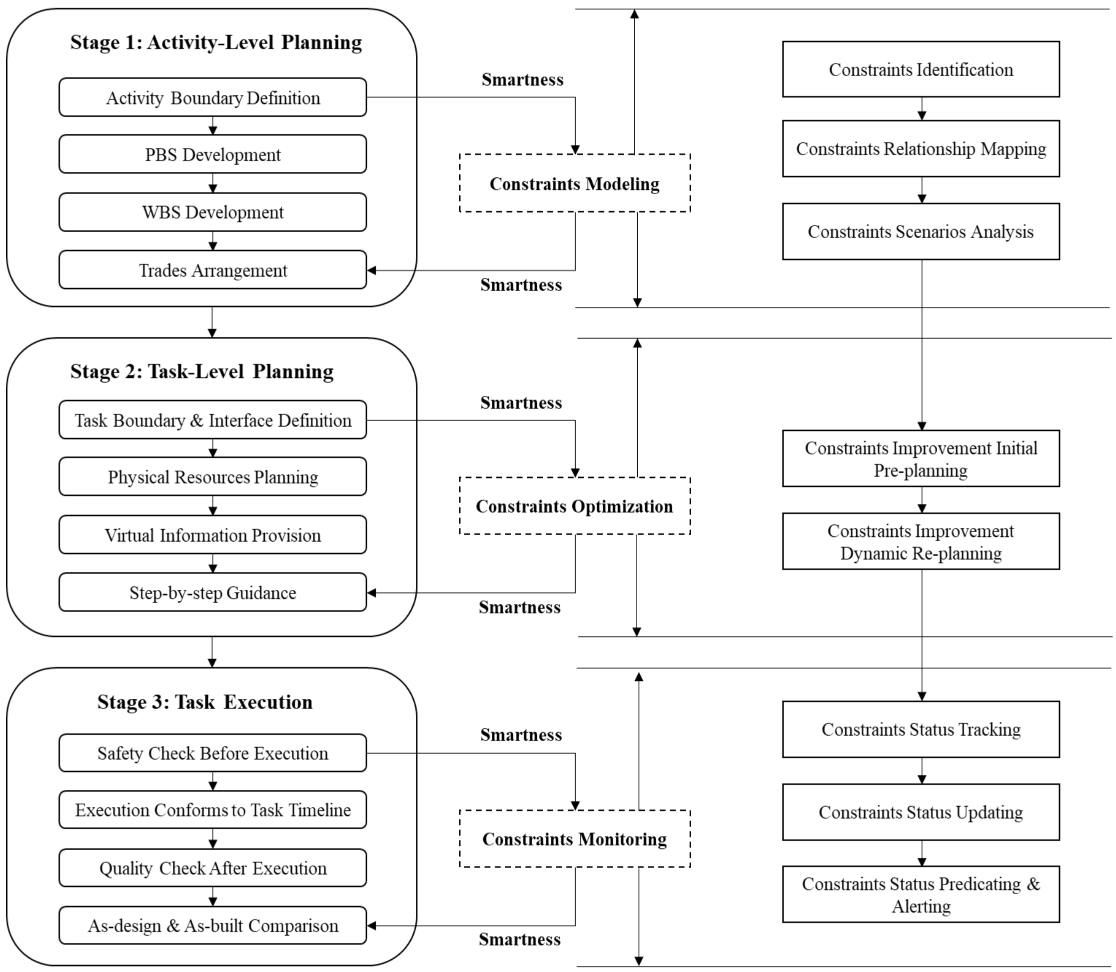


Figure 4.9 The framework of SWP-enabled constraints management in PHP

A smart work package containing prefabricated products related functional and physical information, generated from BIM platform based on the building systems and PBS of PHP, was assigned to a site buffer operator for managing relevant constraints so that efficient on-site assembly process and just-in-time delivery can be achieved. The SWP should identify the critical constraints and interrelationships by networking with other SWP in working status to identify the constraints such as availability of workforce and work face in the assembly position point, the quality of arrived prefabricated products, the availability of space and workforce in site buffer, and their interrelationships such as composition, interface realization, inheritance, and *dependency. When the most critical constraints and their interrelated constraints have been identified, the SWP can assign tasks with optimal solutions to the buffer operator for improving the constraints. For example, the autonomous crane tower near the buffer will pick up the task to transport the prefabricated products from trailer to the buffer in an optimal path, if buffer shortage has been identified as a critical constraint. The efficient layout considering both optimal buffer utilization and hoisting sequencing (e.g., first-in-first-assembly) by adopting advanced optimization algorithms is the crucial part of this task. Thirdly, constraints status tracking, updating, and predicting should be embedded for real-time decision making.*

To achieve the above three objectives, three functions, including constraints modeling, constraints optimization, and constraints monitoring, must be well combined with the core characteristics of SWP for constraints management in PHP.

4.4.1 Constraints Modelling

Constraint modeling is a critical function with the sociability to allow a thorough understanding of interconnections among tasks or activities. There are three steps within this function. The first step is the constraints identification. The traditional process for constraints identification is static and usually executed once. The SWP can enhance this step in a passive autonomy manner by pre-programming the template list of constraints and their classification with an open-data integration approach for constraints instantiation. Although each PHP project is unique, they share some similar types of constraints at the operational level (Li et al., 2018a), and it is possible to develop a database for organizing the potentially significant amount of constraints. Table 4.3 demonstrates the one template of constraints classification in the PHP process, which sourced from the literature review and the on-site survey. These constraints are classified into manufacturing, logistics, and site constraints. Constraints such as incomplete design drawings/BIM models, approvals, and specifications are manufacturing constraints, which restrict the subsequent activities in logistics and on-site assembly. Logistics constraints contain limited weight and height for vehicles on the road, unavailable production schedule, and transportation schedule. Without JIT deliveries, the site buffer may be congested, or underutilized and on-site assembly cannot be efficiently executed. Site constraints include inadequate buffer and workspace, unavailable and unassigned labor resources, lack of collision-free crane path planning, lack of optimal installation sequence, and adverse weather conditions. The reason for this classification is that Manufacturing, logistics, and on-site assembly are the most critical stages in PHP, which can facilitate crews to identify the constraints in their stages. Once the template is embedded into the SWP, a set of pre-defined constraints and their relationships will be available for critical constraints identification.

Table 4.3 Template list of constraints and their classification

Classification	Constraints
Manufacturing	Availability of mold, machinery, storage space, approvals, drawings, BIM models, specifications

Logistics	Adverse weather conditions; unavailable production and transportation schedules; bad conditions of transportation vehicle and route; road/vehicle limitation in weight and height; Lack of real-time vehicle location; Lack of optimal transportation route
On-site Assembly	Availability of prefabricated products and temporary structures; safety &occupational health training; workspace; buffer space Availability of labor, shop drawings, instructions, quality, inspection hold-points, transportation planning, safety checkpoints, installation sequence, crane lift and place location, collision-free crane path planning; Adverse weather conditions

The second step is the constraints relationship mapping. In real PHP projects, constraints are usually not independent and may have dynamic interrelationships. As such, a thorough understanding of these relationships is necessary. Figure 4.10 shows a simple example that includes only one crew with SWP in each selected trade (e.g., manufacturing worker, transportation driver, expeditor, buffer foreman, crane operator, installation worker). The constraints for production (e.g., drawings, BIM models, specifications, machinery) can be handled in the SWP of manufacturing worker. The development of SWP for expeditor needs to rely on well-satisfied constraints of vehicle locations, production, and transportation schedule in SWP of transportation driver. Therefore, any failure of constraints improvement in each SWP may lead to subsequent SWP delay in task executions. The control theory-based system dynamics (SD) model have the capacity to analyze the interactions (e.g., casual loop) and structures (e.g., stock and flow) of the project environments due to their perfect representation of feedback effects. And the Discrete Event Simulation (DES) can simulate sequential operation details and offer detailed information for execution. Thus, the hybrid SD-DES model can be an alternative to be incorporated into SWP to facilitate the constraints relationship mapping. The last step is the constraints scenario analysis, which can be presented in the interface of SWP for both project managers and workers to show the different simulation results on the schedule performance by evaluating the influence of different critical constraints. The most influential one will be selected for further optimization and monitoring.

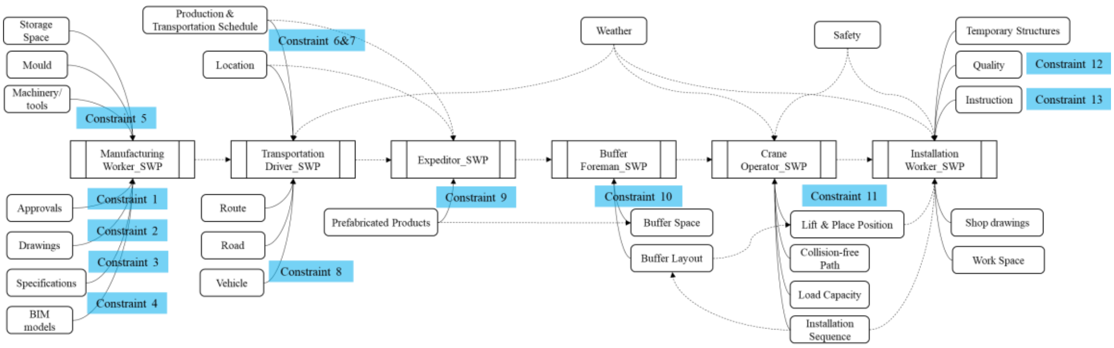


Figure 4.10 An example of constraint relationship mapping

4.4.2 Constraints Optimization

Constraints optimization is the succeeding function of constraints modeling, and the adaptivity can be the prominent characteristic. It focuses on the most influential constraint in the SWP and ensures that it is dynamically, timely and efficiently improved in constraints improvement planning. There are two push-driven processes enabled by SWP in constraints optimization. The first process is to pre-plan with alternative network paths and alternative constraints improvement methods. For example, the resource leveling optimization problem (e.g., winner determination problem) can be worked out under the structure of auction protocol within the greed algorithm, linear programming, and competitive equilibrium (Taghaddos et al., 2012). In this constraints improvement planning problem, different SWPs can submit their requirements (in terms of the bid) for various resources or combinations of resources. The bidding price of each SWP is decided by the individual utility of the resources. The option with the maximized welfare of the project will be selected.

In addition, as PHP projects can constantly change in various stages, such as design, manufacturing, logistics to on-site assembly, it is highly likely that continuous adjustments and fine-tuning are needed. As such, the second process is to establish the dynamic re-planning approach to incorporate the changes to improve the resilience of the planning. For example, Crane lift operations are always restricted by the dynamics constraints, such as moving workers in the crane's operation area, collisions with obstacles (e.g., other cranes) on construction sites, and high-speed wind during lifting. Thus, the crane path re-planning should be performed. SWP can use the data related to the status (e.g., location) of the dynamics constraints to update the optimal path.

4.4.3 Constraints Monitoring

In PHP projects, the latest constraints information is essential for the superintendent or workers to check the progress and issue constraint-free SWP. As such, real-time constraints monitoring is needed. There are three processes within the function of constraints monitoring. The first process is constraints tracking which focuses on tracking each individual constraint. For tracking purposes, a mixed type of autonomy is preferred. For example, the availability of prefabricated products can be tracked by both active and passive RFID (or IoT systems) and visualized in the BIM as the interface of SWP (Li et al., 2018b). The second process is constraints status updating, which concentrates on computing the maturity of a task. The maturity index can be used to support short-term decision-making in a mixed type of sociability. For example, as shown in Fig.4.11, Fig.4.12, Fig 4.13, it is the interface of a smart work package for the site expeditor. Firstly, it can enable site expeditor with the ability to update the status of the prefabricated products' locations in a real-time manner. Figure 4.11 shows each prefabricated product with their ID, status (produced, arrived, or erected), time, latitude, and longitude measured by GPS. At the same time, the digital twins (e.g., BIM models) of smart objects (e.g., prefabricated products mounted with RFID and GPS) can be visualized at regular intervals or via ad-hoc networking on the expeditor interface of SWP for monitoring (See Figure 4.12). Additionally, it can display locations of trucks in the google map and reveals the task maturity of logistics associated smart work packages for each truck and driver by three status (truck loading, cross-border, arrived) in Figure 4.13. This can facilitate the prefabricated products being transported to achieve JIT delivery, i.e., the pull perspective. The final process within this function is constraints checking and prediction. The constraints checking aims to compare as-planned constraints improvement plan and real-time constraints status. Historical variation can be used to train and predict the next variation in a robust manner.

Data

Hide Show

ID	Latitude	Longitude	Method	Status	Time
B5-37F-01-TX8	22.414649	113.975509	GPS	Arrived	21/04/2016 10:30:20 GMT +0800 (HKT)
B5-37F-03-TX4	22.414266	113.975537	GPS	Arrived	21/04/2016 10:30:28 GMT +0800 (HKT)
B5-37F-03-TX8	22.414235	113.975537	GPS	Arrived	21/04/2016 10:30:40 GMT +0800 (HKT)
B5-37F-03-TX9	22.414519	113.975143	GPS	Arrived	21/04/201610:30:58 GMT +0800 (HKT)
B5-37F-04-TX8r	22.414175	113.975421	GPS	Arrived	21/04/2016 10:31:14 GMT +0800 (HKT)
B5-37F-04-TX9r	22.414276	113.975421	GPS	Arrived	21/04/2016 10:31:29 GMT +0800 (HKT)
B5-37F-05-TX8	22.414576	113.975485	GPS	Arrived	21/04/2016 10:31:48 GMT +0800 (HKT)
B5-37F-05-TX9A	22.414602	113.975483	GPS	Arrived	21/04/2016 10:31:59 GMT +0800 (HKT)
B5-37F-06-TX2r	22.414641	113.975514	GPS	Arrived	21/04/2016 10:32:10 GMT +0800 (HKT)

Figure 4.11 Location status of each prefabricated product

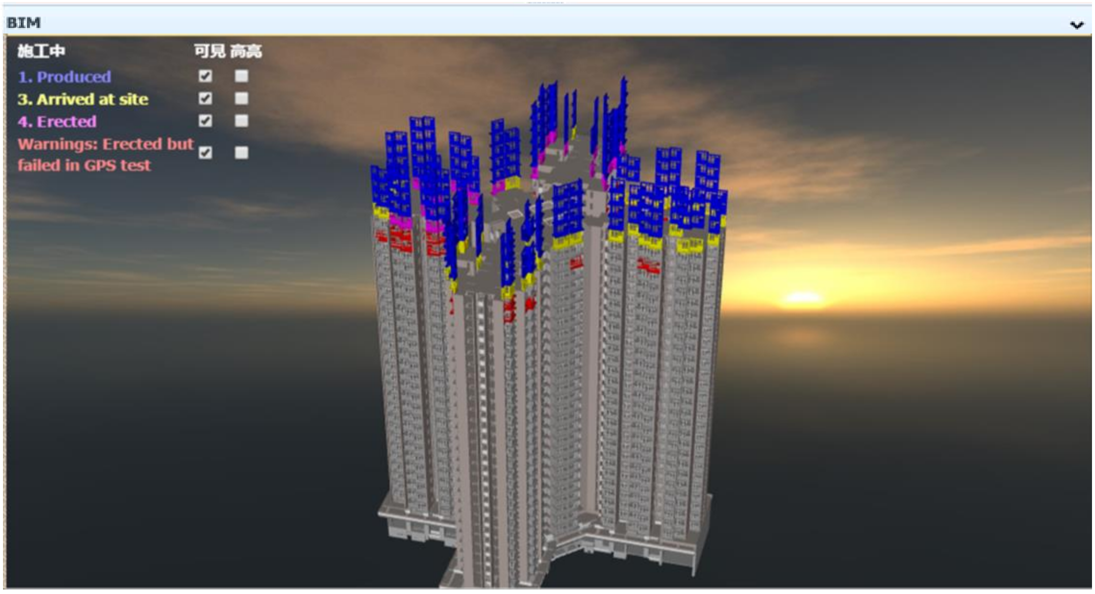


Figure 4.12 Visualized status of each prefabricated product in BIM

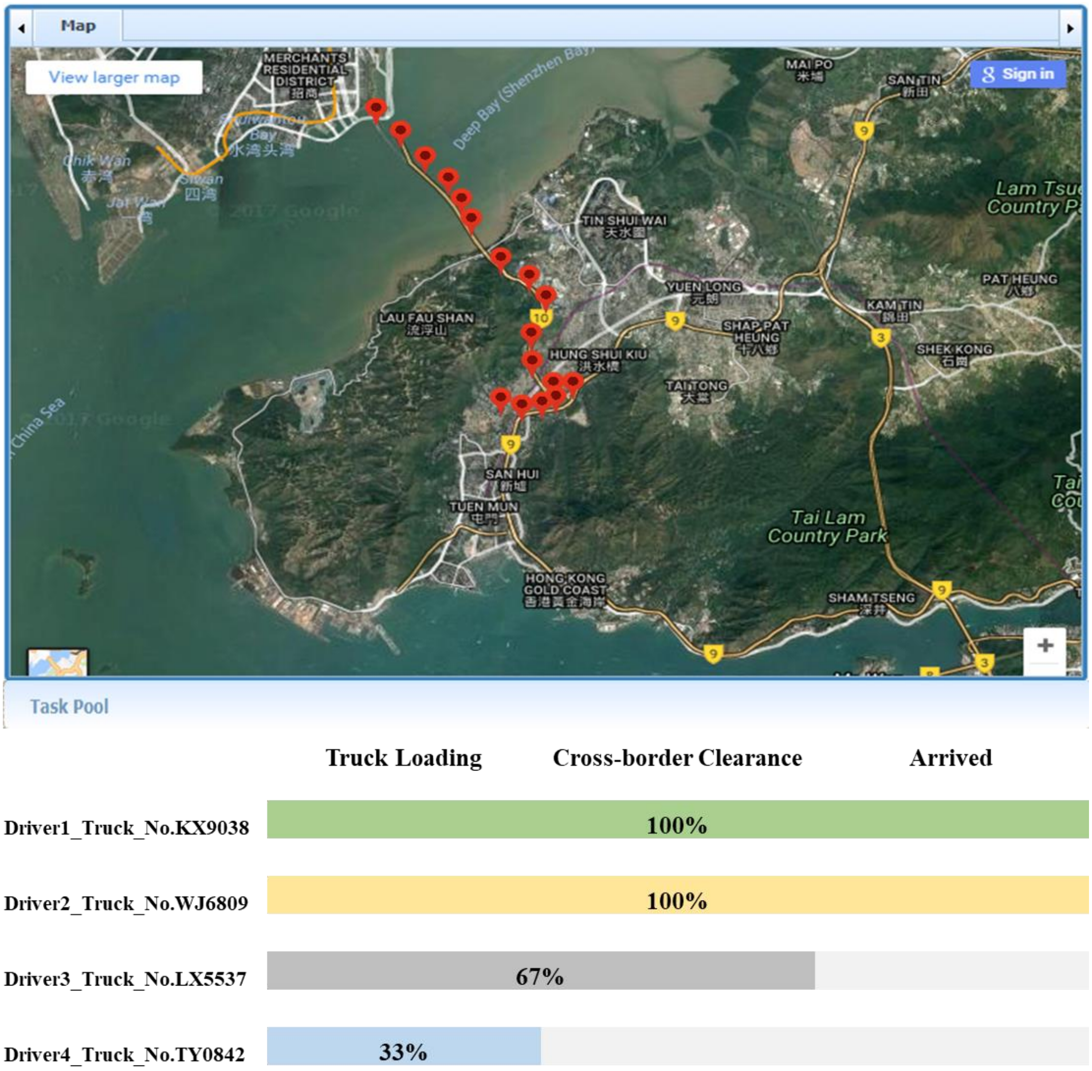


Figure 4.13 Visualized location status of each truck and the task maturity of each driver

4.5 The Functional Structure of SWP: Layered System Model

To achieve the characteristics and functions of SWP, a three-layered system is proposed (See Figure 4.14).

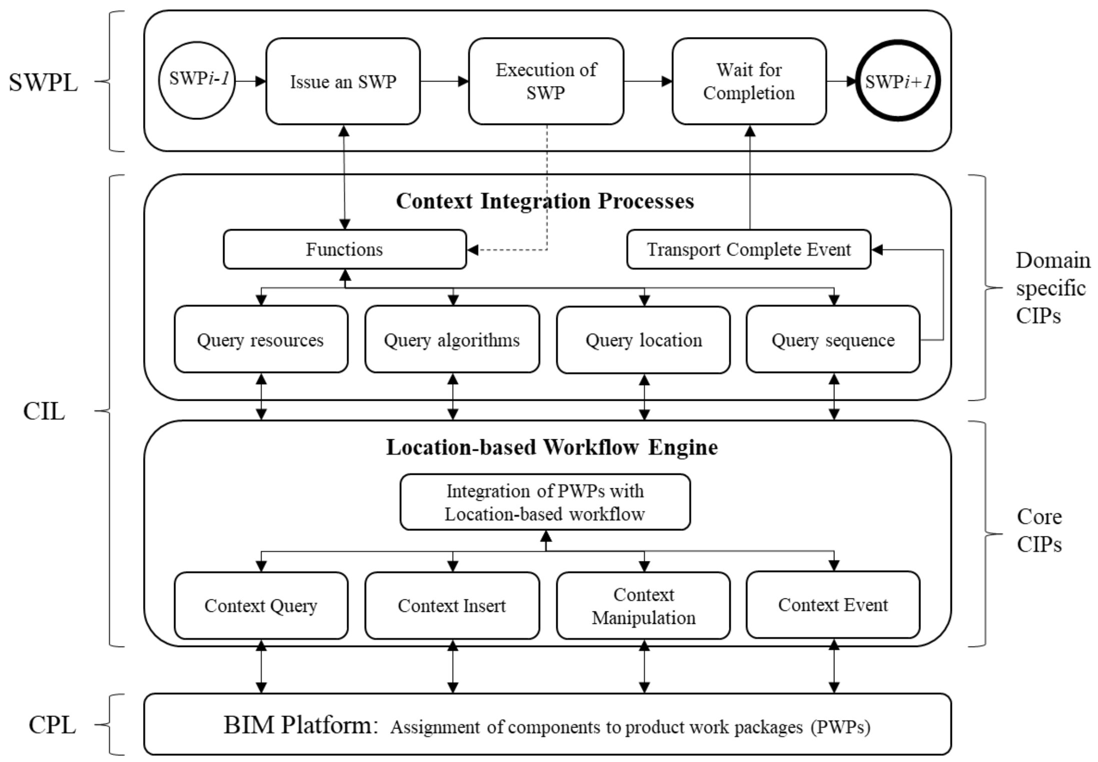


Figure 4.14 Layered system model of SWP

The *context provisioning layer* (CPL) is capable of managing the context information of PHP processes, which is often referred as both physical and functional information (e.g., dimension, quantity, specifications, location, resources status). For CPL, the BIM platforms can be adopted because it has proven to be an effective digital platform to offer users with the ability to generate, integrate, analyze, simulate, visualize and manage the physical and functional information of a facility (Li et al., 2017d). In addition, it can also support the development of various context-aware applications through application programming interfaces (APIs). The BIM models can also be used to integrate context from multiple sources (e.g., dynamic sensor data, smart construction objects, internet of things) for value-added services. For example, the BIM models can be utilized to break down the design into numerous units, and each unit comprises various materials, components, and modules. All the prefabricated products within a unit can be grouped into a product work package (PWP), which is in accordance with the production breakdown structure of building systems. The PWP will then be decomposed into SWPs by integrating the context of the workflows (process), work faces (location), duration, and resources.

The *context integration layer* (CIL) adopts the output of CPL to accommodate information, algorithms, and functions into more advanced representations and provide domain-specific functions needed by SWPs. Compared with CPL, there is no off-the-shelf system for CIL. The primary contribution of this model is to present the concept of how to design this layer. We, therefore, propose two processes for CIL. The first process is related to the core context integration processes (CIPs) within a location-based workflow engine to integrate the PWP with the context information (e.g., specific technical procedure, duration, the location of work face, resources) to generate the well-formatted work packages by introducing partitioning algorithms. The integration of PWPs with workflow by CIPs serves an autonomous pattern. A Core CIP receives a call from the workflow (a higher-ranking Core CIP of upstream SWPs) and remodels the request to the required format of the service including context query, insert, manipulation and event. Context queries facilitate the query to be synchronized with context information, e.g., with a query language. The query result can serve as a variable to be injected into the complex workflow. If the query language allows data manipulation, a workflow can enable the function of context insert and change.

The second process is related to domain-specific CIPs and can offer context information at various semantical levels for SWPs. The domain-specific CIPs include two primary functions: one is to merge specific functional elements to the well-formatted work packages from core CIPs to form SWPs; the other is to simplify the interfaces (e.g., web service interface) of SWPs for accessing their functionality.

Finally, the SWP layer (SWPL) can not only issue a smart work package with the mobile, wearable, and executable capacity but also provide a platform to interact with other SWPs. In addition, any execution failure can trigger the dynamic re-planning function to provide more adaptive SWP. The experts also evaluate the proposed layered system model by their expertise and project experience, and the comments are summarized as follows: "This functional structure of SWP fully utilizes the capabilities of existing BIM platforms and smart construction objects to help equip the workers with more value-added information and make them more skillful on task executions." (senior IoTs engineer, TSL) "It is feasible to embed this layered system model into the service-oriented architecture of the previous project 'IoT-enabled BIM Platforms for Prefabrication Housing Production.'" (senior BIM system architect, Gammon Construction)

4.6 Validation

4.6.1 Validation Design

According to the role setting and the proposed framework of SWP-CM, 16 SWPs were developed for the simulation game. There are three connected scenarios (manufacturing, logistics, and on-site assembly) conducted in this game, which the simulation layout has been shown in Figure 4.8. The detailed processes of these three scenarios can be found in Li et al. (2017a). In this study, 13 constraints designed by the authors were incorporated into the game, which includes lack of approvals from site manager, design drawings, BIM models, specifications, tools, production schedule, transportation schedule, prefabricated products (e.g., material, components, modules, units), buffer space, assembly instructions, quality and inspection hold-points, crane lift and place location, and vehicle limitation in weight and height. If the project team can not improve these constraints in an efficient manner, the game may suffer delay.

The first round of the game simulated the SWP-CM framework. The project manager synchronized the constraints list and the constraint relationship map to the SWP of each crew, which represented in the interface of each mobile device. Detailed constraints analysis results (e.g., influence to schedule performance which can be simulated by the hybrid system dynamic (SD)-discrete event simulation (DES) model) can be triggered by clicking the specific SWP button. For example, as shown in Figure 4.15, when clicked "Expeditor_SWP," the expeditor can find all related constraints and other interactional SWPs. And after clicking the specific constraint in the SWP, the optimization strategies (lean principles such as pull methods, Just in time delivery, standardized work serve as the optimization strategies in this simulation game) and monitoring view can be presented. Thereinto, the pull-driven production schedule optimization strategies are adopted in this SWP (See Figure 4.15) to expedite the production process. With SWP-CM implementation, Group A detected and analyzed all constraints in the first 9 minutes, and adopted the optimization and monitoring strategies to improve them timely. Regarding constraints monitoring, RFID tracking technology and BIM visualization interface have been adopted to track and update the statuses in a real-time manner(as shown in Figure 4.15). The first round totally used 35 minutes, and the performance of Group A was evaluated by the percentage of plan completion (PPC), productivity index, and extra cost.

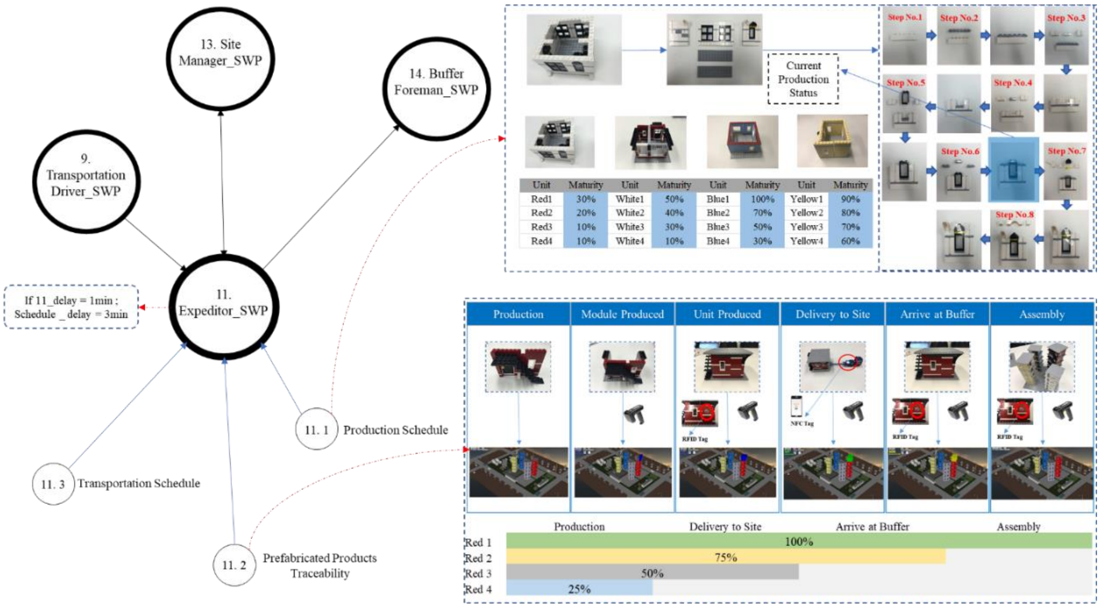


Figure 4.15 Detailed constraints improvement in Expeditor_SWP

Second round simulated the traditional constraints improvement method. The following changes are made, while other conditions remain the same.

(1) Constraints modeling, including the relationship map and analysis results, were not provided to Group B. According to the feedbacks of the 14 industry professionals, constraints identification, relationship mapping, and analysis are conducted informally and generally on the basis of experience. Thus, the traditional practice may vary from

crew to crew and may not offer a comprehensive constraints modeling process.

(2) Constraints optimization strategies were late implemented and only developed when the constraints happened. In the traditional practice, the foresight capabilities of the crew are limited. In this simulation, they can call for a meeting to discuss optimal solution strategies when constraints occurred.

(3) The players were not allowed to directly communicate with others who have geographical barriers in real situations or walk around for monitoring others work progress in a real-time manner. In this simulation, they can arrange regular coordination meetings to report their own progress.

As there is no implementation of SWP-CM, all the 13 constraints were not timely identified until the second 9 minutes. Delays were suffered due to the late removal of the constraints (e.g., shortage of tools and prefabricated products) and the performance was also measured by the same indicators.

4.6.2 Validation Results

After the two-round simulation, the performance of the two groups was measured by the PPC, extra cost, and productivity index. These were calculated using the following rules:

(1) PPC: This indicator can measure the actual completion at the end of each time interval. The time interval is fixed at 9 min in this study. From the final product's view, the number of assembled units is used to calculate the PPC. There are four buildings to construct, and each building is assembled from five units, indicating a total number of

20 units. The formula to calculate PPC is

$$\text{PPC} = Q_a \,/\, \boldsymbol{Q_t} \quad (4.1)$$

Where Q_a = the number of assembled units, Q_t = the total number of units (20).

(2) Extra cost: This may result from the overly produced units that are transported to the construction site, the defective units that need rework, and the manufactured-in-process (MIP) units that cause delay. The cost of each unit can be found in the authors' previous work (Li et al., 2017a). The cost of each component contains the cost of material, labor, equipment, and transportation. The extra cost is calculated to evaluate the economic performance of this game.

(3) Productivity Index: This is a measurement of the ability to manufacture, transport, and assemble. The following three separate indices are used:

$$\text{a. } P_m = (Q_p - Q_{d1}) \,/\, (T_{f1} - T_{s1}) \quad (4.2)$$

where P_m = the productivity index of manufacturing; Q_p = number of produced units in the plant; Q_{d1} = number of defective units in the plant; T_{f1} = finish time of the production of the last unit; and D_1 = duration from T_{s1} to T_{f1} and $D_1 = T_{f1} - T_{s1}$.

$$\text{b. } P_l = (Q_l - Q_{d2}) \,/\, (T_{f2} - T_{s2}) \quad (4.3)$$

where P_l = the productivity index of logistics; Q_l = number of transported units; Q_{d2} = number of defective units in the logistics; T_{f2} = finish time of the transportation of the last unit; and D_2 = duration from T_{s2} to T_{f2} and $D_2 = T_{f2} - T_{s2}$.

$$\text{c. } P_a = (Q_a - Q_{d3}) \,/\, (T_{f3} - T_{s3}) \quad (4.4)$$

where P_a = the productivity index of on-site assembly; Q_{d3} = number of defective units in the assembly process; T_{f3} = finish time of the assembly of the last unit; and D_3 = duration from T_{s3} to T_{f3} and $D_3 = T_{f3} - T_{s3}$.

The results are shown in Tables 4.4-4.6, respectively. Table 4.4 demonstrates the actual duration and the PPC values of the two round. The duration of 35 min was recorded in the first round while the second round took 45 min, which suggested that 22.2% reduction in project duration is achieved through the implementation of SWP-CM. The main underlying reason was the late identification and improvement of the constraints in the second round, and it spent more time understanding the constraints and figuring out the optimization strategies. Table 4.5 represents the results of the simulation game at extra cost. The extra cost of $7460 was recorded in the second round while there was no extra cost in the first round. In the second round, as the push system without constraints monitoring was adopted, two units were overproduced, and one unit was manufacturing-in-process (MIP). By integrating the pull method and JIT with the real-time constraints monitoring, overproduction and MIP can be eliminated effectively. The defective units were measured by a comparison between the as-designed and as-built unit. If there is a difference, the extra cost will occur. The defective units inspected in the plant will lead to rework immediately without generating an extra cost, whereas the defective units identified after the logistics will lead to the extra cost. The availability of design drawings, BIM models, quality, and inspection hold-points can be fast satisfied in the first round, which resulted in the no defective unit compared with the second round of 2 defective units. Table 4.6 shows the productivity index of the two rounds. The productivity is significantly improved in all three phases, including manufacturing (P_m : 0.53 → 0.67; 26% increase), logistics (P_l : 0.88 → 1; 14% increase), and on-site assembly (P_a : 0.49 → 0.65; 33% increase). Efficient information sharing and communication in the first round guaranteeing the real-time constraints modeling, optimization, and monitoring can be considered as the main contribution to the increase in productivity.

Table 4.4 The percentage of plan complete in the simulation game

Round	Actual Duration (min)	PPC at the end of the first 9 min (%)	PPC at the end of the second 9 min (%)	PPC at the end of the third 9 min (%)	PPC at the end of the fourth 9 min (%)	PPC at the end of the fifth 9 min (%)
Round 1	35	20	45	75	100	-
Round 2	45	10	30	55	75	100

Table 4.5 The extra cost in the simulation game

Round	Overproduced units (Qty)				Defective Units (Qty)				MIP(Qty)				Total Extra Cost ($)
	Red Unit	White Unit	Blue Unit	Yellow Unit	Red Unit	White Unit	Blue Unit	Yellow Unit	Red Unit	White Unit	Blue Unit	Yellow Unit	
Round 1													0
Round 2	1	1			1		1					1	7460

Table 4.6 The productivity index in the simulation game

Round	Q_p	Q_{d1}	Q_l	Q_{d2}	Q_a	Q_{d3}	D_1(min)	D_2(min)	D_3(min)	P_m	P_l	P_a
Round 1	20	0	20	0	20	0	30	20	31	0.67	1	0.65
Round 2	22	1	22	0	20	1	39	25	40	0.54	0.88	0.49

4.7 Discussion

Constraints management in modern PHP projects is essential because PHP processes are separated into different stages. Existing approaches to constraints management have several shortcomings, including low transparency of constraints status, and non-optimal or inflexible constraints improvement planning (Wang et al. 2016a). The previous manual and people-centric approaches in constraints management disregard the potential of IT to accurately, timely and agilely in managing constraints, thus enabling the reliable workflow in PHP scenarios. With *smart* characteristics including adaptivity, sociability, and autonomy, SWP can strengthen constraints modeling, monitoring, and even optimization. Accordingly, SWP can improve human deficiencies or skills in tasks execution to save time and cost. SWP can identify and analyze the latest constraints in a pull or push manner, provide optimal constraints improvement planning at different levels such as robustness, flexibility, resilience, and track, update, and predict the constraints status autonomously.

SWP provides an immense opportunity to improve the workflow management in the global modular/prefabricated construction industry. SWP can significantly enhance the power of object-oriented BIM, which has been broadly recognized as a potential of integrating physical objects of product-oriented PHP and informational components to form situation-integrated analytical systems which can respond intelligently to the dynamic changes of real-world scenarios and offer data-oriented lean solutions (Li et al. 2017b). Current BIM models are mostly created in an as-designed condition, with updates in the subsequent stages including construction and maintenance. To make BIM a handy information hub in tasks execution with data-oriented lean solutions, as-built information is urgently needed to timely exchange with BIM. Presently, as-built data updates are primarily based on manual site survey or fragmented information technologies adoptions, which are time-consuming, error-prone, and non-value added information (Shrestha and Behzadan, 2018). To some extent, BIM development for physical project execution has come to a bottleneck with as-built information being synchronizing between BIM and tasks execution in a real-time and value-added manner to support constraints management. SWP can be adopted to bridge the value-added information gap between BIM and information technologies supported objects (e.g., smart PHP objects). The sociability of SWP means that they can interact with other SWPs or synchronize as-built information with BIM in a pull or push manner, and the adaptivity of SWP can make them respond to changes in a robust, flexible and resilient manner. The characteristic of autonomy enables SWP to respond in a proactive or passive manner.

Given the capacity of SWP to interact with other platforms, SWP can also benefit from the development of the Internet of Things (IoT), an emerging paradigm that has attracted considerable attention in the lifecycle of PHP (Li et al., 2018b), In the IoT paradigm, the constraints status can be connected at any time and anywhere. The gateway, an IoT-enabled industrial computer, can provide a communication link between physical sensors and SWPs. Thus, IoT can enable the SWPs to be a loosely coupled, decentralized, multi-agent system. The adaptivity held by SWP is a core property in the IoT ecosystem, as the flexible and resilient actions can make the planning and control of constraints more dynamic. With the characteristic of autonomy, SWP can connect with and handle the autonomous objects (e.g., vehicle, crane, robotics) based on specific protocols, e.g., a fill-up based trigger. Once the smart workflow is established, information sensed by each autonomous object can be shared with SWP in a proactive manner. These all contribute to the underpinning philosophy of construction industry 4.0 (Longo et al., 2017).

Furthermore, a smart work package can be generated from BIM by decomposing the BIM models and integrating the functional information such as tasks sequence, workflow, resources, location with the decomposed physical information including building systems and prefabricated products. Its information can be pulled out from context provision layer for assisting constraints modeling (e.g., automatic analysis of the topological constraints and their interrelationships), optimization (e.g., visual guidance and interactive representation of the work sequence can be obtained by applying optimal lean solutions), and monitoring (e.g., the resource requests can be evaluated and monitored in a real-time manner). The functions of SWP are developed and integrated into the context integration layer in a specific format (e.g., ifcXML), which can be connected to BIM. Files using the IFC schema can be interoperated on BIM platforms, which facilitates better information sharing and exchange (Lee et al. 2016). SWP also reduces the manual operations including reformating or reinterpreting information (e.g., constraints status) when using BIM, thus eliminating the possibility of error caused by human intervention during data processing. It is envisaged that the proposed SWP can address the bottleneck that limits BIM expansion and present opportunities to make BIM a genuinely dynamic workflow management system rather than the static model management system.

It can be envisaged that SWP will progressively override conventional PHP constraints management to develop into an effective workflow management approach in the future. However, there are still numerous challenges to face. Firstly, from an organizational perspective, there will probably be resistance to diverge from the current constraints management practices in order to embrace smartness. Meanwhile, although SWP can help simplify interface management between tasks/activities carried out by different sub-contractors, the adoption of SWP for constraints management is more challenging in PHP projects with multiple tiers of subcontractors. Secondly, from a technical perspective, the interoperability of SWP will also be a challenge. The smartness of SWP relies on efficient data exchange. Without a universal standard for SWPs, there will be no smartness (though presently SWP can be operated based on BIM interfaces which are interoperated through ifcXML). The PHP industry is also fragmented. No individual can drive the industry toward fully integrated advanced technologies development and adoptions (Niu et al., 2016). The third challenge, from an economic perspective, is the expense of developing and deploying SWP. The PHP industry is comparatively slow-moving to embrace the new wave in the adoption of new technologies, and organizations within the industry would be very sensitive to expand on new technologies.

4.8 Chapter Summary

PHP has fragmented processes, which may generate numerous constraints in the critical chain of PHP. If the constraints cannot be timely improved, the reliability of workflow may be affected, and schedule delay and cost overrun will occur. The primary contributions of this study to the body of knowledge are threefold. Firstly, Inspired by the theories of work packaging and SCOs, SWP is defined as PHP workflows which are decomposed in accordance with PBS of building systems that are made smart by augmenting with the capacities of visualizing, tracking, sensing, processing, networking, reasoning so that they can be executed autonomously, adapt to changes in their physical context, and interact with surroundings to enable more resilient process. Secondly, equipped with three characteristics sociability, adaptivity, and autonomy, a continuous improvement framework for constraints management with three functions, including constraints modeling, constraints optimization, and constraints monitoring is proposed and illustrated by several examples and scenarios. Thirdly, a formal structured SWP representation is proposed by developing a layered system model involving context provisioning layer (CPL), context integration layer (CIL), and smart work packaging layer (SWPL) to realize these three functions.

Results from the validation process signify the benefits when implementing the framework of SWP-CM in PHP. 22.2% reduction of project duration was achieved, and no defective units were generated in the round of SWP-CM. Productivity was also improved, particularly in the manufacturing and on-site assembly stage. Thus, it can be concluded that SWP provides enormous opportunities to improve constraints management in PHP, particularly in conjunction with BIM. It can extract the context information (both physical and functional information) of product work packages from CPL (BIM platforms integrating with IoT). It can also insert the value-added as-built information into the BIM platforms in a pull or push manner. SWP can also be combined with the IoT-enabled gateway to act as a loosely coupled, decentralized, multi-agent system to make the constraints status be connected at any time and anywhere.

However, It should be noted that SWP for constraints management is in the early stage of its development. There are several barriers to the development and implementation. For example, there are technical difficulties related to the integral approach in constraints identification and interrelationship mapping, the efficient algorithms for dynamic re-planning in constraints optimization, and robustness hardware (e.g., autonomous robots, vehicles, cranes) and software (location-based workflow engine, interoperability of connected system) for constraints monitoring. There are also challenges related to technology acceptance, organizational changes, and cost issue. By overcoming these challenges, it is believed that SWP can help establish safer, more adaptive, more proactive, more efficient, and more sustainable PHP workflows.

The detailed functional scenarios will be illustrated in the following chapters.

CHAPTER 5 SWP-enabled Constraints Modeling Service

5.1 Introduction

Although the SWP is expected to improve the constraint management, modeling the constraints (i.e., identification and relationship mapping) through an automatic and dynamic approach is the very first step toward a “zero-constraint” environment. Previous studies primarily focused on understanding the constraint types, such as physical, resources, and information (Blackmon et al., 2011; Wang et al., 2016a). However, SWP-enabled critical constraints identification and understanding the interrelationships of them have seldom been explored. To better explore the SWP-enabled constraints management system of PHP from a holistic view, constraints modeling including the identification of constraints, mapping their dynamic interrelationships, and constraints scenarios analyzing should be investigated before optimizing and monitoring them. This chapter concentrates on the on-site assembly process of PHP due to it is the driving center for delivering the final product, and this chapter also proposes a two-phase solution to model the constraints, which includes 1) encapsulating social network analysis (SNA) module into SWP to automatically identify the trades associated constraints in the on-site assembly process, and 2) developing a hybrid dynamic model which integrates system dynamics (SD) and discrete event simulation (DES) to map the interactions and interrelationships of these constraints. The specific objectives of this chapter are presented as below: (1) to automatically identify the trades associated critical constraints; (2) to dynamically explore interactional and interdependent relationships of these constraints; (3) to simulate and analyze the impact on the schedule performance under various constraints scenarios.

5.2 Constraints Identification

The SNA sub-service of constraints modeling in the SWP can automatically identify the critical constraints and their interrelationships. The functions of SNA sub-service can be divided into three parts (See Figure 5.1).

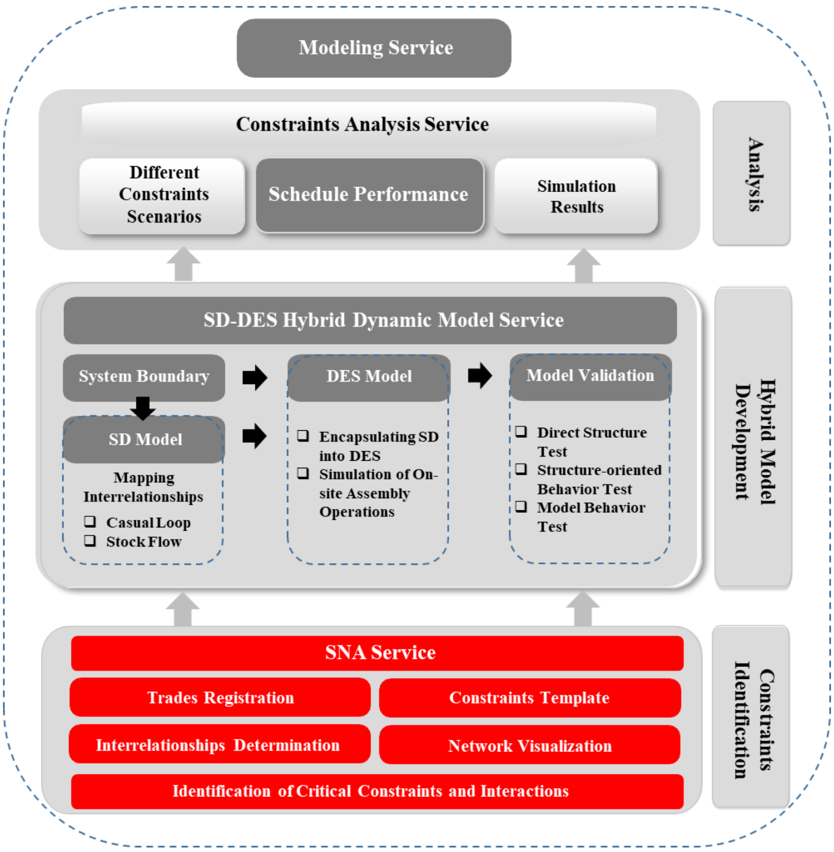


Figure 5.1 SWP-enabled constraints modeling service

(1) The workers of different trades register or log-in SNA sub-service in their mobile device and get the constraints template. The initial list of constraints is

generated from the look-ahead meeting of a real PHP project owned by the Hong Kong Housing Society (HKHS) (see Table 5.1). The templated constraints are pre-programmed with an open-data integration approach for constraints instantiation.

(2) The interrelationships among identified constraints are determined by links representing the influence of constraints over another constraint. There are two steps in this process. The workers of different trades (The trade list is collected from on-site assembly process of the same PHP project which can represent a typical four-day assembly cycle (FDAC) (see Table 5.2) were required to clearly set the direction of potential influence according to their empirical knowledge in the service interface, and the direction of relationships can be mutual. For example, the influence generated by T_1C_2 on T_3C_4 was distinct from the influence of T_3C_4 on T_1C_2, and they are considered as two different links. After tabulating the identified links, they can be quantified by two metrics including the *intensity of influence* (adopting a five-point scale where "0" and "5" signify the lowest and highest levels) and likeliness of the influence occurrence (adopting a ten-point scale where "0" and "1" represent the lowest and highest levels, i.e., 0.1, 0.2, etc.). The multiplication of the *intensity of influence* and *likeliness* offers a basis for evaluating the influence level between two trades associated constraints. When no influence occurs between two nodes, the influence level is zero.

(3) The SNA sub-service calls the NetMiner tool (an SNA application analytics) to visualize and analyze the adjacency matrix lists of link and node. There are three steps in this process. The on-site superintendent can visually exam the primary constraints and their relationship distribution in the network. The metrics value and description of network density and cohesion can be displayed to reflect the overall connectedness and complexity of the network. In addition, the pre-selected node-level metrics (e.g., out-degree/out-status centrality, node betweenness centrality, and out-closeness /eigenvector centrality) can be computed to investigate the characteristics and roles of individual nodes for determining the critical constraints. Besides node-level metrics, link betweenness centrality was also calculated to assess the critical interrelationships among constraints. It can help disclose the cause-and-effect relationships of these constraints. As shown in Fig 5.2, the output of SNA sub-service is a list of critical constraints and critical interrelationships among these constraints, which is used in the subsequent SD-DES hybrid model, and more details can be found in the authors' previous study (Gong et al., 2019). The trades can re-evaluate the constraints, and the SNA service can also re-generate the output in a real-time manner.

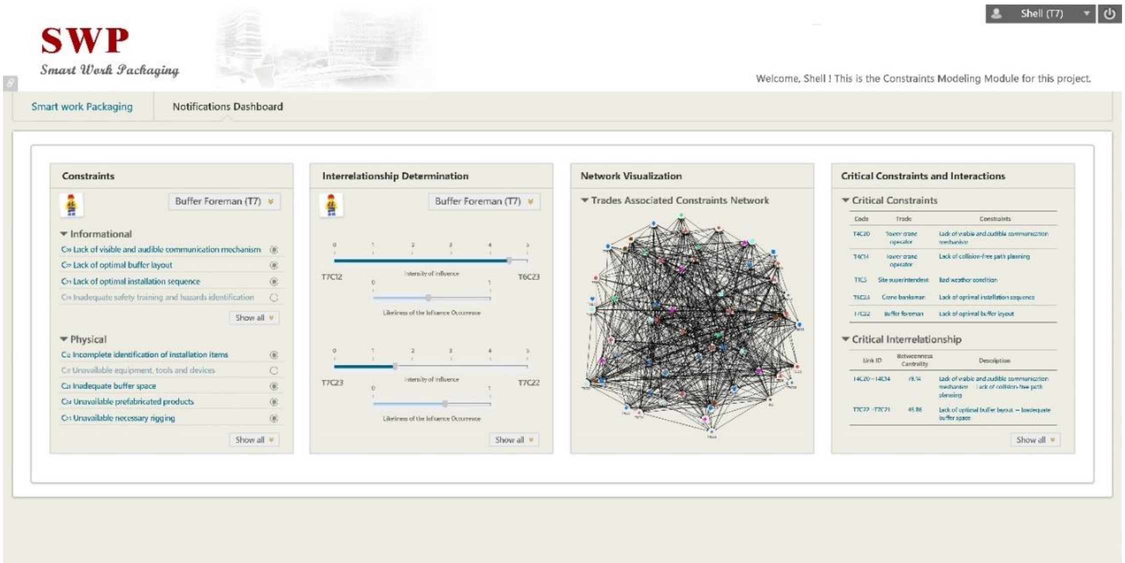


Figure 5.2 The interface of constraints modeling for constraints identification

Table 5.1 Constraints List

ID	Constraints	ID	Constraints
C1	Incomplete shop drawings and BIM models	C17	Unavailable equipment, tools, and devices
C2	Incomplete specifications	C18	Lack of crane maintenance plan and instruction
C3	Lack of permits	C19	Lack of blind zone operation procedure/instruction
C4	Unavailable and unassigned labour resources	C20	Lack of visible and audible communication mechanism
C5	Bad weather conditions	C21	Inadequate buffer space
C6	Unavailable production and transportation schedule	C22	Lack of optimal buffer layout
C7	Lack of traceable status of prefabricated products	C23	Lack of optimal installation sequence
C8	Bad conditions of transportation vehicle and route	C24	Unavailable prefabricated products
C9	Unavailable quality control hold-points	C25	Unavailable necessary rigging
C10	Unavailable connection points for handling	C26	Inadequate workface/work space
C11	Lack of inspection and testing instructions	C27	Unavailable installation instructions
C12	Incomplete identification of installation items	C28	Unavailable temporary structures
C13	Lack of lifting load capacity	C29	Inadequate safety training and hazards identification
C14	Lack of collision-free path planning	C30	Unavailable safety checkpoints

C15	Unavailable lift and place location in the assembly process	C31	Incomplete special personal protection equipment (PPE) instructions
C16	Incomplete plan for movements and location of the crane		

Table 5.2 Trades in the on-site assembly process

ID	Trades
T1	Site superintendent
T2	Expeditor
T3	Quality inspector
T4	Tower crane operator
T5	Tower foreman
T6	Crane banksman
T7	Buffer foreman
T8	Prefabricated products Installer
T9	General laborer
T10	Safety supervisor

5.3 Development of Hybrid SD-DES Model

This hybrid SD-DES model sub-service is developed to help workers and site managers to investigate the influence of the critical constraints and interrelationships (identified in the above SNA sub-service) on the schedule performance of the FDAC in the on-site assembly process. To achieve this objective, the development of the system boundary, the SD model and DES model are explained below.

5.3.1 System Boundary

The definite system boundary can facilitate to generate specific system structures and behaviors for meeting the research objectives. In this chapter, the hybrid SD-DES model consists of three subsystems: the FDAC process, constraints, and schedule performance. The connection between the three subsystems can be presented in Figure

5.3. This model can be used as a practical service to help workers and site managers to investigate the interrelationships of constraints in the tasks execution process that influence the schedule performance of the FDAC. (1) The FDAC subsystem (See Figure 3.3) comprises activities related to prefabricated products and in-situ concrete. (2) The schedule performance subsystem mainly consists of the planned schedule and the actual schedule to measure their differences. The PHP assembly process will delay if the actual schedule lag behind the planned schedule.

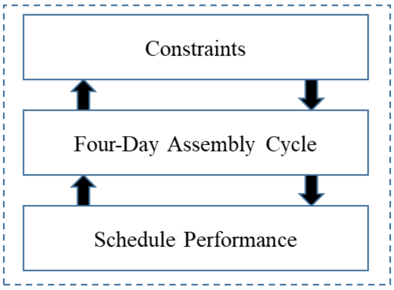


Figure 5.3 The relationship between the three parts of the model

According to the literature review and on-site surveys conducted in Gong et al. (2019), constraints can mainly impede the on-site assembly progress from three facets: resource availability, operation efficiency, and quality concerns. In the compact construction site for the assembly process, resources refer to labor, prefabricated products, machinery (e.g., crane) and workspace. The workflow can be reliable with sufficient resources, while constraints in resource availability will provide a negative impact on the PHP schedule. Thus, resource availability can have interactions (e.g., positive reinforcement) with schedule performance. For example, if the schedule is compressed, it can increase the number of resources (e.g., labor, crane) to recover the schedule delay. Conversely, the certain increment in resources can accelerate installation rate to prevent schedule delay. Operation efficiency indicates the proficiency and accuracy of the machinery and labor, and the constraints in operation efficiency still depress the productivity in PHP project even though the information and communication technologies have been widely adopted in the construction site (Li et al., 2017c). It is also the reason to develop smart work packaging approach in the authors' series of studies. Efficient operations can speed up the installation rate, whereas inefficient operations can increase the installation error rate, thereby, leads to the schedule delay. In return, when the schedule delay occurs, workers and machinery may become rushed to conduct unsafe and fatigued operations. And the operation efficiency may decrease due to the low installation rate and high installation error rate. Quality concerns can be serious defects of prefabricated products, which are detected when they are arrived on-site or in the assembly process. These defective prefabricated products should be reworked or reproduced in the plant and extra time will be consumed in transporting new prefabricated products back to the site, thereby, resulting in schedule delay. Oppositely, pushing to expedite the progress and overtake the delayed schedule may raise the possibility of quality issues. Thus, quality concerns can also be interrelated with other subsystems of the model.

5.3.2 System Dynamics (SD) Model

To perform a detailed quantitative analysis of system's structure and behavior, the previously defined and described casual loop relationships in Section 5.2 and Section 5.3.1 are transformed to an SD diagram (See Fig.5.4) to address the subsystems of constraints and the schedule performance for both prefabricated products installation and in-situ tasks.

The SD model is based on the SD scheme adopted in several studies (Nasirzadeh and Nojedehi, 2013; Li et al., 2018a; Wu et al., 2019). In SD, stocks, dynamic variables, and flows are the basic building blocks. Stocks monitor cumulative quantities (e.g., task completion rate); dynamic variables monitor non-cumulative quantities (e.g., labor and crane efficiency); and in- and out-flows are used to connect stocks to indicate the increasing and decreasing rate of the stock value. SD also has parameters whose values are fixed during the simulation and are used to depict the static attributes of a system (e.g., basic inspection rate and production rate of prefabricated products). All the SD elements are linked together to form feedback loops that reflect the underlying mechanism of a system (Wu et al., 2019). This SD model works as a standardized element to depict the specific FDAC process with surrounded constraints. The rationale of this SD model is supported by four modules, namely, assembly process module, resource availability module, operation efficiency module, and schedule performance module. The details of these modules are discussed in the following sections. It should be noted that the SD structures of installation and in-situ tasks are similar. Thus, in the following sections, (1) - (4) introduces the modules for installation tasks, whereas the modules of in-situ tasks are introduced in (5) by highlighting the differences.

(1) Assembly Process Module

This module is the main skeleton of the SD model for installation tasks, which simulates different statuses of prefabricated products by SD stocks (see Fig.5.4), such as "Products To Be Assembled," "Assembled Products" and "Inspected Products." The "Products To Be Assembled" stock refers to the total amount of prefabricated products (e.g., prefabricated facades) that have been delivered to an on-site buffer and should be assembled. This is linked to another "Assembled Products" stock by a flow named "Installation Rate," which is determined by some dynamic variables, such as "Crane Efficiency," "Labor Efficiency" and "Resource Availability." At the quality checking stage, the installed façades are translated into the "Inspected Products" stock at the "Inspection Rate," which is determined by the parameter "basic Inspection Rate" and several constraints identified using the method introduced in Section 5.3.1. The mechanism of other stocks, dynamic variables, and flows, such as "Products To Be Delivered," "Products To Be Re-assembled," "Delivery Rate" and "Re-installation Rate," follow the same principles.

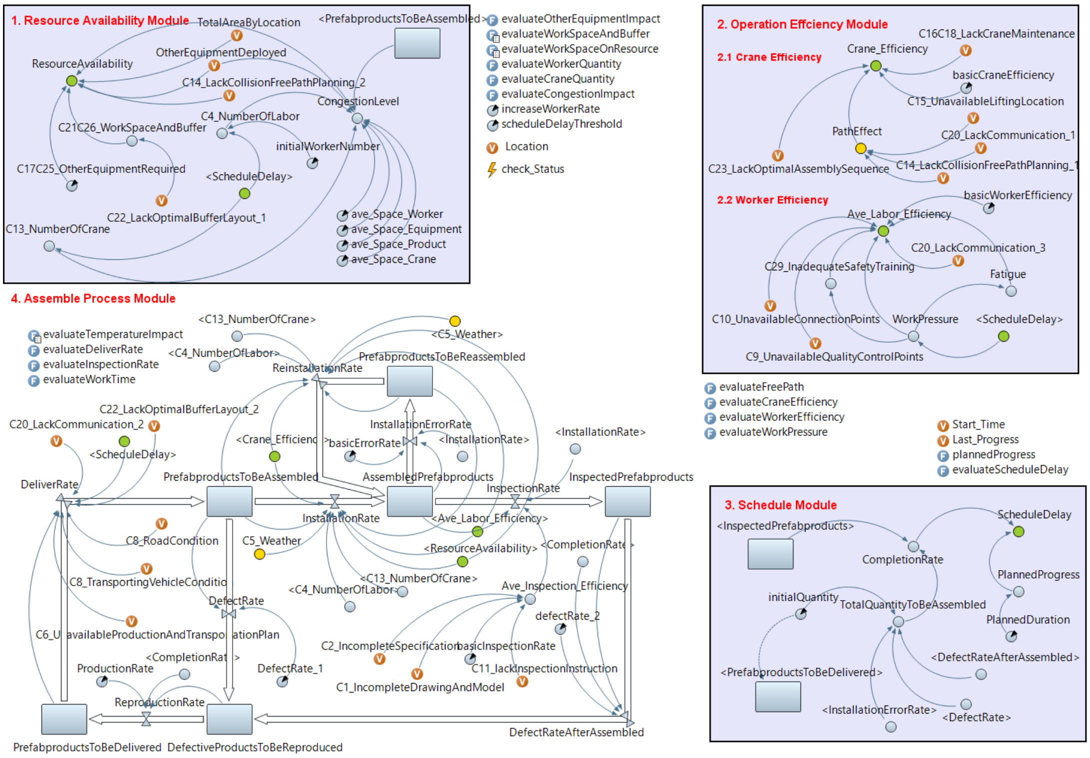


Figure 5.4 System dynamic model

(2) Resource Availability Module

The resources in this study include labor, material (e.g., prefabricated products), machinery (e.g., crane), and workspace (e.g., buffer, workface). An optimal resource availability level can keep the installation rate at a reasonable range to align with the planned schedule. In RAM, the critical feedback loop is determined by two SD variables. One loop starts from the critical constraint C22: lack of optimal buffer layout, identified by the SNA sub-service in Section 5.2. This constraint can affect inadequate buffer space (i.e., C21), and constraints related to availability and capacity of labor and cranes (i.e., C4, C13, and C23). Moreover, C22 also affects the stock “Products To Be Assembled” indirectly by the flow “Delivery Rate” in the APM. The other dominant SD variable is “PSD,” standing for the predicated schedule delay. “PSD” can directly push to increase the number of labor and cranes, and indirectly affect the number of prefabricated products by “Delivery Rate.” However, the labor and cranes could not exceed the expected maximum quantity limited by the buffer space or workspace. This module is integrated with the APM bidirectionally. For example, “Resource Availability” is embedded in the APM as one major affecting factor of the flow “Installation Rate”. At the same time, the stock “Products To Be Assembled” in the APM is embedded in the RAM which affects the congestion level of workspace.

(3) Operation Efficiency Module

The operation efficiency includes the workers’ efficiency and cranes’ efficiency. The workers’ efficiency is largely determined by constraints related to information, quality and safety, such as C20: lack of visible and audible communication mechanism, C9: unavailable quality control hold points, and C29: Inadequate safety training and hazards identification. The relationships among the work pressure, fatigue, and other constraints that can hinder safety and quality operations have also been investigated in previous studies (Lee, 2017). Thus, the work pressure and fatigue degree can also affect the workers’ efficiency. The crane-related constraints are in the critical path of the assembly schedule, which has also been identified as the critical constraints in SNA sub-service. If these constraints are not timely removed, crane efficiency in terms of transporting prefabricated products (from lift point to the place point) in a Just-in-time (JIT) manner cannot be achieved. For example, the lack of optimal installation sequence and the lack of collision-free path planning can lead to numerous rework in the horizontal and vertical transportation of prefabricated products. Additionally, bad weather conditions (e.g., heat-stress) that always happen in the summer of Hong Kong can impede the progress of the PHP project or reduce worker efficiency, therefore, affecting the installation rate. The OEM module is integrated into the APM unidirectionally, i.e., the OEM only compute the worker and crane efficiency data and transfer it to the APM.

(4) Schedule Performance Module

This module is used to calculate schedule delay when constraints are not timely removed. For this purpose, the percentage of plan completion (PPC) and the actual percentage of completion (APC) are computed by extracting data from APM. The two indicators are then used to evaluate "PSD," which is sent back to APM, RAM, and OEM. Therefore, actions such as employing extra workers, and renting additional cranes can be taken to remove constraints based on the degree of delay. Some details of the calculation in this module can be seen in Table 5.3.

Table 5.3 Data inputs of the SD-DES model

Model Inputs Categories	Model Inputs	Data Sources
Parameters	All SD parameters (See Fig.5.5 and 5.6)	Project documents
Dynamic variables	All SD dynamic variables, stock, and flows (See Fig.5.4 and 5.5)	Table 5.4
Constraints	Constraints C1 – C31 (See Table 2.2)	A previous study (Gong et al., 2019) and interview with engineers

(5) Modules for In-situ Tasks

An FDAC process, as shown in Fig 3.3, also includes in-situ tasks, such as wall reinforcement and conduit installation, slab and beam rebar and inspection, and wall, slab and beam concreting. All the tasks can be modeled by a similar SD structure, which also includes four parts similar to the APM, RAM, OEM, and SPM. However, there are several differences. A Work Progress Module is set up to replace the APM, including four stocks, i.e., “Work To Be Completed,” “Completed Work,” “Inspected Work” and “Work To Be Redone,” respectively. No prefabricated products are needed for in-situ tasks. Therefore stocks, dynamic variables, and flows relating to prefabricated products delivery and production are omitted. Second, in the RAM and OEM for in-situ tasks, the workspace congestion caused by crane and crane efficiency is no longer considered because the material transported by crane for the in-situ tasks is not on the critical schedule path according to the project documents. Furthermore, in the SPM, the mechanism to compute schedule delay is the same, but dynamic variables used to compute “Total Quantity To Be Completed” are different. The structures of modules for in-situ tasks are shown in Fig 5.5.

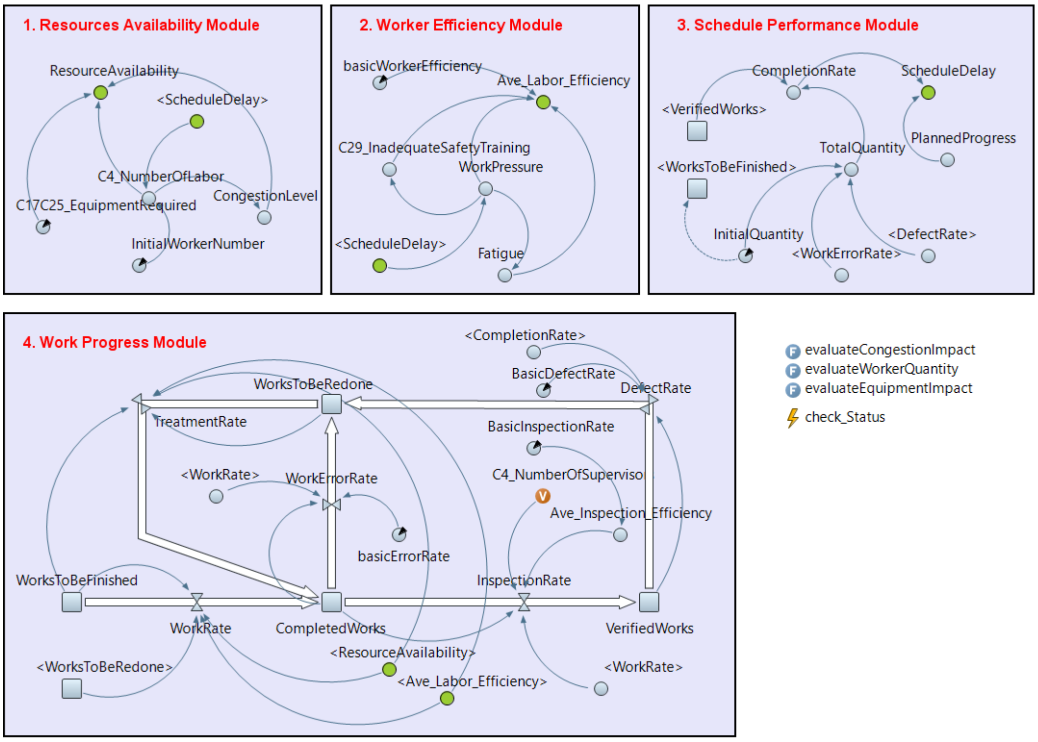


Figure 5.5 System dynamic model for in-situ concrete related activities

5.3.3 Encapsulating SD model into the DES model

An FDAC cycle requires to arrange multiple specific tasks with proper preceding and succeeding dependencies. To mimic this process, as shown in Fig 5.6, a DES model is built, which addresses the FDAC subsystem of the system boundary. Building blocks in the DES model are "delay" and "hold." The "delay" block refers to an ongoing installation or in-situ task; the "hold" block controls the pace of construction according to the project plan and completion rate of preceding tasks. There are two types of "hold" block. One type, e.g., the "hold" between "Wall_Rebar_A" and "Slab_Beam_Rebar_A" in Fig 5.6, prevents succeeding tasks from starting too early to stick to the original plan in Fig 3.3, which is necessary to avoid workers being idle due to early completion of preceding tasks (Kenley and Seppänen, 2006). The other type, however, forces succeeding tasks to wait until all preceding tasks are completed, such as the "hold" before “Concrete_A.”

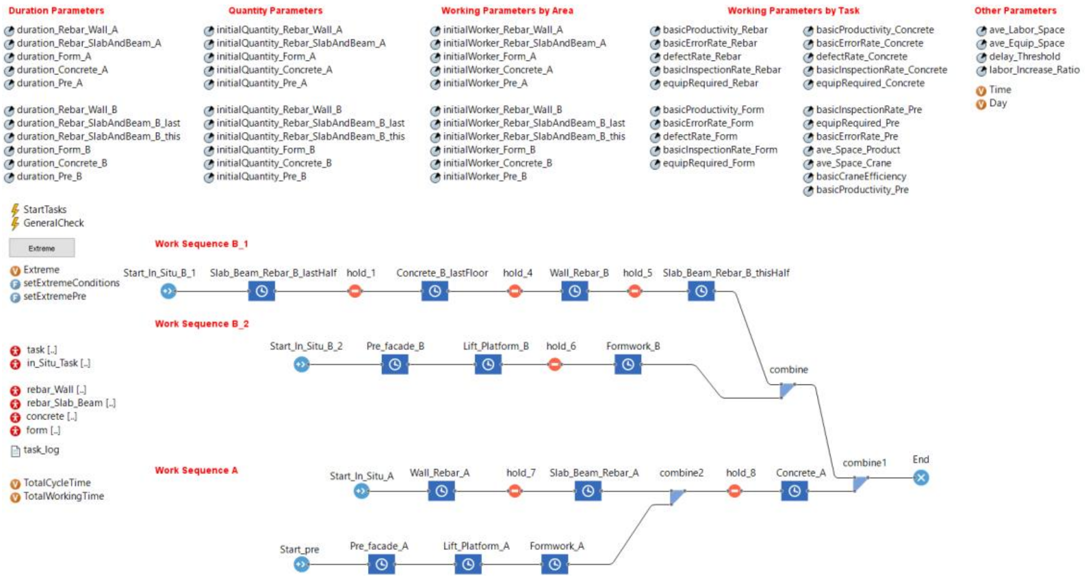


Figure 5.6 The hybrid SD-DES model for the FDAC

The conceptual structures of installation and in-situ tasks defined in Section 5.3.2 are used to generate and assign tasks into the DES model. For this purpose, a technique in object-oriented programming, i.e., encapsulation, is applied, where a class is defined as a blueprint of all objects belonging to that class by grouping (or encapsulating) common information of the objects into a logical unit. As illustrated in the SD structures, installation and in-situ tasks have distinct characteristics. Thus, they are defined as two classes, with all relevant information encapsulated in their SD models. The installation task class generates tasks such as “Pre_facade_A” while the in-situ task class generates tasks such as “Concrete_A.” The encapsulation contributes three merits to the SD-DES model: (1) It keeps the properties integrality of each task module; (2) It facilitates the scalability of the DES model; and (3) It enhances the reusability of SD models.

The integration mechanism between DES and SD is bidirectional and is shown in Fig. 5.7. On the one hand, each task is generated and assigned into a "delay" block at the time *a*, and is released at time *b*, when two conditions are satisfied: (1) the earliest start time defined in the project plan is reached; (2) the variable "APC" in the SPM becomes 100%. On the other hand, in the DES model, a timer is activated in "delay" blocks to record the time spent for each task by subtracting *a* from *b*. Thus, the sum of all timers is the total working time (TWT) of all tasks whereas the total cycle time (TCT) of one FDAC cycle is recorded at time *c* (measured by the model engine's timer directly) when the "End" block in Fig. 5.6 is reached. TWT is greater than TCT since some tasks are performed in parallel. TWT and TCT are important indicators for model validation and results comparison (see Section 5.5.2 and 5.5.3). Meanwhile, "Total Work Hours" is derived from TWT and is sent back to SD models to evaluate values of dynamic variables (see Section 5.5.1).

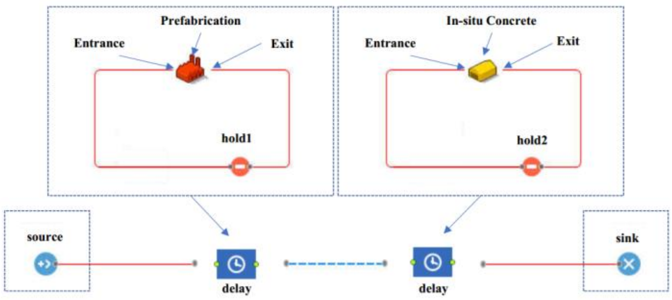


Figure 5.7 The DES task module with encapsulation method

All variables in the SD models are linked to the database in the SD-DES model service. When the model starts, data can be extracted from the database. Meanwhile, the results of the simulation can be saved to the database for further analysis. In addition, a set of interfaces and data input/output plug-ins are developed in the SD-DES model service to capture, store, and visualize the real-time modeling and simulation process.

5.4 Constraints Analysis

The constraints analysis sub-service can be activated when the hybrid SD-DES model sub-service has been successfully developed. This kind of scenario analysis can work as a sub-service of SWP to quantitatively measure the influence of these critical constraints on schedule performance under different constraints scenarios. The simulation results can not only be visualized by considering various constraints scenarios at the different time points of the FDAC but also provide decision support by predicting the assembly duration variation when different constraints are not timely removed at different time points. In this constraints analysis sub-service, a set of constraints scenarios are proposed based on real project experience, and a comparative analysis is conducted between these scenarios.

5.5 Case Simulation

5.5.1 Data Collection and Quantification of the SD-DES Model

Prior to launching the simulation, the SD-DES model must have accurate data inputs. According to the attributes of these data inputs, they are categorized into three categories, i.e., parameters, dynamic variables, and constraints. Data sources of each group are summarized in Table 5.3 and are explained below.

Parameters, such as “Basic Inspection Rate” and “Basic Work Efficiency,” have fixed values during the simulation and usually serve as the baseline to evaluate values of dynamic variables. The values of parameters are collected by reviewing project documents, such as planned schedules, construction plans and bill of quantities. Dynamic variables are SD elements (introduced in Section 5.3.2) whose value are determined by other elements (e.g., constraints, stocks, parameters, and other dynamic variables) linked to them. Thus, the value of a dynamic variable is not collected but computed, by embedding equation in the variable, considering all elements linked to it. Finally, constraints are divided into two groups according to their interrelationships identified in Section 5.5.2. One group consists of dependent constraints where their effect is affected by other constraints. For instance, C14 Lack of collision-free path planning is affected by C20 Lack of visible and audible communication mechanism, and the effect of C14 on “Crane Efficiency” will increase if C20 is not removed. The other group consists of independent constraints, which only affect others but are not affected during the project. These constraints are related to the environment, supply chain and project planning problems, such as C5 Bad weather conditions, C8 Bad conditions of transportation vehicle and rout and C29 Inadequate safety training and hazards identification.

Then, the quantification of dynamic variables and constraints is completed in three ways. First, equations in similar SD models from qualified journals are searched, which are mainly used to calculate values of dynamic variables. Using such equations in is a common practice in SD model building to reduce development time and increase model reliability (Wu et al., 2019). Besides, some equations can be built directly based on the structures of SD model and common knowledge of project management. Finally, a project-level approach is adopted to quantify the effect of constraints on dynamic variables and the mutual effect between constraints, because such information is highly project-dependent and off the shelf equations cannot be found. For this purpose, engineers of the case project are asked to give an estimation, and the average value is taken. For instance, the negative effect of C14 Lack of collision-free path planning on "Crane Efficiency" will be further increased by if C20 is not removed.

Given the limited space, Table 5.4 gives some examples of establishing equations in the SD modules of installation tasks, which includes all the three ways to quantify the SD model. It should be noted the FDAC procedure is very mature and standard in Hong Kong (Jailon and Poon, 2009). Thus data collected from a typical FDAC project, and the estimation provided by experienced engineers can be considered as stable and representative.

Table 5.4 Examples of quantification methods in the SD model of installation tasks of prefabricated products

Equation Aim	Module	Equation	Source
Calculating “PSD”	SPM	$\mathrm{APC} = {}^{\mathrm{InspectedProducts}}/_{\mathrm{TotalProductsToBeAssembled}}$ $\mathrm{PlannedInspectedProducts} = f(\mathrm{WorkHours})$; f is a table function to produce planned completion rate given the time (i.e., WorkHours) that has been spent on a task $\mathrm{PPC} = {}^{\mathrm{PlannedInspectedProducts}}/_{\mathrm{TotalProductsToBeAssembled}}$ $\mathrm{PSD} = \min\left(\left({}^{\mathrm{PPC}}/_{\mathrm{APC}} > 1 ?\left({}^{\mathrm{PPC}}/_{\mathrm{APC}}\right) : 1\right), 2\right)$; PSD appears when PPC is greater than APC but cannot exceed 2	Nasirzadeh and Nojedehi (2013); Li et al. (2018a); Wu et al. (2019)
Calculating “C5’s effect” on “WorkerEfficiency.”	OEM	$\mathrm{Defficiency} = 1 - 0.57\% \times (t(\mathrm{ModelTime}) - \mathrm{basicTemperature})$; t is a table function to produce temperature given the model time $\mathrm{WorkerDefficiency} = \mathrm{WorkerEfficiency} \times \mathrm{Defficiency}$	Li et al. (2016); Yi and Chan (2017)
Calculating “Fatigue”	OEM	$\mathrm{Fatigue} = 1.44 - 2.2 \times 10^{-6} \times \mathrm{TotalWorkHours} - 9.47 \times 10^{-3} \times \mathrm{avgWorkHours}$	Hanna (2005); Wu et al. (2019)
Calculating “Congestion”	RAM	$\mathrm{Congestion} = {}^{\sum \mathrm{OperationSpace} \times \mathrm{Number}}/_{\mathrm{TotalWorkSpace}}$ The operation space in RAM includes workers, equipment, products and space for crane operation	Chua et al. (2010)
Calculating “InstallationRate”	APM	$\mathrm{InstallationRate} = \left({}^{\mathrm{PrdouctsToBeAssembled}}/_{(\mathrm{PrdouctsToBeAssembled} + \mathrm{PrdouctsToBeReassembled}}\right) \times (\mathrm{CraneEfficiency} \times \mathrm{NumberOfCranes} + \mathrm{WorkerEfficiency} \times \mathrm{NumberOfWorkers} \times \mathrm{ResourceAvailability})$	Nasirzadeh and Nojedehi (2013); Emuze et al. (2014)

Calculating “TotalProductsToBeAssembled”	SPM	$\text{TotalProductsToBeAssembled} = \text{initialQuantity} + \text{InstallationErrorRate} + \text{DefectRate} + \text{DefectRateAfterAssembly}$	
Calculating “InstallationErrorRate”	APM	$\text{InstallationErrorRate} = \text{InstallationRate} \times \text{errorRate}$	SD structure/Project management knowledge
Calculating “DefectiveProductsToBeReproduced”	APM	$\text{DefectiveProductsToBeReproduced} = \text{InspectedProducts} \times \text{defectRateAfterAssembly}$	
Calculating “DeliverRate”	APM	**IF** any of C3, C6, C8, C22 is not removed $\text{Defficiency} = 0.9^{n}$ n = the number of unremoved constraints $\text{DeliveryRate} = \text{basicDeliveryRate} \times \text{Defficiency}$ **IF** PSD > 1.5 $\text{Delivery Rate} = \text{Delivery Rate} \times 1.1$	
Calculating “InspectionRate”	APM	**IF** any of C1, C2, C7, C11 is not removed $\text{Defficiency} = 0.95^{n}$ n = the number of unremoved constraints $\text{InspectionRate} = \text{basicInspectionRate} \times \text{Defficiency}$	
Calculating “CraneEfficiency”	OEM	**IF** any of C15, C16, C18 is not removed $\text{Defficiency}^{1} = 0.95^{n}$ n = the number of unremoved constraints **IF** any of C14, C23 is not removed $\text{Defficiency}^{2} = 0.9^{n}$ n = the number of unremoved constraints $\text{CraneDefficiency} = \text{CraneEfficiency} \times \text{Defficiency}^{1} \times \text{Defficiency}^{2}$	Estimation from engineers
Calculating “WorkerEfficiency”	OEM	**IF** any of C9, C10, C29, C30, C31 is not removed $\text{Defficiency}^{1} = 0.95^{n}$ n = the number of unremoved constraints **IF** any of C19, C27, C28 is not removed $\text{Defficiency}^{2} = 0.9^{n}$ n = the number of unremoved constraints	

Calculating "C20's effect" on "C14."	OEM	$\text{WorkerDefficiency} = \text{WorkerEfficiency} \times \text{Fatigue} \times \text{WorkPressure} \times \text{Defficiency}^1 \times \text{Defficiency}^2$ **IF** C14 is not removed $\quad \text{Defficiency} = 0.9^n$ $\text{n} = 2$ if C20 is not removed; $\text{n} = 1$ otherwise $\text{CraneDefficiency} = \text{CraneEfficiency} \times \text{Defficiency}$
Calculating "NumberOfWorkers"	RAM	$\text{NumberOfWorkers} = \text{initialWorkerNumber}$ **IF** PSD > 1.5 $\quad \text{NumberOfWorkers} = 1.5 \times \text{initialWorkerNumber}$
Calculating "NumberOfWorkers"	RAM	$\text{NumberOfCranes} = \text{initialCraneNumber}$ **IF** PSD > 1.5 $\quad \text{NumberOfCranes} = \text{initialCraneNumber} + 1$
Calculating "Congestion's effect on ResourceAvailability"	RAM	**IF** Congestion < 0.33 OR congestion >0.66 $\quad \text{ResourceAvailability} = \text{ResourceAvailability} \times 0.8$

Note: all the names of parameters, constraints, and dynamic variables used in this table can be found in Table 2.2 and Fig. 5.4

5.5.2 SD-DES Model Validation

This section verifies the validity of the SD-DES model with two tests, i.e., direct structure test (DST) and Structure-oriented Behavior Test (SBT).

(1) Direct Structure Test (DST)

Direct structure test (DST) directly performs qualitative comparison between the model structure and the real system, which includes three sub-tests: (1) structure and parameter confirmation tests, which examines if all the causality, feedbacks, and parameters of this model can be reflected from the real system; (2) dimensional consistency test, which examines the dimensional consistency of equations and ensures that there is no illogical parameter; (3) boundary adequacy test, which ensures all crucial variables keep in line with the research objectives (Barlas, 1996). As mentioned in Section 5.3.2 and Section 5.5.1, the SD structures and equations are established based on verified works while the DES model is built by referring to the mature FDAC cycle. Furthermore, the model structures and the selection of parameters and variables have been explained to the project managers of the case project to gain their agreements. Thus, the model meets the requirements of DST and can reflect the real project.

(2) Structure-oriented Behavior Test (SBT)

Structure-oriented behavior test (SBT) is a quantitative test, which investigates model-generated behavior patterns to uncover potential structural flaws (Wakeland et al., 2005). It can be achieved by extreme-condition test, behavior sensitivity test, and integral error test.

Extreme Condition Test: the extreme-condition test exams, whether a model is reasonable under extreme conditions. Given the aim of the study is to investigate the influence of constraints, the status of constraints are used to set up extreme conditions. For example, the most optimistic and pessimistic cycle time (TCT) of constructing 33 typical floors adopting FDAC, according to the project plan, is 132 (i.e., 4 days per floor) and 231 days (i.e., 7 days per floor), respectively. The test results are shown in Table 5.5. After 200 simulation runs, when no constraint exists, the average TCT and deviation rate is 132.50 days and 0.71%, respectively, whereas when all constraints are not removed, the average TCT and deviation rate is 230.06 days and 4.75%, respectively. Both results are acceptable (i.e., the deviation rate is less than 5%) and comply with the plan.

Table 5.5 Results of extreme condition test

Floor	Optimistic Duration	Simulated Duration	Error Rate	Pessimistic Duration	Simulated Duration	Error Rate
4/F	4	4.05	1.25%	7	6.90	-1.43%
5/F	4	4.04	1.00%	7	6.61	-5.57%
6/F	4	3.98	-0.50%	7	6.67	-4.71%
7/F	4	4.02	0.50%	7	7.23	3.29%
8/F	4	4.01	0.25%	7	7.42	6.00%
9/F	4	4.01	0.25%	7	6.65	-5.00%
10/F	4	4.01	0.25%	7	6.70	-4.29%
11/F	4	4.03	0.75%	7	6.85	-2.14%
12/F	4	4.02	0.50%	7	6.50	-7.14%
13/F	4	4.03	0.75%	7	6.82	-2.57%
14/F	4	3.97	-0.75%	7	6.51	-7.00%
15/F	4	4.01	0.25%	7	6.58	-6.00%

16/F	4	3.96	-1.00%	7	6.53	-6.71%
17/F	4	4.02	0.50%	7	6.70	-4.29%
18/F	4	4.04	1.00%	7	7.45	6.43%
19/F	4	4.01	0.25%	7	7.17	2.43%
20/F	4	4.04	1.00%	7	7.36	5.14%
21/F	4	3.93	-1.75%	7	6.69	-4.43%
22/F	4	4.02	0.50%	7	7.33	4.71%
23/F	4	4.01	0.25%	7	7.16	2.29%
24/F	4	4.01	0.25%	7	7.50	7.14%
25/F	4	4.05	1.25%	7	6.78	-3.14%
26/F	4	4.04	1.00%	7	7.38	5.43%
27/F	4	4.03	0.75%	7	7.23	3.29%
28/F	4	3.95	-1.25%	7	6.60	-5.71%
29/F	4	4.06	1.50%	7	6.48	-7.43%
30/F	4	3.99	-0.25%	7	7.15	2.14%
31/F	4	4.02	0.50%	7	7.45	6.43%
32/F	4	4.04	1.00%	7	7.20	2.86%
33/F	4	4.03	0.75%	7	6.49	-7.29%
34/F	4	4.01	0.25%	7	7.55	7.86%
35/F	4	4.05	1.25%	7	7.14	2.00%
36/F	4	4.01	0.25%	7	7.28	4.00%

Sensitivity Test: This test detects parameters to which FDAC tasks are sensitive and asks if the real system exhibits similar high sensitivity to these parameters. To interpret in details, ten parameters are selected, i.e., “Basic Worker Efficiency,” “Error Rate” and “Basic Inspection Rate” for both in-situ and installation tasks, as well as “Basic Delivery Rate,” “Defect Rate,” “Defect Rate After Assembly” and “Basic Crane Efficiency” for installation tasks, because these parameters are essential in the SD model by affecting many other dynamic variables. To assess their potential influence on project duration, each parameter is assigned with a maximum, minimum, and most likely value. For instance, the minimum “Defect Rate” of prefabricated products is 0 whereas the most pessimistic (i.e., maximum) “Defect Rate” in the PHP projects is 10% in Hong Kong (Li et al., 2018a). However, due to the paralleled tasks planning, the variation of TCT is not significant. Thus, the TWT which aggregates the time spent for each task is adopted to eliminate the paralleling effect, and the TWT baseline is 140.86 days in the optimal case. The variety range of each parameter, i.e., the sensitivity is computed using the following equation.

$$\left|\frac{Minimum\ duration - Most\ likely\ Duration}{Most\ likely\ duration}\right| + \left|\frac{Maximum\ duration - Most\ likely\ Duration}{Most\ likely\ duration}\right| \tag{5.1}$$

Table 5.6 summarizes the simulation results. This study uses 20% as the threshold of variation. Thus a variable is treated as sensitive if its variety range exceeds 20% (Li et al., 2018a). As a result, “Basic Delivery Rate,” “Basic Worker Efficiency^{I}” and “Error Rate^{I}” are sensitive variables, which complies with the reality. For one thing, installation is only a small part of the FDAC cycle in terms of total duration. Thus the sensitivity of parameters related to installation is less than those related to in-situ parameters. Among these installation parameters, “Basic Delivery Rate” is most sensitive as it starts the installation and affects subsequent processes; “Basic Worker Efficiency” and “Basic Crane Efficiency” are less sensitive as they depend on the delivery rate of facades meanwhile they are constrained by each other and none of them determines the installation rate alone (see Fig 5.4); “Error Rate^{P}” is not sensitive because the total amount of prefabricated facades is small, and even the pessimistic estimation of the installation error rate is still low given the mature FDAC cycle. For another, “Basic Worker Efficiency^{I}” and “Error Rate^{I}” are sensitive for in-situ tasks as they are the dominant factors behind the construction pace when work is less constrained delivery and crane (see Fig. 5.5)

Table 5.6 Results of sensitivity test for FDAC

Variable	Duration (min/likely/max)	Variety degree (min/max)	Range of variety
$basicWorkerEfficiency^I$	140.86/172.45/195.25	-18.32%/13.22%	31.54%
$basicWorkerEfficiency^p$	140.86/145.04/153.49	-2.88%/5.83%	8.71%
$errorRate^I$	140.86/164.54/179.02	-14.39%/8.80%	23.19%
$errorRate^P$	140.86/148.05/154.83	-4.85%/4.58%	9.43%
$basicInspectionRate^I$	140.86/149.35/159.12	-5.86%/6.54%	12.23%
$basicInspectionRate^P$	140.86/148.91/156.73	-5.41%/5.24%	10.65%
defectRateAfterAssembly	140.86/149.99/154.29	-6.08%/2.87%	8.95%
defectRate	140.86/145.40/147.36	-3.12%/1.35%	4.47%
basicCraneEfficiency	140.86/148.66/158.84	-5.25%/6.85%	12.09%
basicDeliveryRate	140.86/161.01/182.32	-12.51%/13.24%	25.75%

Note: “P” indicates production tasks; “I” indicates in-situ tasks

Integral Error Test : This test investigates whether the model behavior varies with the different integration method or time step. This study uses 4th order Runge-Kutta with the different time step: 0.5, 0.25, 0.125 and 0.0625 day/time, the model behaviors with durations are 132.35, 132.74, 133.18, and 133.52 days, indicating that this model can meet the requirement of this test.

5.5.3 Constraints Analysis

In this section, the five identified critical constraints are fused into the SD-DES model with different scenarios through three simulation tasks. In the initial stage, all constraints are assumed to be satisfied, whereas some critical constraints can re-appear at certain time points. Besides, one FDAC has 4 days, and the planned duration of that cycle is 5760 minutes (4*24*60=5760).

The first task assesses the impact of different constraints on schedule performance when they appear at the same time point. For example, 500^{th} minute after simulation launching is selected as the investigated point, at which all the five critical constraints are scheduled to appear. After summarizing results of 200 simulation runs, a histogram with a density curve of the simulated duration is drawn in Fig.5.8. The simulated duration ranges between 5800 and 8940 mins and has a 95% probability of falling in between 6006.5 and 8758.75 mins, with a median duration of 7060.32 mins. Through the statistical analysis of simulated duration, workers and project managers can adjust and re-plan the task executions at the specific time point.

The second task is to assess the impact of different constraints on schedule performance at various time points. For instance, the scenario, "C5 cannot be satisfied at the 100^{th} minute," which takes the form of $C5^{100th}$, has different impact level on schedule performance compared to the scenario $C5^{800th}$. As shown in Fig.5.9, the horizontal axis indicates the incidence time of constraints, and the vertical axis denotes the results of simulated duration. The larger the length of the box signifies, the more significant impact it will have on the schedule performance. Measured by the median (the band inside the box) value, $C5^{100th} > C5^{800th}$ can be observed at the different time points which indicates that some constraints have more influence on the whole schedule performance at the early stage of the cycle. As another example, the median of $C14^{100th}$ is just slightly higher than $C14^{800th}$, signifying that the inefficient crane operations cannot be significantly reflected in a short time period, which is usually accumulated to a considerable difference in the later stage.

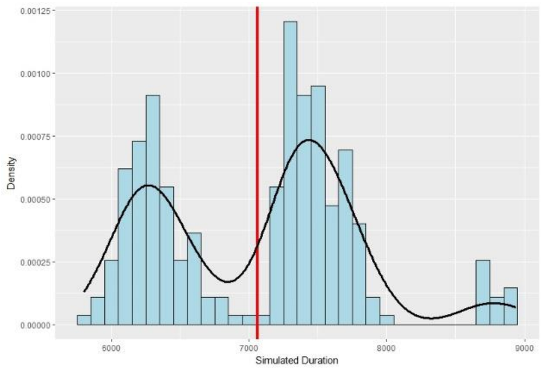


Figure 5.8 Histogram with the density curve of simulated duration in a specific time point

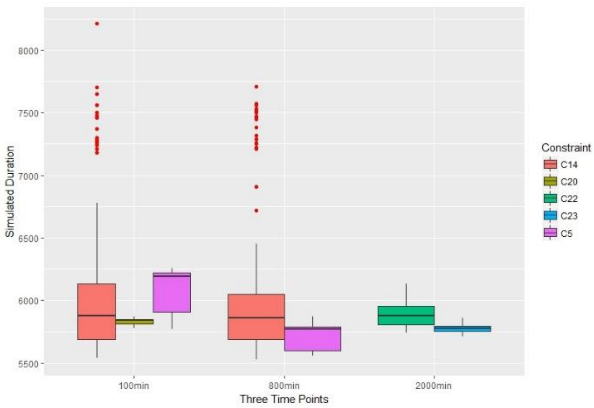


Figure 5.9 Boxplot of the simulated duration in three specific time points

The final task is to find out the constraint that has the most significant influence on the schedule performance of the FDAC cycle. For this purpose, each critical constraint is individually scheduled to appear at 100^{th} minutes. After 200 simulations, density curves of all the five critical constraints are generated and shown in Fig.5.10 Table 5.7 presents the ranking of the constraints in terms of their impact on schedule and includes relevant statistical information of TCT. Based on the mean value of FDAC duration, the constraints can be divided into three levels in terms of their effect on schedule. The first level includes C14 and C5 that can lead to a delay up to 249.85 minutes (i.e., 4.16 hours) in one FDAC cycle. In other words, if C14 is not satisfied, the total delay of the 33 floors can be 137.61 hours, nearly 6 days. The second level contains C22 and C20 that result in delay up to 137.75 minutes (i.e., 2.30 hours) in one FDAC cycle. Finally, the third level includes C23, which causes a minimal delay (i.e., 16.63 minutes) in one FDAC cycle.

divided into three levels in terms of mean value. **The first level includes C14 and C5 that lead to average schedule delays of more than 140 minutes.** The second level contains C22 and C20 that result in the average schedule delays between 70 and 140 minutes. C23 belongs to the third level that has minimal influence on the schedule delay of the FDAC. It leads to less than 20 mins in its average schedule delays.

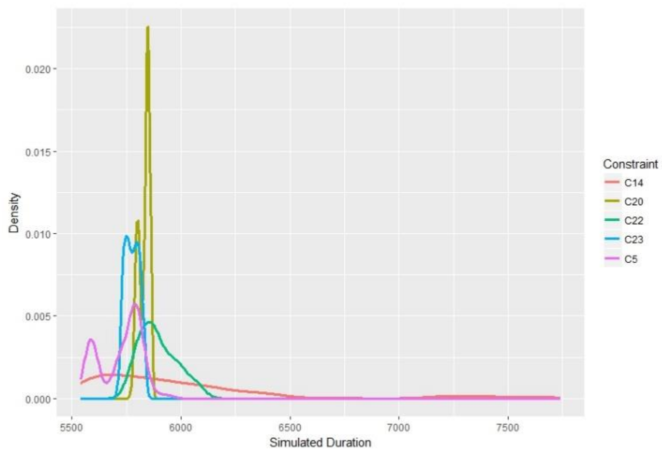


Figure 5.10 Density curves of the simulated duration influenced by critical constraints

Table 5.7 Critical constraints ranking in simulated duration

Critical Constraints	Mean	Median	Min	Max	Standard Deviation
C14	6009.85	5870	5530	8210	491.39
C5	5907.82	5850	5560	6260	227.18
C22	5897.75	5877	5732	6153	97.6
C20	5832.24	5840	5780	5870	23.23
C23	5776.63	5776	5720	5854	30.83

Note: the mean, median, minimum and maximum values are all Total Cycle Time (TCT)

In summary, constraints' impact on schedule delay varies along the timeline of the FDAC. If constraints that cannot be satisfied happen at an earlier stage, they have a more significant impact on schedule performance. To this end, this study provides an in-depth understanding of how the impact of constraints can be systematically analyzed, thus offers valuable insights to the project team to adopt constraints improvement approaches to achieve a reliable workflow.

5.6 Chapter Summary

In order to automatically identify the critical constraints of the on-site FDAC of PHP process and dynamically understanding the interrelationships of them, the constraints modeling service for smart work packaging has been developed within the three sub-services, namely, social network analysis (SNA) sub-service, hybrid SD-DES model sub-service, and the constraints analysis sub-service. The SNA sub-service helps identify the trades associated critical constraints including C5_bad weather conditions, C14_lack of collision-free path planning, C20_lack of visible and audible communication mechanism, C22_lack of optimal buffer layout , and C23_lack of optimal installation sequence. The hybrid SD-DES model sub-service facilitates to dynamically explore the interactional and interdependent relationships of the constraints in the modules of the assembly process, resource availability, operation efficiency, and schedule performance, and encapsulate these dynamic relationships into the DES model. The hybrid SD-DES model has also been validated by the model structure and behavior test to guarantee the confidence and validity of this sub-service.

The constraints analysis sub-service helps dynamics analysis of different critical constraints scenarios and their impacts on the schedule performance.

The main contributions of the proposed constraints modeling service in smart work packaging to the body of knowledge are twofold: (1) enhancing the role of constraints management within dynamic modeling methods (e.g., SNA, SD, DES) and extending its contribution to achieving the sociability of the smart work packaging at the task execution level. Previously, Li et al. (2018a) investigated the risk impact on the schedule performance of prefabrication housing production and developed the hybrid dynamic model to improve the phase schedule which is a certain level of detail schedule covering general activities in PHP. However, there are many deterministic constraints have not been improved and removed in the more detailed schedule (e.g., daily work plan). In this chapter, it is assumed that the best way to improve schedule performance is to enhance workflow reliability at the work package level. (2) extending the process of constraints modeling upon the trades associated work package in a more structural and convenient way. The system dynamics models are established as reusable "task modules" to be encapsulated into the DES model. Thus, this hybrid model can be utilized to other PHP projects due to sufficiently generic nature of this model. This constraints modeling service also provides a comprehensive view of constraints relationships and interconnections, which is beneficial for identifying critical constraints and evaluating the delay influence of each constraint. The influence of delay can also be evaluated at an early stage which leaves enough time for project teams to catch up.

However, the limitations of the developed constraints modeling service require enhancement for creating living digital simulation models by updating themselves from various sources to represent its near real-time modeling. In addition, given the number of interrelationships among the constraints and the variables of the model that influence the schedule performance, collecting the multiple data sources and establishing all dynamic interactions into the model is not workable. Thus, future studies can concentrate on using sensor data which conveys various aspects of the operating condition of smart work packaging to generate the data-driven constraints modeling service.

CHAPTER 6 SWP-enabled Constraint Optimization Service

6.1 Introduction

Building on the previous chapters, the constraints and their interrelationships in the on-site assembly process can be identified, understood, simulated and analyzed in the constraints modeling service of SWP, and the constraint “lack of crane collision-free path planning” has been concluded as the most influential one to the durations of four-day assembly cycle. This mainly owes to the tower crane leads the progress of site activities and makes it the hub of such PHP projects. Therefore, overall performances including productivity and safety are connected to smooth crane operations (Al Hattab et al., 2018).

Path planning has frequently been required in various fields (e.g., air, land, underwater) to provide the safe route from the start to the end point with optimized costs (e.g., time, motion, distance, and energy) (Cai et al., 2018). Additionally, it is recurrently inevitable to replan a path under the dynamic environment. Previous studies have focused on developing various simulations and algorithms to facilitate the path planning process in the field of robotics. These include sampling-based algorithms (e.g., rapidly-exploring random trees (RRT), probabilistic roadmaps (PRM)) (Zucker et al., 2007), node-based optimal algorithms (e.g., Dijkstra, A*, D*) (Soltani et al., 2005), bioinspired algorithms (e.g., genetic algorithm (GA), ant colony optimization (ACO), particle swarm optimization (PSO)) (Zhang et al., 2016; Liu et al., 2016), and mathematic model-based algorithms (e.g., mixed-integer linear programming) (Yilmaz et al., 2008). These techniques have also been widely applied to the crane path planning in the construction field. For example, Sivakumar et al. (2003) adopted A* to automate crane the path-planning task and found that A* search can provide near-optimal paths. However, it was time-consuming. Ali et al. (2005) introduced the GA into the crane path planning to lessen the search time and enhance the quality of solutions. Chang et al. (2012) developed a method for near real-time path planning by using PRM. As the construction sites are complex and dynamic, the variable of time should be included in the path planning, and near all inputs may turn into varying instead of constant. This multiplies the complicatedness of the problem and leads to the demand for more smart algorithms to improve the path re-planning. Concerning the simulations and algorithms to re-plan the path in a dynamic environment, most solutions combine the previous algorithms or improve them based on the real situation. For example, Zhang and Hammad (2012) improved the RRT by using real-time information deriving from sensory feedback to achieve the dynamic path re-planning. Chi et al. (2014) combined the PRM and A* as a balance mechanism between efficiency and solution quality to achieve path re-planning in a dynamic virtual environment. Cai et al. (2018) proposed a multiobjective master-slave parallel genetic algorithm to assist the path planning in narrow and dynamic high-dimensional spaces.

It should be noted that most studies concentrate on developing an algorithm to generate a path to avoid constraints when occurring in the path (Han and Hasan, 2018). However, these paths can only be updated periodically or as a reaction to constraints when there is a collision. Thus, there is an urgent need for an efficient decision mechanism to help determine whether a path should be re-planned or keep unchanged when the constraints dynamically change in a construction environment. To the best of the authors' knowledge, previous methods may not fully demonstrate the nature of a dynamic construction environment, as constraints vary over time, and thus the importance of moves will change based on the situation of the current path. More specifically, if the crane path is re-planned when it collides with constraints or over a specific time interval, the best time for re-planning may be missed.

Thus, this study aims to develop a path re-planning optimization service through smart work packaging (SWP) to assist the crane operator in deciding the necessity of path re-planning. SWP can be a piece of software that is able to assist the operator in accomplishing the lift tasks and is also made smart with augmented capacities of visualizing, tracking, sensing, processing, networking, and reasoning (Li et al., 2019b). For example, crane operator's SWP can numerically assess the impact of workers in crane's working area by computing the distance from the workers' smart work packages and then acquire path values to determine the necessity of path replanning according to the changes in path values in a dynamic environment. The specific objectives of this chapter are presented below: (1) to develop a constraints optimization service for crane path re-planning when constraints occur over time; (2) to classify a set of constraints (see Table 6.1) that can disturb the crane path and instantiate some of them into the physical construction site, instead of focus on all dynamic constraints in construction site; (3) to enable decision making for smart path re-planning by using cost values (distance) from a path to a specific constraint; (4) to simulate the decision making results (e.g., shorter path exists, or no need re-planning in current path) in the building information modelling (BIM) environment.

6.2 Constraints Prioritization

The construction industry has widely recognized the significance of performing detailed control and planning with constraint management to issue executable work plans. For example, the total constraints management process including constraint modeling, optimization, and monitoring have been proposed in previous studies (Wang et al. 2016a). The relationships between constraint modeling, optimization and monitoring can be summarized in Figure 4.2. The constraint modeling has been conducted to explore the interrelationships of constraints at the level of the on-site assembly process of PHP, and “lack of crane collision-free path planning” is identified as the critical constraint. Thus, the constraint optimization aims to optimize the task execution of crane path planning by improving the constraints in its operation process. Through the literature review of previous studies in crane path planning, the dynamic constraints of crane path planning can be summarized from aspects of internal and external in Table 6.1. In addition, the priority of constraints has also been evaluated from the interviews of crane operators the HK Institute of Construction crane training center.

Table 6.1 A list of dynamic constraints related to path planning task

Concern	Description	Priority	Constraint
Collision	On-site moving obstacles directly disturbing loads path with a random frequency (e.g., other moving cranes) can be assumed as the critical dynamic constraints.	Critical	External
Worker/vehicles	Site crews/vehicles pass through the crane's working area can be assumed as back and forth movements of constraints with the random speed and frequency	Non-critical & non-ignorable	External
Weather	Adverse rain/wind during lifting can be assumed as back and forth movements of constraints that directly pass through the load's path with the high speed and frequency	Critical	External
Environment	Normal wind/rain during lifting can be assumed as one-way movements of constraints that pass through the load's path with the normal speed and frequency	Non-critical & ignorable	External
Operator Fatigue	Mis-operations under extreme fatigue can be assumed as dynamic constraints to disturb the load's path with the random frequency	Critical	Internal

Visibility	Blind spots can be assumed as dynamic constraints to disturb the load's path with a random frequency	Critical	Internal
Crane loading balance	The loading capacity can be assumed as dynamic constraints to disturb the load's path with a random frequency	Critical	Internal

6.3 SWP-enabled Constraints Optimization Service

Proposed in previous chapters, smart work packaging (SWP) is an innovative approach for operations or task executions that made smart with the augmented capacities of visualizing, tracking, sensing, processing, networking, and reasoning so that they can be executed autonomously, adapt to changes in their physical context, and interact with surroundings to enable more resilient process. Instead of introducing an entirely novel system to PHP sites, an SWP-enabled operation system relies on smart construction objects (SCOs) (e.g., prefabricated products and human resources equipped with RFID tags) and internet-of-things (IoT) enabled BIM platform, which already involved in the on-site assembly process of PHP (Niu et al., 2016; Li et al., 2018b).Without compromising existing informational objects and platform, these SWPs are augmented with smart and interconnected properties to assist operations. For example, a smart crane path planner may be able to make decisions that whether need path replanning by retrieving/computing the location/distance information of the dynamic constraints (e.g., moving obstacles) from informational objects and platform. The three core characteristics of SWP, adaptivity, sociability, and autonomy refer to SWP's abilities in responses to changes, information exchange, and action-taking, respectively. Each core characteristic is further classified into sub-properties with different level of functions (exemplified by a tri-axial graph and interpretative table in Figure 6.1), the exploitation of which allows the potentials of SWP for task executions to be achieved. The decision-making mechanism needed in the path re-planning for this chapter is also the trial to activate the potential of resilience in SWP's adaptivity.

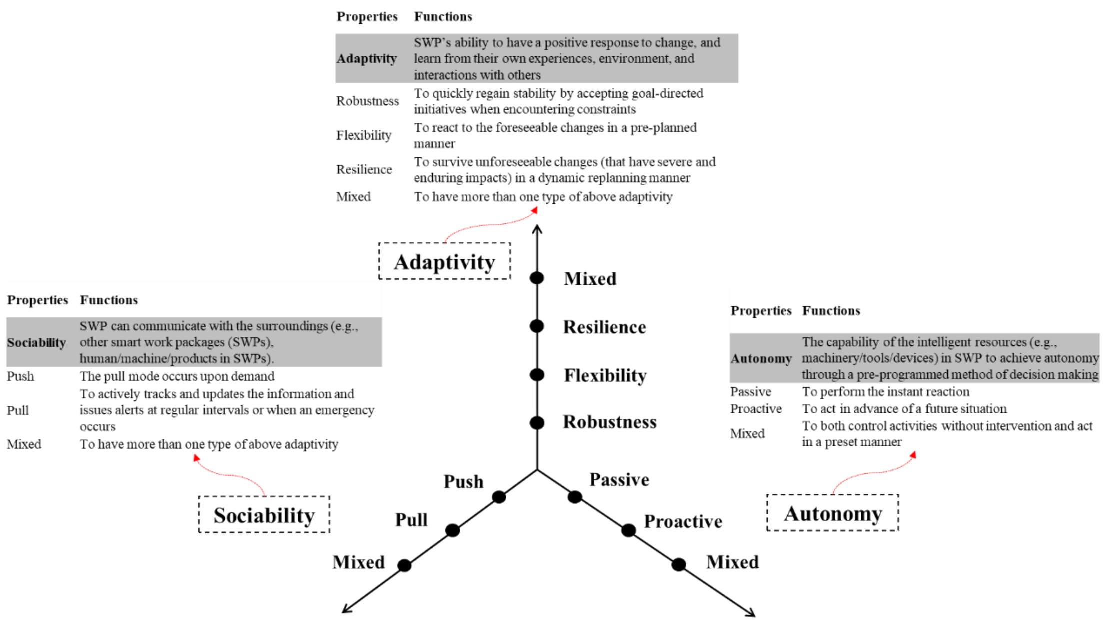


Figure 6.1 The core characteristics of SWP

6.3.1 System Architecture

In this section, the SWP-enabled constraints optimization service is proposed. The architecture of this service is shown in Figure 6.2. This service is supported by the smart construction objects (SCOs) and smart BIM platform. The SCOs are built by equipping the site dynamic objects (potential external constraints) such as cranes, crews, vehicles, and prefabricated products with the various sensing and tracking technologies (e.g., RFID, sensors for monitoring wind speed and rain load, WiFi, camera, and laser) for achieving smartness in data generation and collection. This process can both enrich and exchange the information with smart BIM platform. Then, after the interactions between the crews and virtual BIM platform/physical machine, the characteristics (e.g., adaptivity, sociability, autonomy) of smart work packaging (SWP) can be activated to execute the tasks through different services. A generic workflow for SWP-enabled constraints optimization service can be outlined in Figure 6.3. Firstly, the As-is construction environment and existing constraints can be detected and built into the BIM environment in crane operator's SWP. This can activate the autonomy properties to facilitate the SWP to autonomously generate the initial path planning and visualize it for crane operator. Then, SWP can activate the sociability properties by communicating with SCOs to detect the dynamic constraints and prioritize their importance. These dynamic constraints including other moving cranes with overlapped operation area (critical), moving crews/vehicles in the crane operation area (non-critical & non-ignorable), normal wind/rain (non-critical & ignorable). The location information of these dynamic constraints is collected to calculate the distances between constraints and loads. These distances can be transformed to update the cost values of the original path. Finally, the adaptivity properties can be activated to decide whether conduct path re-planning or not. To accomplish the initial path planning, constraints classification, and decision on path re-planning in this workflow, several assumptions, and problem formulations are conducted in the following sections.

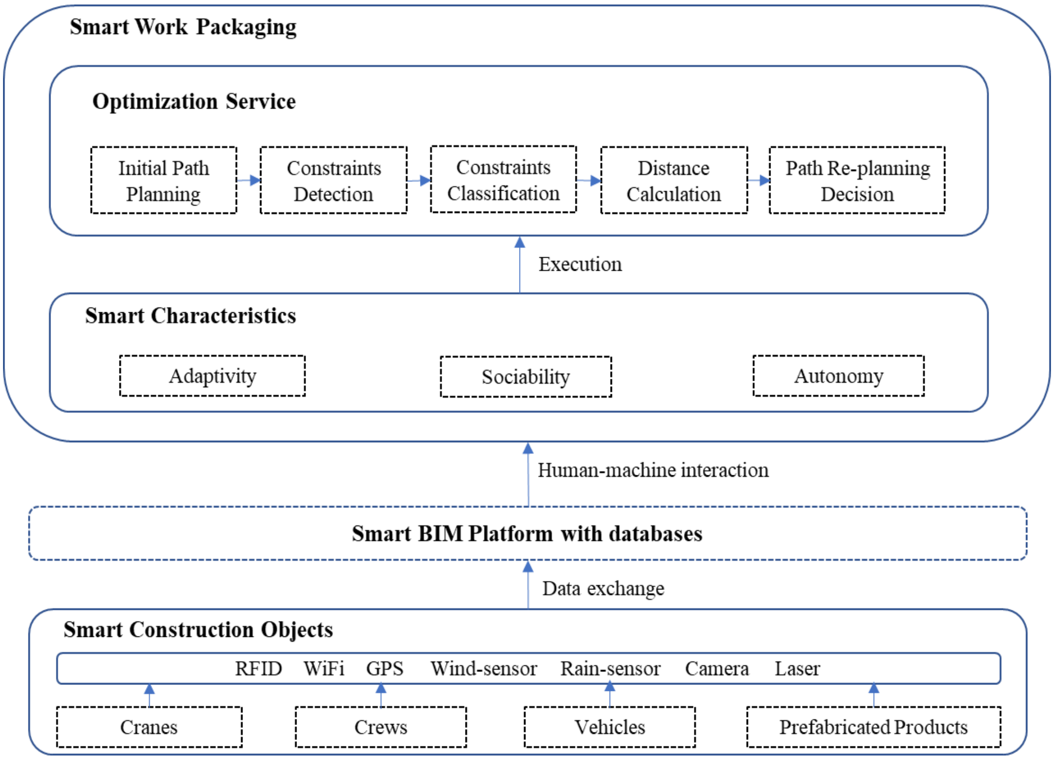


Figure 6.2 The architecture of SWP-enabled constraints optimization service

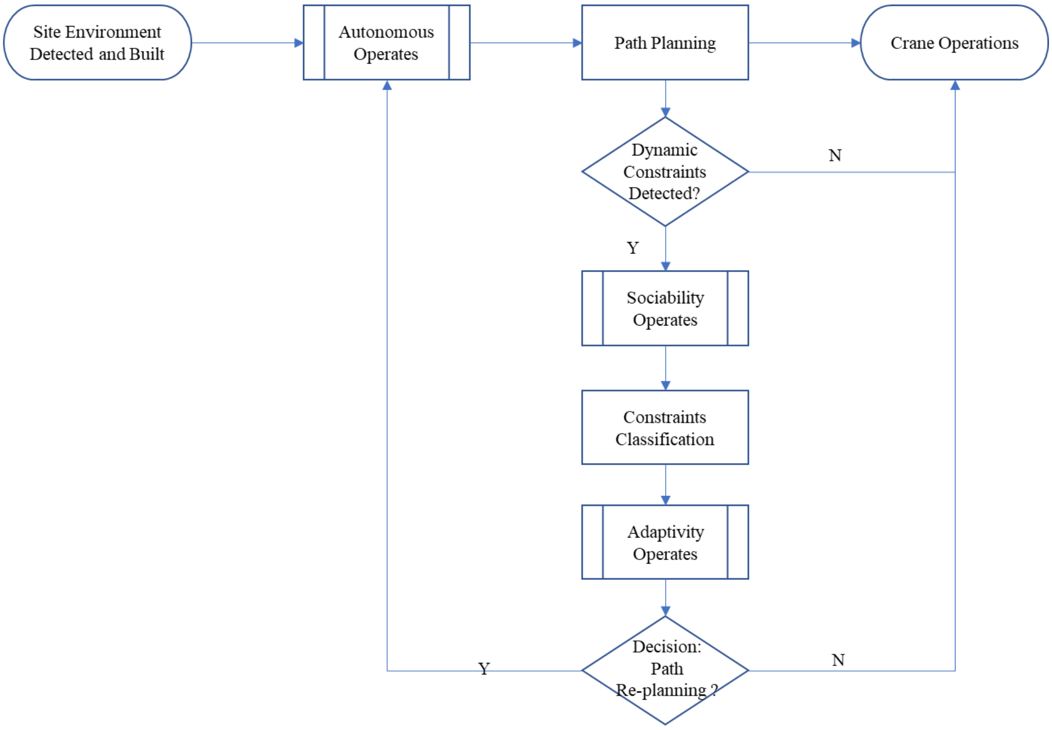


Figure 6.3 A generic workflow for SWP-enabled constraints optimization service

6.3.2 Assumptions

Inspired by the methods in Han and Hasan (2018), and Chi et al. (2014), a resilient decision-making approach in SWP of crane operator can be developed for crane path re-planning in a dynamic construction environment through using path cost values that diffused from a specific group of constraints. Accordingly, several assumptions should be proposed in the following:

(1) The roadmap graph in Configuration space (C-space) is displayed on a three-dimensional grid that composed by the equidistant cubes. The path planning method proposed in this study is built on the Probabilistic Roadmap (PRM), which equidistant geometrical points are sampled and connected (including the start and goal point) in the C-space. The process of PRM can be usually shown in Figure 3.4. The graph structure G in C-space can be formulated as:

$$\mathrm{G} = (v, e) \tag{6.1}$$

Where v is the vertex that represents each geometrical point, and e is the edge that connects the vertexes. Because the roadmap graph is assumed to be a three-dimensional equidistant cubic grid, the connections between vertexes are the sides or diagonals of cubes. In order to identify loads of a tower crane in the sampled grid, the C-Space transformation is adopted (Chi et al., 2014). As shown in Figure 6.4 (Chi et al. 2014), the location of the loads can be transformed from Cartesian space (X, Y, Z) to the 3-DOF tower crane's configuration (θ, γ, l). Where θ denotes the rotation angle of the crane turntable, γ stands for the rotation radius of the crane jib along with the distance between the current trolley and the mast, and l means its current hoisting distance between jib and hook. All the motions of the crane can be transformed into a point in the C-space. However, crane operators usually can only maneuver 2-DOFs of a tower crane together (Chi et al., 2014). For example, although rotating the jib while hoisting the loads can reduce the operation time, they are limited by the perception capacity of operators. This situation is not considered by the PRM, which may allow the generated path by PRM to be infeasible in practice. Even though the planned path is feasible to operate, the crane operator needs to be very cautious on extra DOFs that may exceed the operator's perception capacity of human manipulation (e.g., control sticks) and lead to risks in safety and schedule. To deal with this issue, the cubic grid sampling method is proposed in C-space. Take Figure 6.5 as an example to illustrate the rationale, sampling points are linked horizontally for a single DOF configuration, and vertex can be connected diagonally for a 2-DOF configuration. The sides of the cubic can only be connected between neighboring points.

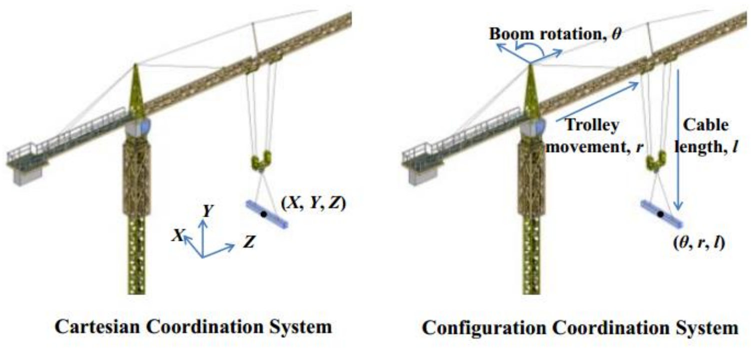


Figure 6.4 The transformation from the Cartesian space to configuration space

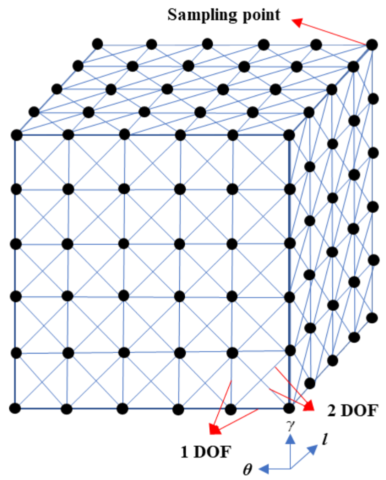


Figure 6.5 Cubic grid with equidistant sampling points in the C-space

(2) The dynamic constraints occur in a known construction environment. It means that the points of start and end are known and pre-determined, and dynamic constraints can move in any direction at any speed. Each constraint in Cartesian space transforms to the various polygons overlapped on the grid vertexes in the C-space (See Fig.6.5), which is C-obstacle. The C-obstacle denotes a cluster of motion (θ, γ, l) of tower crane must be avoided.

(3) A load of crane moves one side or one diagonal of the square for each time interval. The notation for this study has been listed in Table 6.2. The runtime is represented as T, which also denotes the movement times due to the assumption that one move is generated during each time interval. A path P_T can be defined according to T, and $v^{t,T}$ can be denoted as a set of grid vertexes near the path P_T that from the current vertex to the goal vertex. Variable t represents grid vertex order in P_T as t ={1, 2, …, N_T} where N_T signifies the count of grid vertexes from the current vertex to the goal.

Table 6.2 Notation

Code	Definition
V	List of vertexes sampled in the roadmap graph
v	Grid vertex, $v \in V$
T	Runtime/ movements times on the path
P_T	A path at T represented by the vertexes from the current to the goal
$v^{t,T}$	t th vertex in P_T
C	List of constraints
c_{i}	i th constraint $i \in \lvert C \rvert$
V_f	List of feasible vertexes in the roadmap graph
v_f	Feasible grid vertex, $v_f \in V_f$
v_{start}	The start vertex of the loads, $V_{start} \in V_f$
v_{goal}	The goal vertex of the loads, $V_{goal} \in V_f$
l_s	The length of each square side
l_d	The length of each square diagonal

After the establishment of the above assumptions, the constraint-free path re-planning in this study can become an optimization problem which contains two stages: initial path planning and path re-planning decision-making.

6.3.3 Formulation of initial path planning

The initial path planning is to detect the optimal edge combinations from the start vertex to the goal vertex based on the condition of initial constraints. The distance of the cubic edge (the connection between two vertexes, e.g., side and diagonal) indicates the unit of cost value, and the optimal path is to search for the route with minimum cost values. Compared with Dijkstra's algorithm that is time-consuming to assess all edges of the grid to find an optimal solution, A* search algorithm with a partial heuristic function can help balance efficiency and performance for evaluating the quality of current solutions and removing impossible paths during search processes (Chi et al., 2014). As shown in Equation (6.2):

$$f(T) = \mathrm{g}(T) + h(t) \qquad (6.2)$$

Where g(T) denotes the function computing the precise cost values from the starting vertex to the current vertex and $h(t)$ stands for a heuristic estimate function to estimate the predicted cost values from the current vertex to the goal. In addition, detection of initial constraints is an essential part of initial path planning, and it can guarantee each part of the path does not collide with neighboring constraints in the C-space. The paths obstructed by constraints may provide inoperable guidance for operators. The collisions can be identified by the ray tracing method, which check whether the two vertexes of a side can "see" each other or not (Chi et al., 2014).

6.3.4 Formulation of path re-planning

The path re-planning decision-making process starts with the categorization of constraints according to their priorities and positions, rather than treating all constraints uniformly. Through the interviews of six senior crane operators and four crane coaches in the crane training center of HK Institute of Construction, the classification of dynamic constraints in crane path planning is proposed from internal and external aspects, as can be seen in Table 6.3. The movements of constraints can lead to changes in the distance between the planned path and specific constraints. These changes are recorded by the cost values of the path, which is computed by the diffusion of specific constraints. Decisions of path re-planning are then made according to the dynamic differences in cost values of the path.

(1) Formulation of constraints and cost value

All constraints can be classified based on the priority listed in Table 6.1 to form the categorization in Table 6.3 To define each sub-class of constraints accurately, for $c_i \in C$, let the shortest path at T be $P_T^{-c_i}$ (when c_i does not exist) or P_T^{-C} (when C do not exist). Additionally, allow a function $Z(\bullet)$ return one if there are more than one intersection between a constraint and a path, otherwise zero.

Table 6.3 Constraint classification and definition

No.	Constraints	Definition
1	Critical Constraints (CC)	Def1: $CC = \{c_i \mid Z(c_i,\ P_T^{-C}) = 1 \text{ and } Z(c_i, P_T^{-c_i}) = 1, \forall\ c_i \in C\}$
2	Non-Critical Constraints (NCC)	Def2: $NCC = C - CC$
2.1	NCC-Not-ignorable (NCC^{NI})	Def3: $NCC^{NI} = \{c_i \mid Z(c_i, P_T^{-c_i}) = 1, \forall\ c_i \in NCC\}$
2.2	NCC-Ignorable (NCC^{I})	Def4: $NCC^{I} = \{c_i \mid Z(c_i, P_T^{-c_i}) = 0, \forall\ c_i \in NCC\}$

Critical constraints (CC) is a group of constraints that collides with both $P_T^{-c_i}$ and P_T^{-C} as in Definition 1. Definition 2 defines that non-critical constraints (NCC) is a group of constraints by deducting CC from C, which signifies that $CC \cup NCC = C$ and $CC \cap NCC = \emptyset$. NCC can be classified into NCC^{NI} and NCC^{I} according to whether the constraint is ignorable or not when conducting the re-planning. For example, the moving site workers or trucks can be described as NCC^{NI} since they are the non-ignorable safety concerns during crane operation. While normal wind or rain can be described as NCC^{I} because it rarely influences crane lift tasks. NCC^{NI} is defined as a group of constraints that collide with $P_T^{-c_i}$, while NCC^{I} can be defined as a group of constraints that do not collide with $P_T^{-c_i}$. It indicates that $NCC^{NI} \cup NCC^{I} = NCC$ and $NCC^{NI} \cap NCC^{I} = \emptyset$.

After the definition of different constraints, the numerical influence of CC and NCC^{NI} on a path can be computed by considering them as objects that diffuse influence (See Figure 6.6). And all feasible grid vertexes can obtain the influence values from CC and NCC^{NI}. The larger influence values (smaller cost values) are attached to vertexes near to CC or NCC^{NI}, while smaller influence values (larger cost values) are attached to vertexes distant from CC or NCC^{NI}. This influence diffusion process assumes that NCC^{I} does not affect the path. These values are calculated by the distance between the vertex and constraints in the grid. Also, the grid vertexes on constraints can be treated as infeasible vertexes which the influence values show with "Inf."

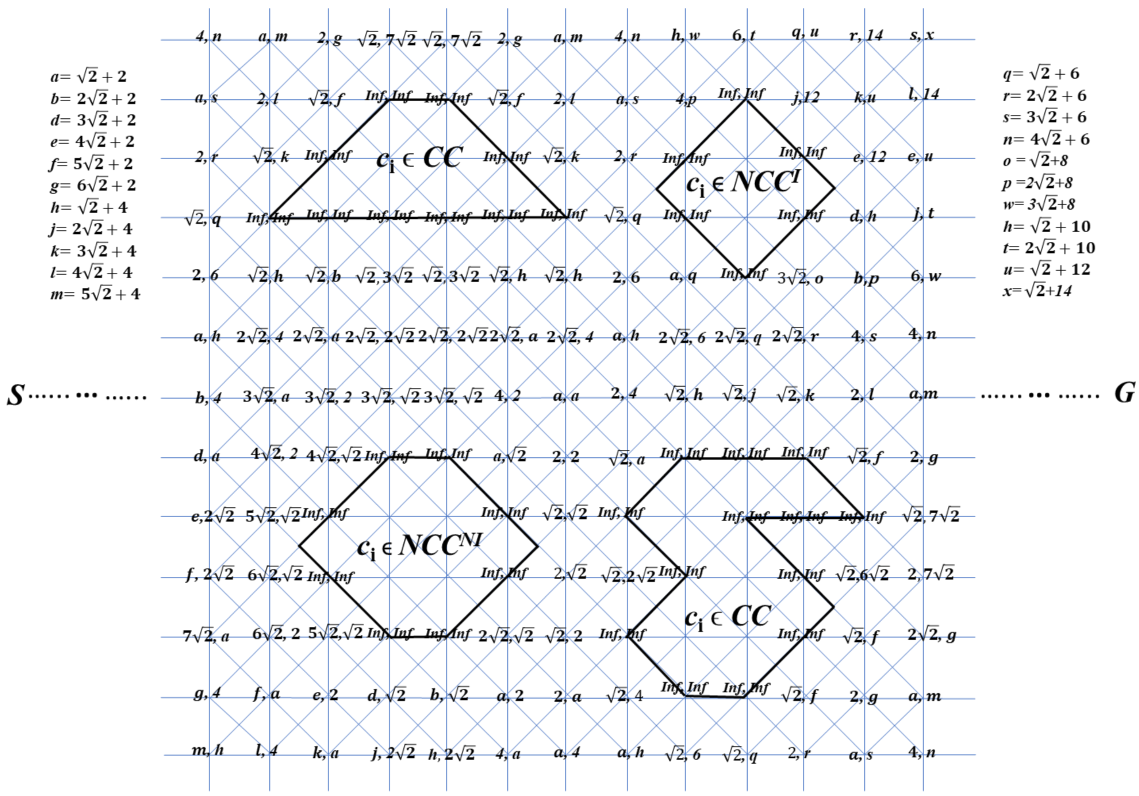


Figure 6.6 Example of cost diffusion presented in the 2D square grid map

To define the detail process of cost value diffusion (the below context will use cost value instead of influence value for consistency) from *CC* and NCC^{NI}, let the cost values from *CC* and NCC^{NI} attached to vertex *v* be represented as $U_{CC}(v)$ and $U_{NCC^{NI}}(v)$, respectively, and let V_{CC} and $V_{NCC^{NI}}$ be lists of vertexes that already acquire cost values diffused from *CC* and NCC^{NI}, respectively. As the process of cost value diffusion is the same for *CC* and NCC^{NI}, Eqs. (6.3)-(6.6) take *CC* as the example to formulate its cost value diffusion process. For all other vertexes not yet attached cost values from *CC* or NCC^{NI}, a set of vertexes adjacent to v_f are $A(v)$, which can be defined in Eq.(6.3)

$$A(v) = \left\{v' \middle| \left\|v' - v_f\right\| \leq l, \forall v' \in \left\{V_f \backslash V_{CC}\right\}\right\} \qquad (6.3)$$

Where *l* is the edge length of each square (side or diagonal). Diffusion is implemented by attaching a cost value increased by $\sqrt{2}$ or 2 from the current value on adjacent vertexes on the sides or diagonals of the square. Then, V_{CC} and V_{NCC}^{NI} are updated. As A (v_f) obtains cost values, and A (v_f) turns into v_f for the next diffusion. Eqs. (6.4)-(6.6) are repeated until all v_f acquire cost values, which means diffusion completed and then V_{CC} or V_{NCC}^{NI} becomes the same as V_f.

$$U_{CC}\left(A(v_f)\right) = U_{CC}(v_f) + \sqrt{2} \quad \text{or} \quad U_{CC}\left(A(v_f)\right) = U_{CC}(v_f) + 2 \qquad (6.4)$$

$$V_{CC} = V_{CC} \cup A(v_f) \qquad (6.5)$$

$$v_f \leftarrow A(v_f) \qquad (6.6)$$

(2) Formulation of dynamic scenarios

Figure 6.6 demonstrates the cost value diffusion process on the roadmap with two, one, and one constraint in *CC*, NCC^{NI}, and NCC^{I}, respectively. The cost values determined by *CC* and NCC^{NI} can be represented with the form ($U_{CC}(v)$,$U_{NCC}^{NI}(v)$). There is no diffusion around NCC^{I} because it is not an object with the capacity of diffusing influence. The decision to re-plan a path depends on the continuation of alterations in the cost values of the path, and the cost values are calculated by the diffusion process from *CC* and NCC^{NI}. Namely, when constraints move, the changes in the path cost values caused by *CC* and NCC^{NI} are observed through moving constraints, and a decision on re-planning the path is made according to this observation. To clarify the changes in cost values in various situations, six scenarios are proposed in Table 6.4.

Table 6.4 Dynamic constraints scenarios

Constraints	Collision with P_T	No collision with P_T
Movements of *CC*	scenario 1	scenario 2

Movements of NCC^{NI}	scenario 3	scenario 4
Movements of NCC^{I}	scenario 5	scenario 6

The cost values attached to P_T from CC and NCC^{NI} can be denoted as $U_{CC}(P_T)$ and $U_{NCC}{}^{NI}(P_T)$, respectively. In these six scenarios, l is believed to be adequately small to assess the need for path replanning from the changes in cost values caused by the dynamic constraints. Actually, If a collision between constraints (CC or NCC^{NI})and P_T, it is apparent that the current solution (P_T) is an infeasible path. Therefore, $U_{CC}(P_T)$ and $U_{NCC}{}^{NI}(P_T)$ display "Inf" in overlaying vertexes. The decision is made to re-plan due to a change in cost values of the path. Conversely, if there is no-collision, changes in cost values of path rely on the situations that group of constraints moved. Thus a decision can be made to replan a path when the current path can be improved in cost values, which will be illustrated in the following six scenarios.

In scenario 1 and 2, if the movement distance of constraints in CC is $d \geq l_s$, $U_{CC}(P_T)$ updates, and P_T is no longer the optimal path. Given N as the length between current and goal vertexes, N is the minimum value of the path length, and CC can make the new path to be longer than N. As a consequence, the new path is generated by surrounding the constraints in CC. The path collides with CC represents an infeasible solution, and $U_{CC}(P_T)$ reflects this infeasibility with the value of "Inf." Since the changes have shown in cost values of the path, a decision should be made to re-plan the path. Even though there is no collision by the movement of CC, a change to $U_{CC}(P_T)$ occurs that indicates the necessity of path replanning due to the improvement of P_T.

Thus, scenario 1 and 2 signify that the movement of *CC* leads to the path re-planning, and the current path surrounding *CC* is neither the shortest path nor a feasible option.

In scenarios *3*, U_{NCC}^{NI} (P_T), similar to U_{CC} (P_T), changes with the movement of constraints in NCC^{NI} : $d' \geq l_s$ regardless of whether a collision occurs and P_T will not be the shortest path. In scenario 4, regarding the relative positions of constraints and P_T, each constraint c_i in NCC^{NI} can either encircle or be far away from P_T. P_T is far away from c_i if a path that detours around c_i is assessed as a shorter path; otherwise, it encircles c_i. Thus, there are two situations in scenarios *4*: (i) When P_T encircles c_i in NCC^{NI} and c_i moves, it is the same as scenarios *1* and *2* that c_i makes the path longer than *N*. Thus, the result is the same as scenarios 1 and 2 ; (ii) When P_T is far away from c_i and c_i moves, although there are changes in U_{NCC}^{NI} (P_T), it cannot be concluded that P_T is not the optimal one. It highly relies on the size and shape of the constraint and the direction of movement.

In scenario *5* and *6*, Regardless of whether or not the collision occurs between P_T and c_i after NCC^I moves, U_{NCC}^{NI} (P_T) and U_{CC} (P_T) remain unchanged, since NCC^I is not an object for cost diffusion. And the colliding parts of U_{NCC}^{NI} (P_T) and U_{CC} (P_T) will not become "Inf" when a collision occurs. Therefore, P_T is still the optimal solution. NCC^I is defined as a group of constraints that do not disturb the planned path.

Finally, the algorithm of decision-making for path re-planning in a dynamic environment can be illustrated summarized in Table 6.5

Table 6.5 The algorithm for decision-making on path re-planning

---

Algorithm SWP_PathPlanner(): Update cost values conforming to the movements of dynamic constraints and re-generate the path if it is necessary

---

V: List of vertexes sampled in the roadmap graph

C: The list of constraints

V_C : List of vertexes overlapped with constraints

V_f : List of feasible vertexes in the roadmap graph

U: Dynamic cost values matrix ($U_{CC}(v_f)$, $U_{NCC}^{NI}(v_f)$) of each feasible vertex in the roadmap graph

P_0: The initially suggested path

v_{start}: The start vertex of the loads, $v_{start} \in V_f$

v_{goal}: The goal vertex of the loads, $v_{goal} \in V_f$

U_{P_0}: Initial cost values matrix ($U_{CC}(P_0)$, $U_{NCC}^{NI}(P_0)$) of each vertex in the initial path

M: The time of the last iteration when arriving at the goal

U_{P_T}: Dynamic cost values matrix ($U_{CC}(P_T)$, $U_{NCC}^{NI}(P_T)$) of each vertex in the path

---

 # Initial Path Planning

```
// Sample the set of vertexes in C-space under the rule of equidistant cube
    V← CubicGridSampling()
    // Detect the set of vertexes overlapped with the constraints C
    V_C← Overlap(V,C)
```

// Subtract the V_C from V to get the sets of feasible vertexes

$V_f \leftarrow$ Subtract(V,V_C)

// Get the cost values matrix of each feasible vertex under initial constraints situation

U$\leftarrow$ CostGenerator(V_f)

// Generate the initial path by A* search algorithm

$P_0 \leftarrow$ AStarShortestPath (v_{start} ,v_{goal} ,U)

// Derive the cost values of the vertexes on the initial path

$U_{P_0} \leftarrow$ Derive(U, P_0)

RETURN P_0 , U_{P_0}

 # Dynamic Path Replanning

// For each iteration T, from 1 to M

FOR T=1, T<M, T++

// Get the cost values matrix of each feasible vertex under each iteration

$U_T \leftarrow$ CostGenerator(V_f)

// Derive the cost values of the vertexes on the previous path and current path

$U_{P_{T-1}} \leftarrow$ Derive(U_{T-1}, P_{T-1})

$U_{P_T} \leftarrow$ Derive(U_T, P_T)

// If the cost values of vertexes on the current path are equal to the previous path (e.g.,initial path)

IF PathCheck ($U_{P_{T-1}}$, U_{P_T}) = TRUE

// P_T remains the path for the next iteration P_{T+1}

$P_{T+1} \leftarrow P_T$

ELSE

12: // If there are any differences between above cost values of two path, a new path is generated. Here P_T is the new path contains the vertex from the start to the goal.

13: $P_T \leftarrow$ AStarShortestPath (v_{start} ,v_{goal} ,U)

14: **RETURN** P_T

6.4 Simulation Verification

6.4.1 Experiment Design

To test the performance of the proposed path re-planning approach, a simulation-based constraints optimization service was developed and demonstrated in the BIM environment. This service is developed on the cross-platform game engine named Unity 3D, which offers the scripting application programming interface (API) in C# with inbuilt physics library to simulate the crane operation tasks, on-site assembly environment, and dynamic constraints. The implemented algorithms include modified PRM method (sample equidistant triangles), A*, and *SWP_PathPlanner*.

To normalize the path value, the distance transform method is adopted and the fitness value of a path at T, $F(P_T)$, is computed as the distance between the immediate start vertex $v^{1,T}$ and the goal $v^{N_T,T}$ as shown in Eq.(6.3). Furthermore, the distance can also be calculated as the product of the edge length of each cube l (l_s or l_d) and N_T (the number of edges in P_T).

$$F(P_T) = \sum_{t=1}^{N_T-1} \| v^{t,T} - v^{t+1,T} \| = l \cdot N_T \tag{6.3}$$

This study designs a virtual on-site assembly environment in the Unity 3D (See Figure 6.7). A 2-DOF tower crane, 13 dynamic constraints including tower crane operating near the targeted one (A), workers walking around the site (B1, B2, B3, B4), workers operating forklift (C), workers working at fixed position (D1,D2,D3), Dump trucks (E1,E2,E3), normal wind/rain (F), and an under-constructed prefabricated building (BIM model) are set up. The movement of the tower crane is guided by the suggested path, and the six scenarios with critical constraints (A), non-critical & non-ignorable constraints (B,C,D,E), and non-critical & ignorable constraints (F) defined in Section 6.3.4 are simulated in the BIM environment. The size of this roadmap graph is [360°, 50 cm, 50 cm] under the configuration coordination system, and the edge lengths of 1-DOF and 2-DOF are set to $\sqrt{2}$ cm and 2 cm, which leads to a total of 900,000 grid vertexes in the roadmap graph. The start ((23.4, 2.4, 1.3), Cartesian coordinates) and the goal ((-6.0, 20.8, 2.1), Cartesian coordinates) are the real lifting and placing point in the BIM environment. Their Configuration coordinates of the start and the goal are (4, 27, 24) and (161, 9, 17).

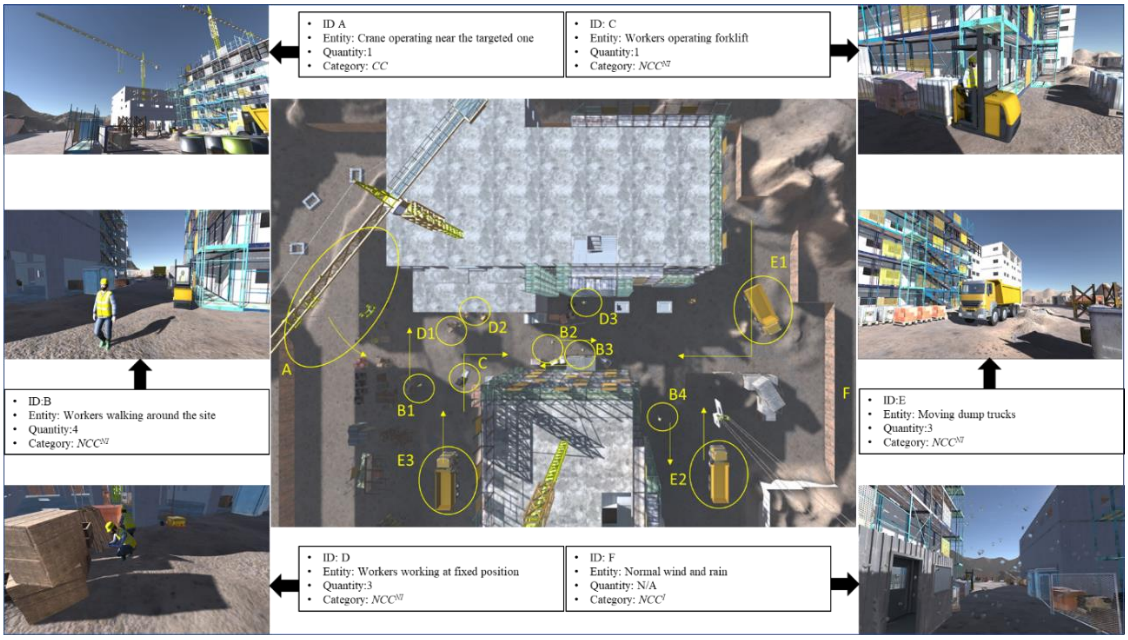


Figure 6.7 Virtual on-site assembly environment with 11 dynamic constraints

Each constraint moves with random distance and direction in a specific iteration except that the movement distance should be a multiple of *l*. Additionally, to meet the real situation, the shape of constraints represented in the 3D roadmap graph without any restrictions rather than must overlap with grid vertexes showed in the methodology part.

6.4.2 Simulation Results

Figure 6.8 demonstrates the original environment, dynamic environment, and the environment with the decision for each scenario in the roadmap graph of BIM environment, where the probability of movement for each constraint is random. (1) In the set of figures for the original environment, the blue dashed line is the shortest path without constraint (P_T^{-C}) and the green dashed line represents the shortest path after the cost value diffusion process (U_{CC} (P_T) and U_{NCC}^{NI} (P_T)). These cost values (reserved integer) are summarized in the form of (U_{CC} (v),U_{NCC}^{NI} (v)) to a list (original environment). Constraints in CC and NCC^{NI} are attached with the matching entity name and ID in the BIM environment. (2) In the set of figures for the dynamic environment, dynamic and static constraints are are also attached with the matching entity name and ID in the BIM environment. Dynamic U_{CC} (P_T) and dynamic U_{NCC}^{NI} (P_T) are updated on the yellow dashed line. These updated cost values are also summarized in the form of (U_{CC} (v),U_{NCC}^{NI} (v)) to another list (dynamic environment) and the changed values are marked in bold for both lists in the original and dynamic environment. (3) In the set of figures for the environment with the decision, the comparisions of path values are conducted and the path is re-planned if any difference occurs. The new path is demonstrated by a red dashed line.

In general, the results represent that the crane lifting task completed from the start to the goal with 66 movements (T). The total number of the dynamic constraints for all iterations was 13. In each T, the minimum, maximum, and an average number of dynamic constraints were 1, 5, 11. Path re-planning conducted 4 times in the 66 movements (*T=9,11,22,34*) signifying that path re-planning was not essential for each *T*, even more than 85% dynamic constraints existed at each *T (e.g., T=10, scenario 4-1)*. The detailed results corresponding to the six scenarios are discussed in the following.

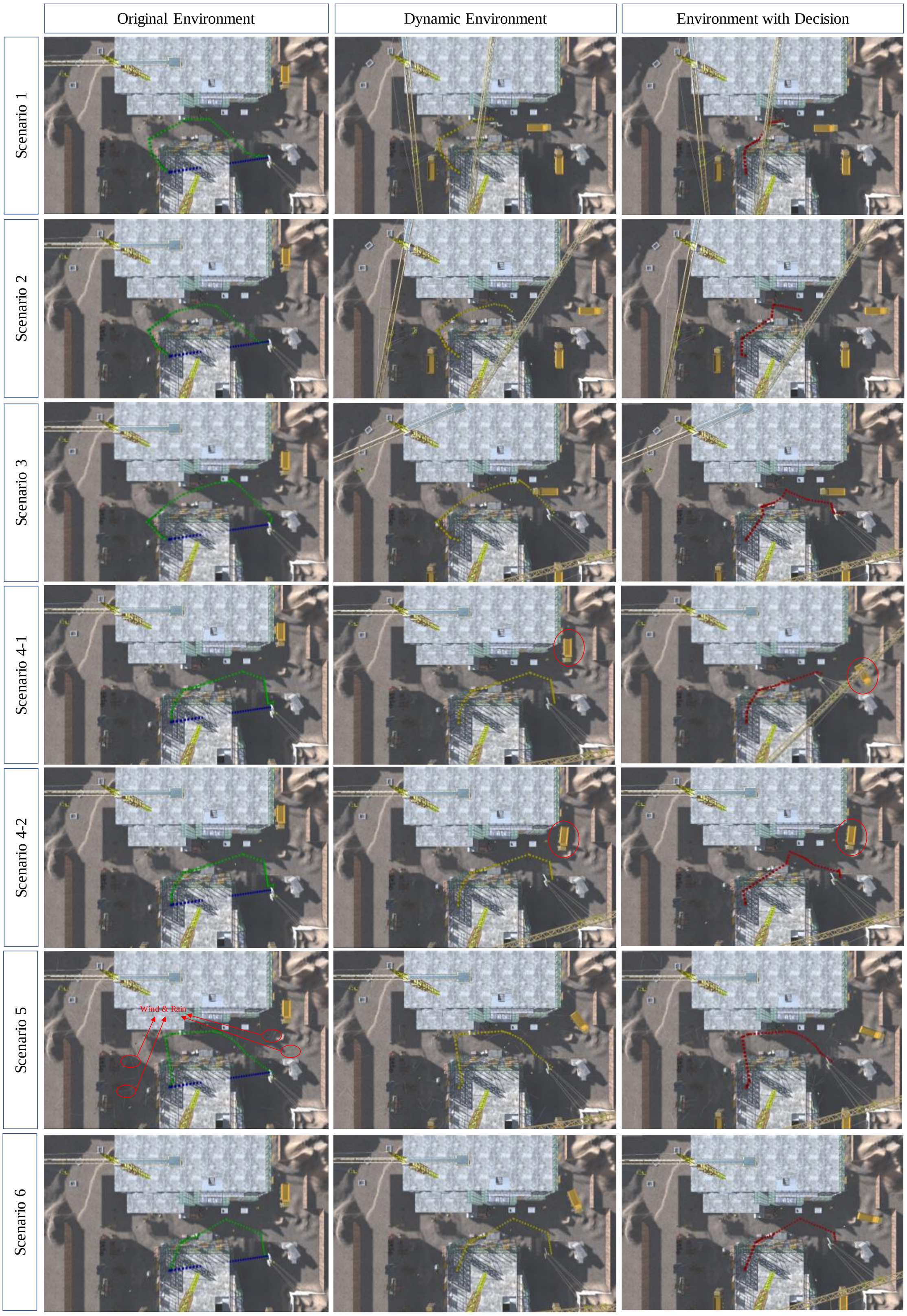


Figure 6.8 Simulation results under six scenarios

(1) In *T=34,* scenario 1 can be validated by the evidence that another crane A in *CC* collided with the path resulting in the path values changed and path re-planning.

Contrarily, scenario 2 is simulated in *T=23*. It shows that another crane A in CC became more distant from the path, and there was no collision, but it also led to path values changed and re-planning.

(2) In *T=9,* scenario 3 occurred that moving crews and vehicles (B,C,D,E) in NCC^{NI} collided with the path and the result is the same as the scenario 1. However, the scenario 4 happened in *T=12* (path value changed and path re-planned, scenario 4-2) and *T=8* (path value changed and keep the original path, scenario 4-1) was totally different because it depends on whether the moving crews and vehicles surrounded or were distant from the path.

(3) In *T=6* and *T=5,* scenario 5 and 6 are assessed to show that there was no path re-planning regardless of the normal wind and rain in NCC^{I} collided or did not collide with the path.

6.4.3 Simulation Validation

This validation is conducted to compare the previous sample-based crane path re-planning method (Chi et al., 2014) with the proposed solution in this study. The reasons for choosing the sample-based path re-planning method as the comparable group can be explained from two aspects: (1) the proposed decision-making mechanism is an improvement on the PRM, which is a representative sample-based path planning method; (2) the average path re-planning duration after several tests of the sample-based method has shown the indifference with the increased dynamic constraints (See Fig.6.9), which indicates the re-planning speed can be consistent to avoid affecting re-planning efficiency. As *SWP_PathPlanner* focuses on reducing unnecessary path re-planning compared with other dynamic re-planning mechanisms such as re-planning when collided (*Collision_Planner*) and periodically re-planning in every *T* (*Periodical_Planner*), the metrics such as number of re-planned paths (NRP) and number of unnecessary re-planned paths (NURP) are used to evaluate its efficiency. The mechanisms of *Collision_Planner* and *Periodical_Planner* are deployed in the traditional PRM method (Chi et al., 2014). As shown in Fig. 6.10, and Fig. 6.11, after hundreds of times of simulation, the average NRP and NURP are both increasing with the increased dynamic constraints for the traditional method. However, the NURP is zero for the proposed solution.

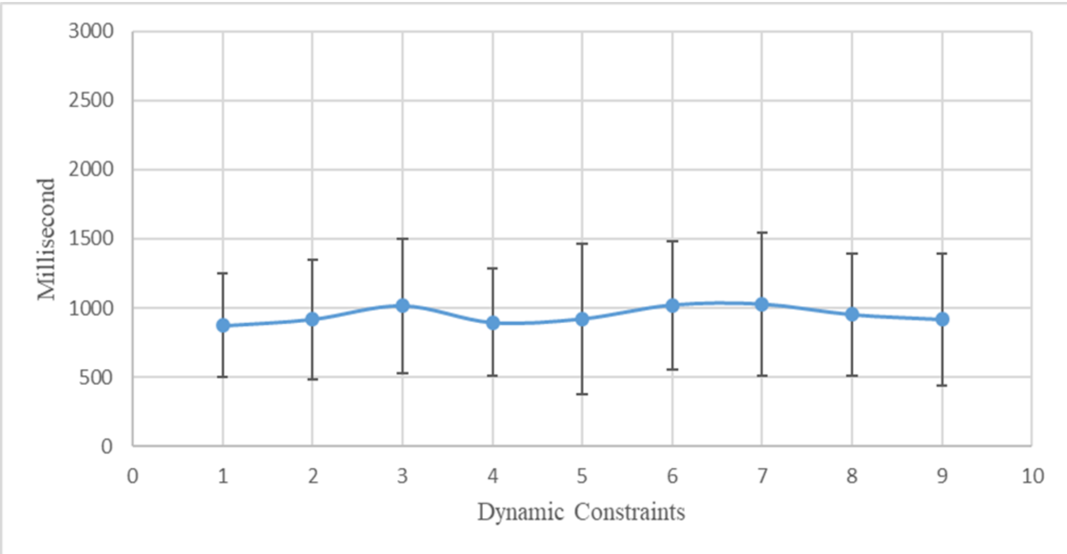


Figure 6.9 Average path re-planning duration of sample-based methods with increased constraints

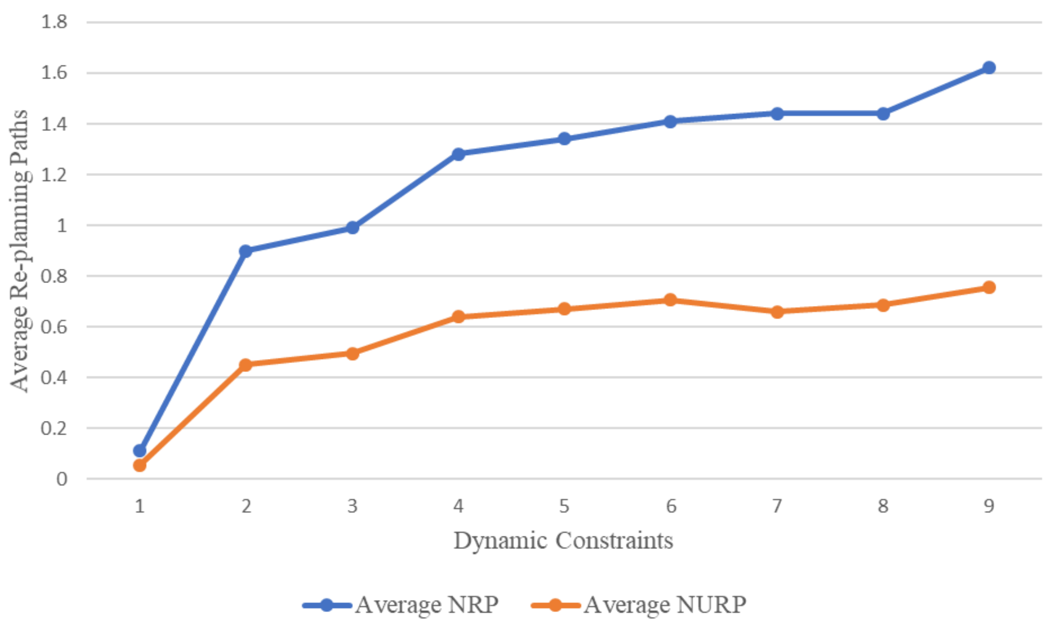


Figure 6.10 NRP and NURP for traditional PRM method

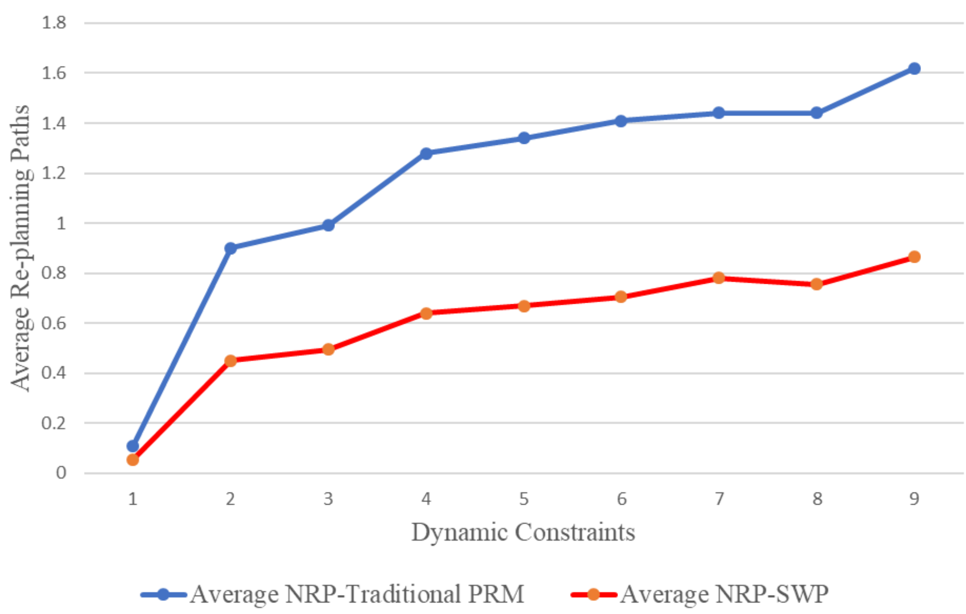


Figure 6.11 Comparison of NRP between traditional PRM and SWP

6.5 Discussion

Smart work packaging (SWP), with its core characteristics of adaptivity, sociability, and autonomy, offers a new insight to resiliently optimize the constraint-free crane path re-planning in the on-site assembly process of PHP. Compared with the previous crane path re-planning approaches used in the construction environment with dynamic constraints, SWP-enabled constraints optimization service for dynamic path re-planning can perform better. For example, (1) *SWP-PathPlanner* can avoid unnecessary crane path re-planning compared with the method of periodical path re-planning which needs conduct the re-planning at each specific time interval. The latter may consume more computational cost since it updates more frequently (Chi et al., 2014); (2) *SWP-PathPlanner* may not miss the shortest paths compared with the method of re-planning when collided, which conduct the re-planning only at meeting with constraints. The latter may lead to a longer path and more crane operations (Zhang and Hammad, 2012). Another important distinguishing feature of the SWP-enabled constraints optimization service is to instantiate the various dynamic constraints considering the practical crane operations in the construction environment. Existing studies on dynamic robot path re-planning have investigated the numerous dynamic path planning methods in a theoretical manner (Han and Seo, 2018; Zhang et al., 2016b). This study, however, has shown that the panoramic and interconnected characteristics of SWP can not only autonomously generate the path and detect/classify the constraints in a networking manner but also make adaptive decisions on the path re-planning.

Several innovations of this study can also be highlighted. Firstly, SWP demonstrates a new workflow to optimize the task execution level constraints by offering an example in crane path planning. Although not all constraints for the crane path planning process are investigated, the lean philosophies in constraints classification (prioritizing) and the smartness in designing optimization mechanism can be an example for dealing with other constraints. Secondly, SWP-enabled constraints optimization service do not try to change the current crane operation habits of the operators, but to make them smarter for improving the bottlenecks, particularly the dynamic ones. Additionally, a digital environment, assuming all data generated from sensors are well used, is developed into the SWP can help guide the operators in advance for path planning in numerous situations such as in training.

This study has initiated the work of introducing smart construction objects (SCOs), work packaging, digital twin, edge computing, and lean philosophies to constraints management of PHP (See Fig.6.12). By modeling the constraints in the on-site assembly process, their interrelationships and the critical constraints can be identified. However, the constraints usually are dynamic, and it would be complicated to optimize them by only adopting emerging technologies. The SWP-enabled constraints optimization service take advantages of both SCOs in data generation and work packaging in providing value-added information to offer more efficient decision making for constraints optimization. These trades associated smart work packages can not only help optimize their internal constraints but also can be further networked and collaborated for improving project performance such as schedule, Just-in-time delivery, and site/buffer layout.

It may be argued that the SWP-enabled constraints optimization service is too ambitious and impractical in real crane operations, the fact that the adaptivity of this smart service can only be verified in a virtual environment is not considered by the authors to be a limitation of this study. Contrarily, it truly reflects the sluggish adoption of emerging technologies in the current PHP processes. For example, if all sensors and well-refined data can be applied for crane path re-planning and guidance, this study would be possible to be tested in the real situation.

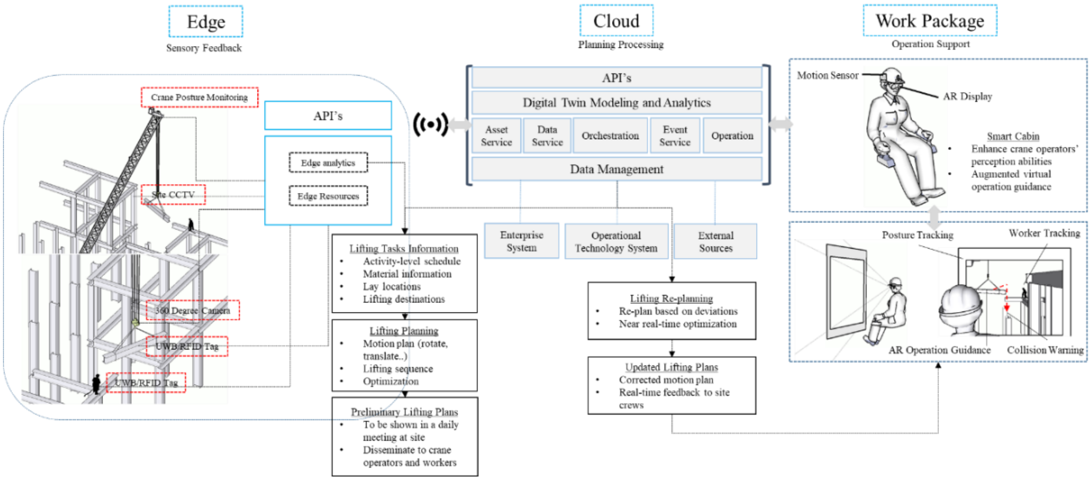


Figure 6.12 Panoramic scenario of SWP-enabled constraints optimization service in crane path re-planning

6.6 Chapter Summary

This chapter provides an in-depth exploration of smart work packaging (SWP) in constraints optimization that concentrates on smart decisions with adaptivity in path re-planning under a dynamic crane operation environment. Deviating from traditional methods that are re-planning a lift path when collided with constraints or over a specific time interval, this study argues for the adaptivity of SWP with a decision-making mechanism to update a path when necessary. By augmenting existing task execution process of crane path planning with the core characteristics of SWP including adaptivity, sociability, and autonomy, SWP demonstrates a generic workflow of initial path planning, constraints classification, path cost values computing, and decisions on path re-planning in the optimization of dynamic constraints. Targeting a real PHP project in Hong Kong, the SWP-enabled constraints optimization service is validated in a BIM environment. The results of this simulation indicate the feasibility of applying this service into practice.

The contributions of this study to the body of knowledge are threefold. Firstly, the architecture of SWP-enabled constraints optimization service can be extended and applied to other constraints improvement. The workflow of this constraint optimization service provides clear steps for other researchers interested in replicating this study. Secondly, while acknowledging the merits of methods in traditional crane path planning and strategies in theoretical robot path planning, this study not only balances the efficiency and path quality but also consider the necessity in path re-planning by employing modified PRM, A*, and *SWP_PathPlanner*. Thirdly, beyond the modeling and monitoring functions supported by SWP, this study argues for the optimization as a new dimension in the constraints management loop, which can improve the constraints in a more scientific manner. Back to this study itself, there are still some future studies can be considered. The continuation of changes in cost values of the path indicated by the distances between the path and specific constraint is the only information required in this study. Other sensory information of constraints in real-situation for decision-making and the uncertainty on the cost value of path caused by the sensory noisy will be considered in the future study. Apart from this, the licensed crane operator can be invited to compare the performance similarity between the path generated from operators' operations and the path generated from SWP_PathPlanner.

CHAPTER 7 SWP-enabled Constraints Monitoring Service

7.1 Introduction

In the PHP, the prefabricated products become more and more complicated for assembly, with the evolution from components (light-weight, e.g., facade) and modules (large and heavy, e.g., volumetric precast bathroom) to pre-acceptance integrated units (larger and heavier, e.g., completed with finishes, fixtures, and fittings) (Han et al., 2014). Given this course of prefabricated products evolution, cranes, with their excellent transportation capacity, perform a decisive role in the assembly of prefabricated products by lifting them vertically and horizontally (Chi et al., 2012). To achieve smooth crane operations, the crane operators should not only have enough physical strength but also be agile in the hearing, eyesight, and reflexes. As such, the operations and judgment of the crane operator will be a crucial factor for safety and productivity particular in the construction site of Hong Kong due to the high level of congestion and dynamics. However, on the basis of constraints prioritization in Chapter 6 (See Table 6.1), the fatigue or drowsiness has been identified as the critical constraint in disturbing the operator’s operations and judgment, which leads to the decreased attentiveness and vigilance, as well as casualties by collisions or falling loads (Tam and Fung, 2011; Marquez et al., 2014). In addition, Tam and Fung (2011) revealed that around 60.5% of the crane operators would continue to work even feeling fatigued due to the long working hours (tight construction schedule) and about 52.6% of the crane operators are lack of breaks due to the inconvenient and narrow workspace (inconvenience of frequent in and out). Thus, automatically monitoring and warning the fatigue can provide timely support for crane operators, site superintendents, and safety directors to make the scientific shifts and breaks.

Although there are seldom studies on developing fatigue monitoring and warning systems for the crane operator, numerous objective approaches have been proposed for detecting the fatigue or drowsiness of vehicle drivers from vehicle trajectory (Thiffault and Bergeron, 2003), physiological signal (Borghini et al., 2014), and facial expression (Ji and Yang, 2002). The first two approaches in crane operation can measure the fatigue by several parameters such as trolley movement speed, loads path deviation, jib rotation speed, heart rate, electroencephalogram (EEG), electrooculogram (EOG), electromyogram(EMG), and electrocardiogram (ECG). These two methods have shown a good accuracy when monitoring physical fatigue of vehicle drivers. However, crane operation trajectory may be affected by other factors (e.g., operation errors due to inexperience, inefficient communication with site signaller) and the physiological signal should be collected by an annoying and invasive way to crane operators. Thus, monitoring the fatigue reflected by facial expressions (e.g., eye state, yawning, nodding) can be a more convenient, fast-speed and cost-effective approach. This kind of approach can analyze the facial features extracted from the videos/images of crane operators, and it performs a high accuracy after the boosting of various deep neural networks as it facilitates the computer to learn by itself for capturing the key features. For example, Zhang et al. (2015) adopted the convolutional neural network (CNN) to detect the yawning by using the features in nose region instead of mouth area due to the head turnings of vehicle drivers. However, it still difficult to distinguish easy-to-confuse fatigue states, such as blinking and closing eyes. Huynh et al. (2016) provided a more practical solution with the 3D-CNN by considering the broader features on the face and temporal information (sequence of video frames). However, it is still a challenge to distinguish the fatigue states with long-term dependencies, such as yawning and talking. Guo and Markoni, (2018), and Lyu et al. (2018) improved the learning model on the temporal information by integrating CNN with Long Short-Term Memory (LSTM) network, which is a type of recurrent neural network (RNN) that can distinguish the states with long-term dynamical features over sequential frames. However, the potential of CNN-LSTM is far from being fully exploited in the domain of driver/operator fatigue monitoring. The primary limitation in previous studies on CNN-LSTM in fatigue monitoring is that the long-term dependencies of periodic fatigue behavior (e.g., distinguish nodding and head tilt along with loads movements, yawning and talking) are learned from positive-sequence video frames considering only forward dependencies, while backward dependencies learned from reverse-order frames has never been explored that means some useful information may be missed.

To address this issue for improving the accuracy in monitoring and alerting of crane operator fatigue, this study develops a hybrid deep neural network by integrating CNN with deep bidirectional LSTM (DBLSTM) network, which enabled by the SWP of the crane operator. The specific objectives of this study are: (1) to accurately detect and align the facial regions with critical fatigue features; (2) to extract the effective facial fatigue features on single-frame images; (3) to distinguish the fatigue state by mining bidirectional temporal clues of sequential features.

7.2 SWP-enabled Crane Operator Fatigue Monitoring Service

Instead of introducing an entirely new workflow in monitoring the constraints in " Lack of collision-free path planning," smart work packaging (SWP) augment existing workflows with smart characteristics including adaptivity, sociability, and autonomy. The crane operator fatigue monitoring and alerting needed in the crane operations for this chapter is also the trial to activate the potential of proactive tracking, updating, and predicting in SWP's autonomy.

7.2.1 System Architecture

In this section, the SWP-enabled constraints monitoring service is proposed. The architecture of this service is shown in Figure 7.1. This service is also supported by the smart construction objects (SCOs) and smart BIM platform. The SCOs are built by equipping the objects such as crane cabinets, operator, helmet and wrist on the operator with the various sensing and tracking technologies (e.g., RFID, sensors for monitoring fatigue, WiFi, camera) for achieving smartness in data generation and collection. This process can both enrich and exchange the information with smart BIM platform. Then, after the interactions between the crews (e.g., safety supervisor) and virtual BIM platform/physical machine, the characteristics (e.g., adaptivity, sociability, autonomy) of smart work packaging (SWP) can be activated to execute the fatigue monitoring.

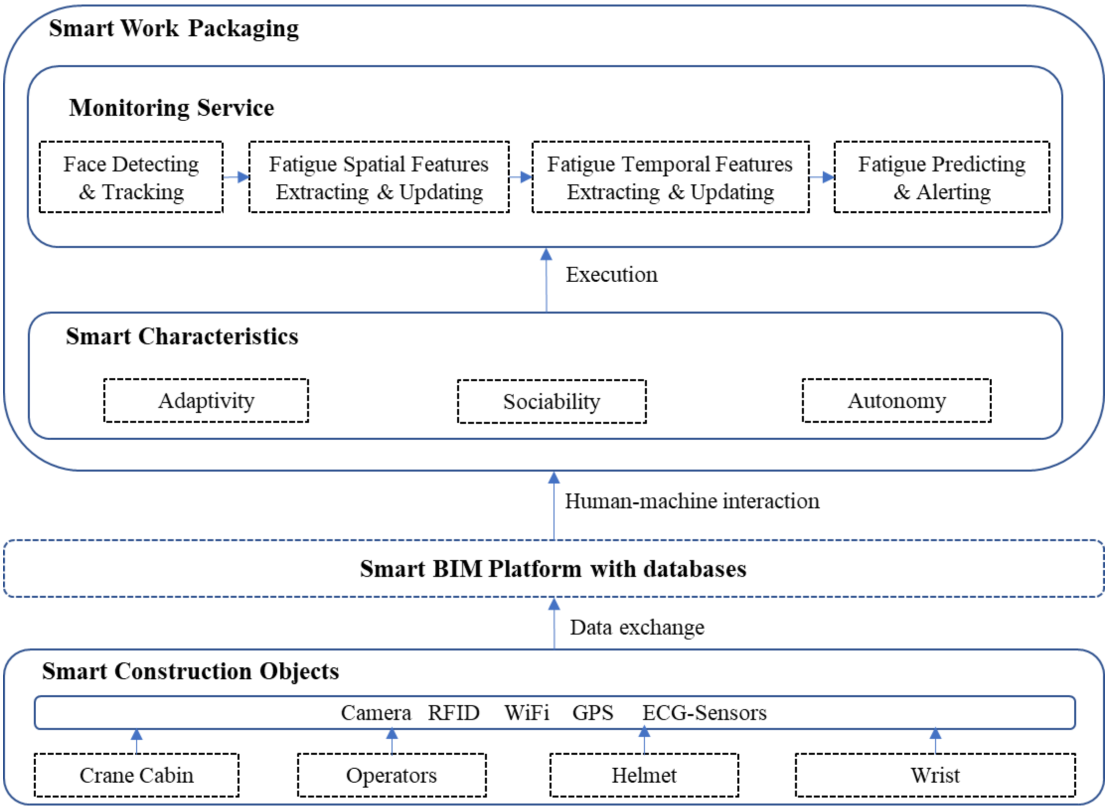


Figure 7.1 The architecture of SWP-enabled fatigue monitoring service

Figure 7.2 presents the architecture of the proposed hybrid deep neural networks embedded in the SWP monitoring service, which comprises three steps and each step maps to a specific model. Firstly, the multi-task cascaded convolutional networks (MTCNN) are adopted as the face detector to locate and align the facial area in each frame of the video. Secondly, the customized CNN model is designed to extract facial fatigue features from individual-frame images. Finally, a sequence of features within a specific time interval is fed into DB-LSTM to model the temporal variation of fatigue. And the Gaussian smoothing is adopted to reduce the noise and improve the fatigue monitoring performance. Each step of the proposed method is detailed in the following sections.

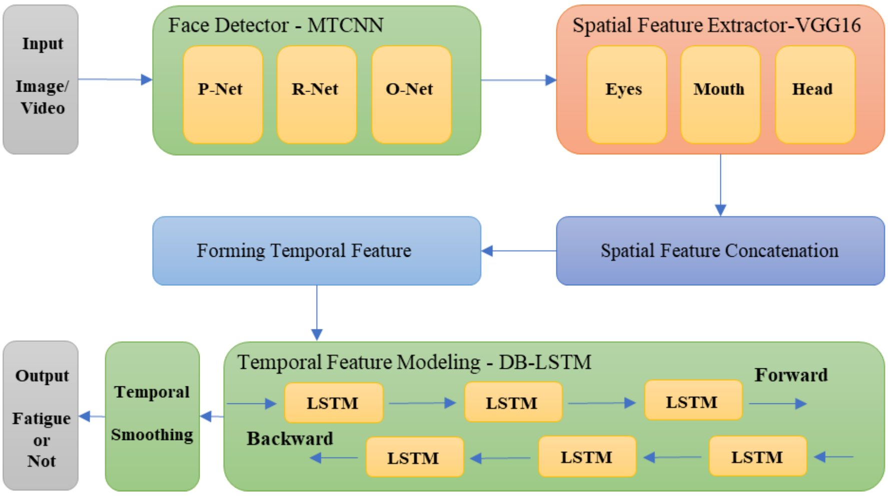


Figure 7.2 The architecture of the hybrid deep neural networks for fatigue monitoring and alerting

7.2.2 Face Detection

Precisely detecting and aligning the facial area of crane operator from an image is very critical to achieve efficient extraction of facial fatigue features and fatigue recognition. One of the famous face detectors proposed by Viola and Jones, (2001) uses Haar-Like features and AdaBoost to train cascading classifiers, which achieves high detection rate in a real-time manner. However, previous studies have proved and indicated that the accuracy and efficiency of this face detector might reduce with large variations of facial regions (Huynh et al. 2016; Choi et al. 2016a). These challenges could be exacerbated for face detection and alignment during crane operations in the real-world situations, such as the large pose variations of the operator who should change pose along with the moving loads, extreme lightings or darkness in operation cabin, and occlusions in front of the face. To fill this gap, the multi-task cascaded convolutional networks (MTCNN) proposed by Zhang et al., (2016a) shows the significant performance improvement in both accuracy and efficiency compared with other face detectors. This study adopts MTCNN to conduct the face detection and face alignment tasks with several stages. Firstly, the input images with various scales should be resized to build an image pyramid. Secondly, a shallow CNN (P-Net) with the input size of 12×12 to fast generate the candidate facial windows that are calibrated based on the bounding box regression vectors, and the highly overlapped candidates are fused by using non-maximum suppression (NMS). Thirdly, a complex CNN (R-Net) with the input size of 24×24 is adopted to reject the non-facial candidates with the same process of calibration and fusion. Finally, a more powerful CNN (O-Net) with the input size of 48×48 is applied to refine the results and produce five landmark points including positions of left-eye, right-eye, nose, left-lid-end, and right-lip-end.

7.2.3 Spatial Features Extractions

The objective of the features extraction is to learn a CNN-based spatial-domain feature extraction model E for capturing fatigue features F from the individual facial images I. As the feature extraction model E would go through each individual image in I, the extracted F should be accustomed and resilient to different input noises. Thus, this study chooses VGG-16 as our fundamental model which has achieved good performance in various datasets of image recognition (Simonyan and Zisserman, 2014). On the basis of original VGG-16, several improvements are conducted to balance the efficiency and accuracy for extracting fatigue feature in a real-time condition. Figure 7.3 demonstrates the improved VGG-16 architecture V. The original VGG-16 which includes 13 convolutional layers (grouped into Conv 1-5), 5 max-pooling layers (pool 1-5), and 3 fully connected feedforward network layers. However, the input of this study has a smaller size image (64×64 RGB images) than the original VGG-16 (224×224 RGB images), which means the number of parameters can be reduced by using smaller fully connected (Fc) network layers (Fc-6, Fc-7, binary classifier) to avoid over-fitting in the improved VGG-16. Given the input to the improved VGG-16 is a fixed-size 64×64×3 face image, the features both in max pooling 5 and max-pooling 3-4 can be used to obtain the discriminative representation. This considers the fact that forward layers of CNN include more detailed information, while the backward layers summarize the global information. This improvement can be beneficial for improving the accuracy of extracting the small region features that are easily ignored by max-pooling, such as the eyes. To this end, a 1×1 convolutional layer is applied into each of pool 3-5 to approximate the Fc 6 by generating three vectors with the same depth (e.g., 256 in this study). This approximation strategy can not only reduce the number of parameters of Fc layers but also facilitate the Fc layers to extract fatigue-related features by pooling operation automatically. The pooled vectors are concatenated to feed into Fc 7 with fewer parameters to extract the more critical features, which forms the F.

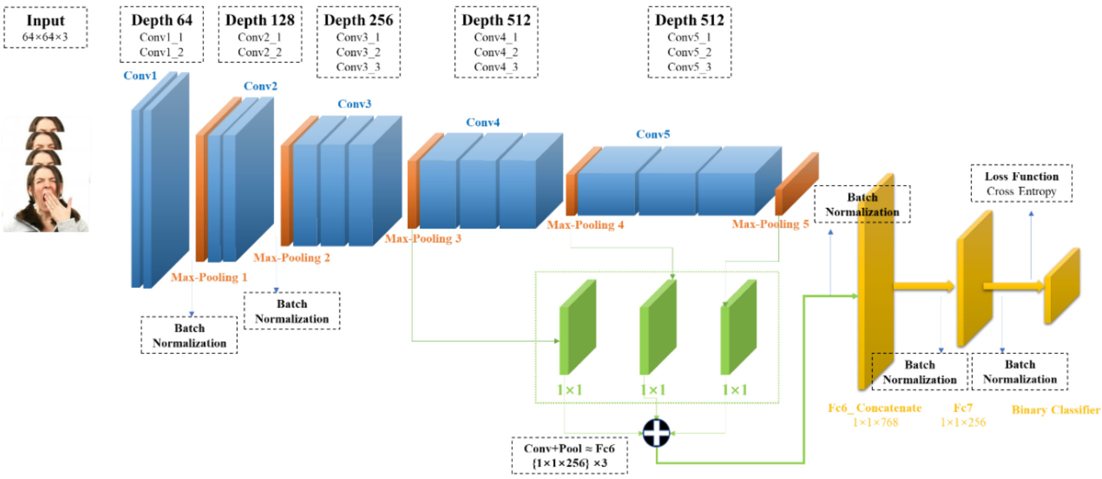


Figure 7.3 The architecture of CNN-based spatial-domain feature extraction model

To enable the faster and stable training process in generating the feature extraction model E with good generalization, another improvement for VGG-16 is to use Batch Normalization (BN) (Ioffe and Szegedy, 2015). BN is a kind of feature scaling technique that can normalize the sample mean and variance of hidden units before or after the process of activation functions over mini-batch data. This normalization process helps lessen the internal covariate shift for allowing using larger learning rates. Meanwhile, the mini-batch including various samples may lead to randomness, which can reduce the probability of over-fitting. In this study, there are 5 BN layers placed before max-pooling layer and Fc layer. Lastly, a binary classifier is placed after Fc7 to predict the fatigue score Y. Given both Y and ground truth label L ϵ {0,1}, the cross-entropy loss function with the Adam optimizer is adopted to minimize the loss. If the Y is larger than 0 and is close to 1, the degree of fatigue for the input is higher, and vice versa.

7.2.4 Temporal Feature Modeling

Although the feature extractor E has already enabled to predict the fatigue score of each frame based on the spatial features, sometimes it is still hard to discriminate the slight dynamic variations that have strong temporal dependencies such as yawning and talking. Therefore, it can be meaningful to consider both backward and forward information in the sequential frames. To this end, the deep bidirectional long short-term memory (DB-LSTM) is used to model the temporal features F. DB-LSTM can process the sequential data from two directions by two separate hidden layers and then feed them into the same output layer. The outputs of forward and backward layers (as shown in Fig.7.4) are both computed by using the basic structure of standard LSTM, See Fig.7.5 (Greff et al., 2017).

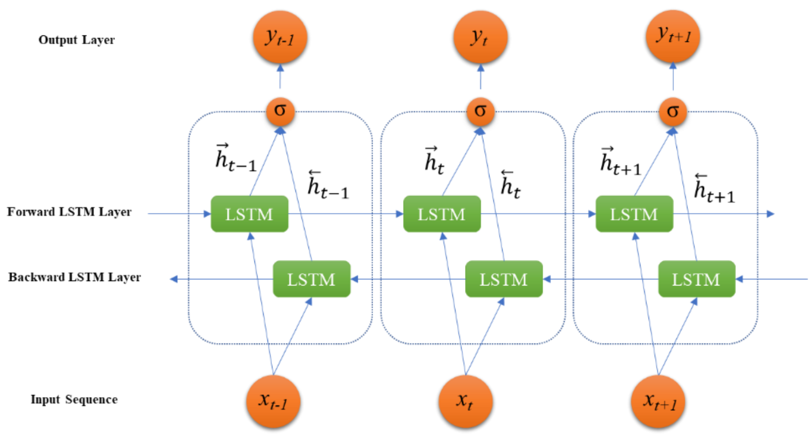


Figure 7.4 The architecture of the DB-LSTM

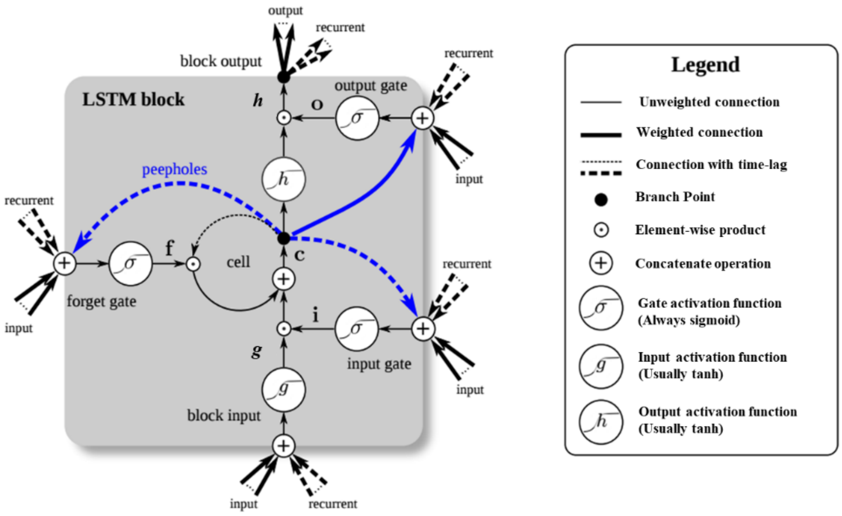


Figure 7.5 The structure of the standard LSTM

DB-LSTM owns a memory cell to save the state vector that is the sequence of the past or future input data. The current state can be updated on the basis of the current input, output, and the previous state saved in that "cell." DB-LSTM has a gated structure which allows the network to forget the previous state saved in cells or to update the latest state based on the new input data. At time t, the input gate vector, forget gate vector, output gate vector and the state of the memory cell can be denoted as i_t, f_t, o_t, and c_t respectively. then c_t can be updated by the equation (7.1)-(7.6).

$$i_t = \sigma_i(W_{xi}x_t + W_{hi}h_{t-1} + b_i) \quad (7.1)$$

$$f_t = \sigma_f\left(W_{xf}x_t + W_{hf}h_{t-1} + b_f\right) \quad (7.2)$$

$$o_t = \sigma_o(W_{xo}x_t + W_{ho}h_{t-1} + b_o) \quad (7.3)$$

$$g_t = tanh(W_{xc}x_t + W_{hc}h_{t-1} + b_c) \quad (7.4)$$

$$c_t = f_t \odot c_{t-1} + i_t \odot g_t \quad (7.5)$$

$$h_t = o_t \odot tanh(c_t) \quad (7.6)$$

Where x_t is the input and σ is the gate activation function, which usually is the sigmoid function. g_t is the state update vector that has activation function "tanh" (hyperbolic tangent function) and is computed from the input of the current state and previous state. Forget gate f_t allows the LSTM to forget its previous memory cell c_{t-1} or further memory cell c_{t+1}, and the output gate o_t adopts a transformation to the current memory cell to produce the hidden state h_t. For three gates, the gate can accept the input vector only if the gate value is 1 and reject the input vector when the gate value is 0. Weight matrices ***W*** and biases ***b*** are the trained parameters. $\odot$ indicates the element-wise product with the gate value. Then, the vector $\boldsymbol{Y_t}$ in feature sequence ***F*** is the concatenated vector by combining the outputs of forward and backward processes as follows:

$$Y_t = \vec{h}_t \oplus \overleftarrow{h}_t \qquad (7.7)$$

Where $\oplus$ represents the concatenate operation.

In this study, each video can be randomly sampled as the training data by dividing it into numerous video clips with fixed length 50. The DB-LSTM temporal network includes 64 hidden units to predict the refined fatigue score Yt of each frame (t=1,…,50). The cross-entropy loss function with Adam optimizer is still applied to minimize the loss.

In the previous stages, both spatial model (CNN) and temporal model (DB-LSTM) are applied to predict the fatigue score of each frame. However, there are still certain noises during the testing on the validation set. To perform well in accuracy, the post-processing techniques including Gaussian smoothing, moving mean/median filtering can be adopted to “smoothing” the predicted fatigue scores.

7.3 Experiment

7.3.1 Dataset

NTHU-DDD: As it is believed that monitoring and alerting of the crane operator fatigue are almost identical to the situation for the vehicle driver, evaluating the performance of this proposed method and comparing with previous methods can be conducted on a very popular dataset named National Tsinghua University Drowsy Driver Detection (NTHU-DDD), which is provided on the challenge of ACCV2016 workshop for driver fatigue detection (Weng et al., 2016). The dataset is collected by an active infrared (IR) illumination with the resolution 640×480 pixels of grayscale videos. The dataset includes the dataset for training and dataset for validation. The training set comprises 18 subjects (10 males and 8 females) with 5 scenarios such as Bareface, Glasses, Sunglasses, Night_BareFace, Night_Glasses, in which the first three were collected at 30 frames per second (fps), and the last two were collected at 15 fps. Each scenario has 4 videos that are a combinational representation of fatigue-related expressions (yawning, nodding, slow blink rate of eyes) and non-fatigue related signs (talking, laughing, looking at both sides). The evaluation set includes another 4 subjects (2 males and 2 females) with 20 videos, and the states of fatigue and non-fatigue are mixed under the above 5 scenarios. The test set is not provided in this dataset and previous studies also just generate the results from the validation set. Thus, this study can only compare the accuracy performance in the validation set with the previous results. The NTHU-DDD also provides the frame-level annotation files and a single digit is applied to indicate the ground truth of the frame. Table 7.1 summarizes the ground truth of fatigue status, eyes, head, and mouth. It is easy to find that the ground truths in each video (each annotation file) are long-term dependencies, which indicates that the states of a frame may rely on the frames in the past or future several seconds.

Table 7.1 The ground truth of state in each frame of NTHU-DDD

States \ Label	0	1	2
Fatigue	Stillness	Fatigue	
Eyes	Stillness	Sleepy	
Head	Stillness	Nodding	Looking aside
Mouth	Stillness	Yawning	Talking & laughing

7.3.1 Implementation Detail

Environment Setting: The experiment, including training and evaluation process, is conducted in a workstation that runs Ubuntu 16 system. The specification and configuration of this computer are in the following:

- CPU: Intel (R) Xeon (R) Gold 5120
- GPU: NVIDIA GeForce GTX 1080 Ti × 2
- 500 GB SSD

Data Pre-processing: For all videos, the MTCNN is used to detect the faces and locate the landmarks for all frames. Then, the detected and aligned face with five landmark points are cropped and resized to a fixed size (64×64). As it will be time-consuming in line with the frame rates of the dataset, e.g., 30fps and 15fps, this study sub-sample the video frames by the factors of 6 and 3 and import the image sequence with the rate of 5fps to the proposed hybrid neural network. After that, the classification results (predicated scores) should be up-sampled back to the original length. In addition, the videos of the dataset are grey-scale. Thus each frame should be replicated three times to turn into 3-channel images so that it can be generalized to process color inputs.

Label Pre-processing: As shown in table 7.1, the statuses of fatigue and eye keep two ground truths (0 or 1), while the statuses of head and mouth own three ground truths (0,1, or 2). Apparently, the statuses, e.g., stillness, looking aside, and talking & laughing are the least related to the fatigue. Therefore, looking aside and talking & laughing can be re-labeled to 0, which is the same as stillness. After that, the SigmoidCrossEntropyLoss is used for all the annotations in the training process.

Training: (1) The Keras is used to build and fine-tune ***E.*** As BN is adopted, the training data list should be shuffled to guarantee the randomness. For the solver, Adam is chosen with mini-batch size 64, fixed learning rate 0.001, weight decay 0.001, and momentum 0.9 & 0.99. The ***E*** is trained up to 50000 iterations, taking less than 4 hours. The classifier of ***E*** is removed, and the extraction of features ***F*** will be used in the next step. (2) The video clips should be randomly sampled with fixed length 50 frames (equivalent to 10s) from training set as the input of DB-LSTM. For the solver, a larger learning rate (0.005) and batch size 8 is adopted. Other settings keep identical as (1). The DB-LSTM is trained up to 1000 iterations and spends less than 5 min. Before the clip length (***L***) of

DB-LSTM used for training is fixed at 50, several trials have been conducted to find a satisfied ***L***. To improve the smooth of prediction, the training is conducted in an overlapped manner. For instance, given input with 100 frames and ***L*** = 50, 3 video clips (1-50, 26-75, and 76-100) can be fed into the DB-LSTM. The stride size is fixed to ***L/2***, and the prediction results of overlapped frames are merely averaged. (3) Given the results of (2) tested from the evaluation set, numerous clips can be uniformly sampled with length K + 200 and stride 200, where K = 201 is the kernel size of the 1-D convolution. All clips can be fed into a Gaussian smoothing network with a single 1-D linear Conv layer to generate the smoothed scores. As there is no zero paddings, the length of output can be 401-(201-1) = 201. The learning rate is fixed to 0.001, and the weight decay is set to 0. The Gaussian smooth is trained up to 1000 iterations, taking less than 2 min.

7.4 Results and Discussion

Figure 7.6 demonstrates the average loss among 20 videos of the training set (orange line), and the evaluation set (blue line). The spatial features extraction model ***E*** already achieves 85.82% accuracy of fatigue despite its prediction is purely on the basis of a single frame. Figure 7.7 represents the comparison of DB-LSTM and LSTM on accuracies and convergent performance in the evaluation set. The temporal network LSTM considers the temporal variation of the fatigue status, and thus improves its accuracy to 92.20%. It should be noted that a longer clip length T during testing can obtain higher accuracies. Finally, after modeling DB-LSTM, it achieves 93.60%

accuracy of drowsiness.

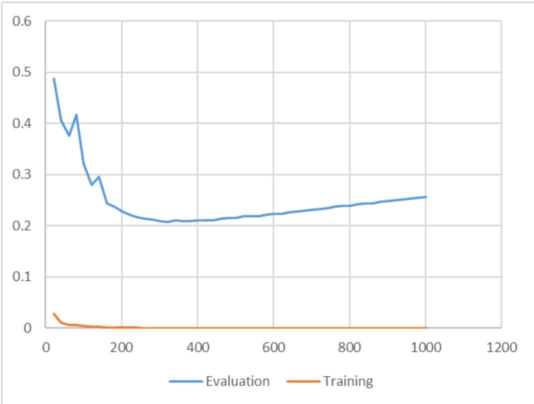


Figure 7.6 Loss curve of DB-LSTM for both the training set and evaluation set

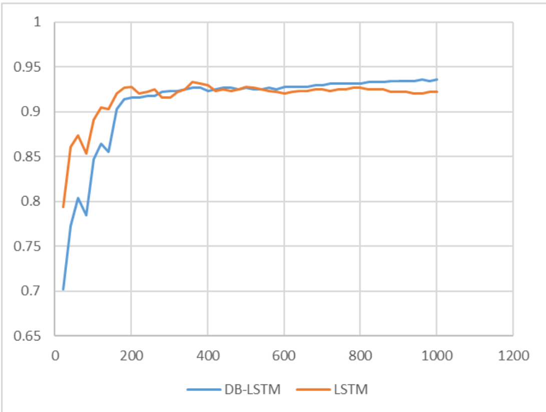


Figure 7.7 The comparison of DB-LSTM and LSTM on accuracies and convergent performance in the evaluation set

Table 7.2 represents the average F1 scores and accuracies for different scenarios on the evaluation set. For accuracy, the proposed hybrid neural network performs excellent under the sunglasses scenario (98.82%) and Non-Glasses scenario (95.41%). As for F1 scores in all scenarios, it is difficult to show the proposed method that offers a biased prediction.

Table 7.2 Average F1 scores and accuracies for different scenarios

	F1-Score	Accuracy	Number of clips
Night_nonglasses	0.8080	0.8800	125
Night_glasses	0.6061	0.8839	112
Glasses	0.9617	0.9440	125

Non_glasses	0.9655	0.9541	109
Sunglasses	0.9870	0.9882	170
All	0.9286	0.9360	641

7.5 Chapter Summary

This chapter proposes a hybrid neural network as the module of SWP to monitor and alert the fatigue status of the crane operator on the videos. The improvements and contributions in this chapter are threefold: (1) expand the vehicle driver drowsiness detection to the crane operator fatigue monitoring and alerting; (2) to detect and align the face, and extract the spatial features, the customized CNN is developed based on the baseline models which have excellent performance; (3) a deep bidirectional LSTM (DB-LSTM) is developed by considering both forward and backward dependencies to generate the temporal model, which can learn combinational representations in both space and time. The experiment results indicate that the proposed hybrid neural network outperforms numerous state-of-the-art methods. Further improvements and extensions can be made based on this chapter. Firstly, the dataset for crane operators should be established instead of using datasets from vehicle drivers. Additionally, devising more powerful features by combining multiple signals such as ECG, human audio, other physiological signals can be considered to achieve better accuracy and efficiency in fatigue monitoring.

CHAPTER 8 Dissemination of SWP-CM: A Simulation Game

8.1 Introduction

Despite the merits of using smart work packaging for constraints management (SWP-CM) in PHP, numerous implementation barriers have been identified. It is found that one of the barriers that prevent a successful SWP implementation is the training or pedagogical approaches to transfer and share the work packaging method, theory of constraints, lean principles and information technologies behind it within an organization (Li et al., 2017c). To facilitate the dissemination of SWP-CM related techniques and knowledge into the industry, it is critical to train future practitioners on the implementation of such knowledge and techniques. This chapter, therefore, concentrates on the development and application of an SWP-CM simulation game for PHP (hereinafter referred to as SWP-CM). Game-based simulations are practical hands-on learning tools for students and practitioners in the PHP field (Sacks et al., 2007). SWP-CM, through the simulation of some facets of the theory of constraints, lean principles, prefabrication production, information technologies, and work packaging method in a role-playing game, can be used to reinforce the learning and understanding of how to integrate SWP with constraints management to improve the productivity of PHP among students and practitioners. SWP-CM works with a smart BIM platform and SCOs that requires proficient operations and collaborative working from all players to plan and control the whole process of PHP. It can provide practical learning in the simulation. Furthermore, SWP-CM adopts Lean Construction principles such as standardized work, pull, and Just in Time (JIT) to facilitate the implementation of the SWP when the lean principles are utilized to facilitate the processes of constraints modeling, optimization, and monitoring. The primary objective of this study is, therefore, to investigate SWP-CM as an effective training and pedagogical tool for the teaching and learning of the theories and techniques related to SWP-CM in PHP.

8.2 SWP-CM Simulation Game

Lego™ based simulation games have been commonly adopted in construction management, which delineates the lean principles and information technologies. Sacks et al. (2007) developed a LEAPCON simulation game to investigate pull flow, reduced batch size, and multi-skilling by comparing it with the traditional construction process. The results show that lean technologies can significantly improve areas such as customized design, cash flow, and waiting time. González et al. (2015) presented a simulation game LEBSCO as a learning tool to transfer the knowledge of lean production principles into construction. The simulation game is also helpful to improve the understanding of lean principles among students. A simulation game in LNG (Liquefied Natural Gas) industry was also used to evaluate a constraint management framework which involves lean principles and information technologies such as BIM, RFID, GPS and other sensing technologies (Wang et al., 2016a). However, it should be noted that these games have some limitations: (1) The Lego™ materials utilized in previous studies are too simple to represent real-life situations, such as the process of

PHP in this study; (2) The concepts and tools of Lean Construction principles and information technologies, particularly the advanced techniques and concepts behind the real PHP practices, were not sufficiently taught in previous games (González et al., 2015). (3) The integration of information technologies into the BIM platform has been discussed more as a conceptual framework in previous studies (Wang et al., 2016a).

Although the SWP-CM is expected to lift productivity, after the implementation of SWP-CM in the previous scenarios and trials, the lack of training has been identified as the key factor to impede the adoption of SWP-CM in the industry. Current teaching/training methods are also ineffective in disseminating the knowledge, which consequently hinders the best use of SWP-CM. This chapter conducts a two-round role-play game to train and teach SWP-CM related control and planning techniques for students and practitioners in a series of workshops. The first round is based on the traditional practice of PHP. The second round adopts SWP-CM related techniques to complete the PHP process.

8.2.1 Study Groups

The sample group consists sixty-eight participants for this research, and it was chosen from a group of postgraduate students and undergraduate students in the department of building and real estate at The Hong Kong Polytechnic University, Hong Kong, China, during a series of designated days. This simulation game is intended to be repeated in four workshops. Each workshop consists of seventeen participants (Thirteen undergraduate students and four postgraduate students), which all have the background of construction management. Particularly, Ten of Postgraduate students had more than three years of work experience in the construction industry. This personnel composition could be advantageous in collecting important comments, suggestions, and insights from the perspectives of both academic scholars and industry practitioners. The aim of the experiment is to investigate the SWP-CM systematically before using it to teach students and train practitioners. Some adverse effects in the experiment, including the Hawthorne effect (McCarney et al., 2007) and practice effect (Goldberg et al., 2010) have also been considered. The former illustrates the phenomena that individuals adjust or improve their behavior in response to their awareness of being observed, while the latter represents the phenomena that people adapt or improve an aspect of their behavior when they are tested more than once. To address these adverse effects, the participants' groups and roles are not informed before the setup, and they are not informed whether each group will adopt similar approaches or will have the same purpose.

8.2.2 General Outline

This simulation game that intends to enhance the learning and understanding of SWP-CM in prefabrication housing production among students and practitioners. To achieve the aim, it integrates aspects of Smart BIM platform, SCOs, TOC, work packaging method, and Lean Construction principles. To simulate a real-world PHP environment by building Lego™ houses, it educates and trains players about TOC, work packaging method, lean principles and information technologies in a fast-paced and interactive way.

The simulation game comprises two rounds. The first round is related to the use of traditional planning and control (without SWP-CM tools), and the second round is related to the implementation of SWP-CM. These two rounds are then comparatively analyzed to demonstrate the benefits of the SWP-CM approach. The project goal of each round is to construct four buildings with the shortest duration, the highest accuracy, and the maximum percentage of plan completion (PPC). The simulation design is shown in Figure 4.3. As can be seen in Figure 4.3 there are three PHP phases which are simulated in this game, including (1) Manufacturing. Each building is assembled from five units, and each unit is composed of two modules, and each module consists of several components such as floor slab, façade, window, door, wall panel, tie beam, staircase. Units refer to high-level building blocks which are completed with many three-dimensional building sections. Modules represent elements which are on a hierarchical level above components. Materials represent elements on a hierarchical level below components. The unit should be completely assembled before it is delivered to the site; (2) Logistics. The primary tasks of logistics company include receiving transportation order, establishing a transportation schedule (e.g., select drivers and trucks) and controlling the transportation process. The drivers should deliver the units in time and prevent quality loss, and (3) Site assembly. The building assembly takes place on the construction site, which consists of several activities, including delivery check, site preparation, unit hoisting, and unit installation. The owner should also conduct a final check before the project delivery. Upon completion of each round, the cost and time, and PPC are calculated.

This simulation game has twelve specific roles that are determined based on real PHP projects. The specific role of each participant is listed in Table 8.1. This simulation game can be played with at least 12 people, but not exceeding 21. These numbers of players are decided by several rounds of testing. The minimum number of players is also determined by a number of rules, including 1) The critical roles should always be occupied by at least one player; 2) More players should be assigned to the roles that have a higher workload (e.g., there are at least three players as manufacturing workers, who are responsible for component, module, and unit assembly); 3) Some player can have multiple roles (e.g., the project manager can be both the owner and timer of the project). The maximum number of players is established by considering the workload of each role, as well as the space constraints of the simulation game.

Table 8.1 Personnel requirement in SWP-CM

Role	Min	Avg	Max	Brief Description
Owner	-	1	1	Owner of the construction project
Project Manager	1	1	1	Overall management of the project
Plant Manager	1	1	1	Controls the module manufacturing
Site Manager	1	1	1	Controls construction on site
Logistics Manager	1	1	1	Controls module transportation
Transportation Driver	1	1	2	Transport the module/unit
Expeditor	1	1	1	Control of shipping and storage

Buffer Foreman	1	2	2	Management of site buffer
Crane Operator	1	1	2	Manual hoisting of modules
Installation worker	1	2	2	Manual assembly of modules
Manufacturing worker	3	4	6	Manual sub-assembly of modules parts
Timer	-	1	1	Monitors and announces time
Total Personnel	12	17	21	

8.2.3 Expected Knowledge Output

Many concepts behind SWP-CM are taught during the simulation. The simulation highlights the primary aspects of BIM/RFID technologies, constraints management, and lean principles, keeping it uncomplicated and workable. These concepts are clarified by comparing a traditional PHP process with an SWP-CM one. The concepts are interpreted and listed below:

- Prefabrication Housing Production (PHP): Components/ modules/ units are manufactured before they are delivered to construction sites for on-site installation. This concept may enable the participants to understand the conceptual difference between materials, components, modules, and units after introducing lean principles. It should be noted that it is not allowed to release the workflow of PHP or any other standardized work steps in the traditional round to mitigate the practice effect.
- Constraint Management: It is a critical concept in the planning and control of PHP, which ensures that work plans assigned to construction practitioners are successfully (Blackmon et al., 2011). Constraints may include risks identified in the

future such as incomplete drawings and specifications, shortage of workforce and materials, lack of temporary structures, limited workspace, uncompleted preceding works, inclement weather, lack of work permits and safety issues, which can be divided into four types including technological, resource, spatial and information (Wang et al., 2016a). The players may experience many constraints in the traditional round, and some constraints can be removed in the SWP-CM round by using SWP-CM technologies.

- Standardized Work: It is a fundamental tool in lean principles to creating a repeatable and predictable process. This simulation game adopts standardized work chart (SWC) and work element sheet (WES) to break down the working process to form various work packages for each crew. These work packages can help the workers improve the quality and productivity in the SWP-CM round of simulation.
- Just-in-Time (JIT): It is a concept in inventory management where prefabricated products are produced and transported to meet the site demand at the right time, in the right location, and with the right amount. This concept can be implemented by adopting a pull system. In the traditional round, the manufacturing workers are pushed to produce regardless of the demand from the site. In the SWP-CM, the construction site can order and monitor the exact units by using the smart BIM platform and SCOs.
- High transparency in information communication: This concept involves the use of BIM as a collaborative platform to visualize the overall construction process and

enhance information sharing among the plant manager, logistics manager, site manager, project manager, and owner. The smart BIM platform is adopted in the SWP-CM to enhance the transparency of information communication.

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

8.2.4 Simulation Game Process

In the traditional round of the game (See Figure 8.1), the owner places an order and delivers design drawings to the project manager. All design drawings in this game are represented by the pictures of units (see Figure 8.2). The project manager receives the order, checks the design drawings, and coordinates collaboration between manufacturing, logistics, and on-site assembly.

The plant manager discloses the design to manufacturing workers and plans the production process based on his individual perspective without considering the actual demand in the downstream process. Manufacturing workers are required to produce as many as possible in compliance with the design drawings. Final products will be inspected by the plant manager and delivered by a logistics company. The logistics manager allocates drivers to transport the products to the construction site. On-site assembly activities are push-based (i.e., passive), and it is difficult to plan the schedule and resources. Regarding the constraints management process, it conforms to the process in the second round of Section 4.5.1.

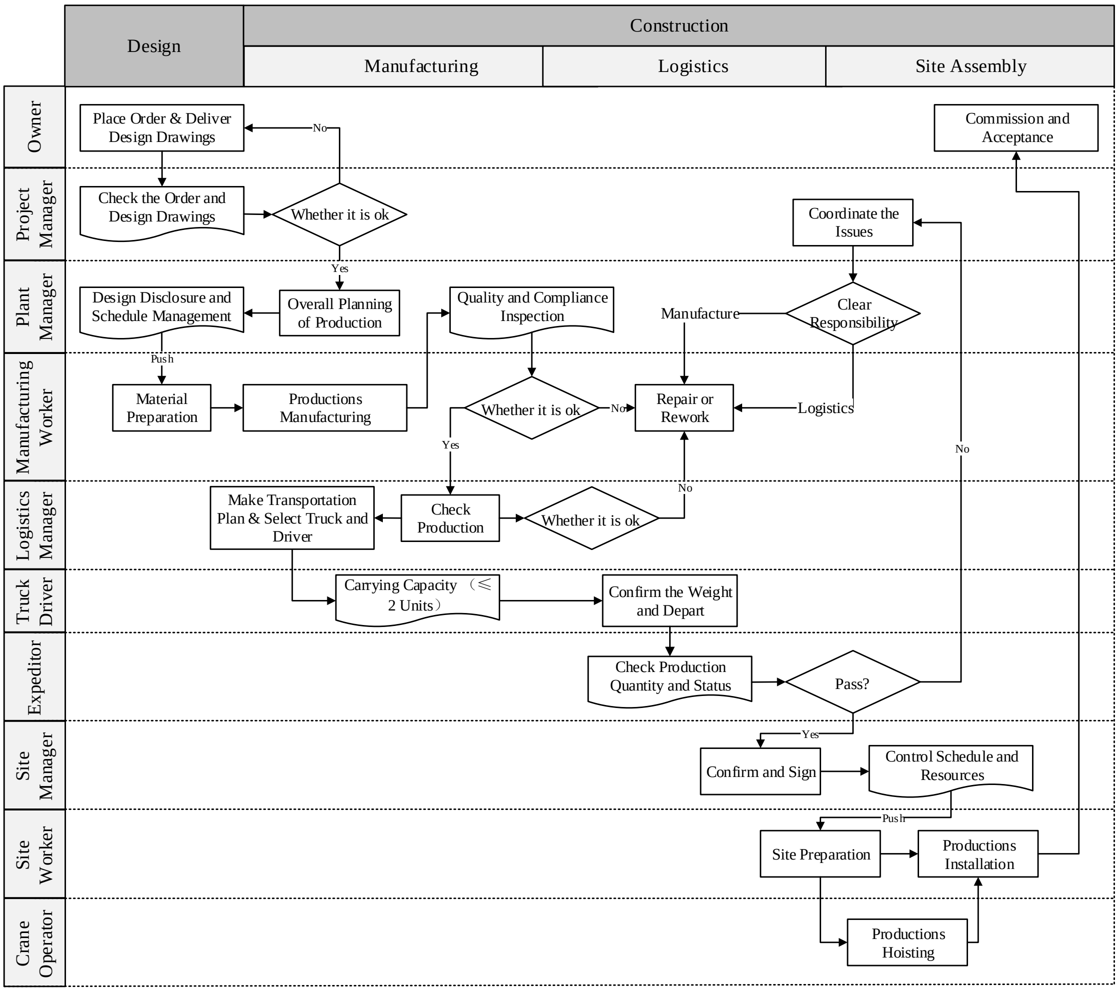


Figure 8.1 Traditional round process

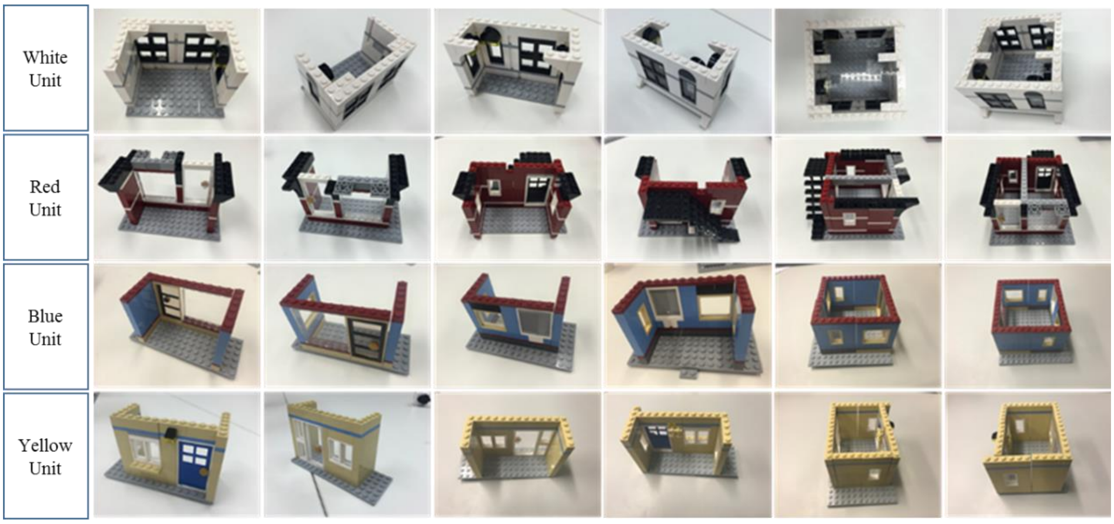


Figure 8.2 Design drawings of four buildings in the traditional round

In the SWP-CM round, the following modifications are made and highlighted in Figure 8.3, while other conditions remain the same as in the traditional round:

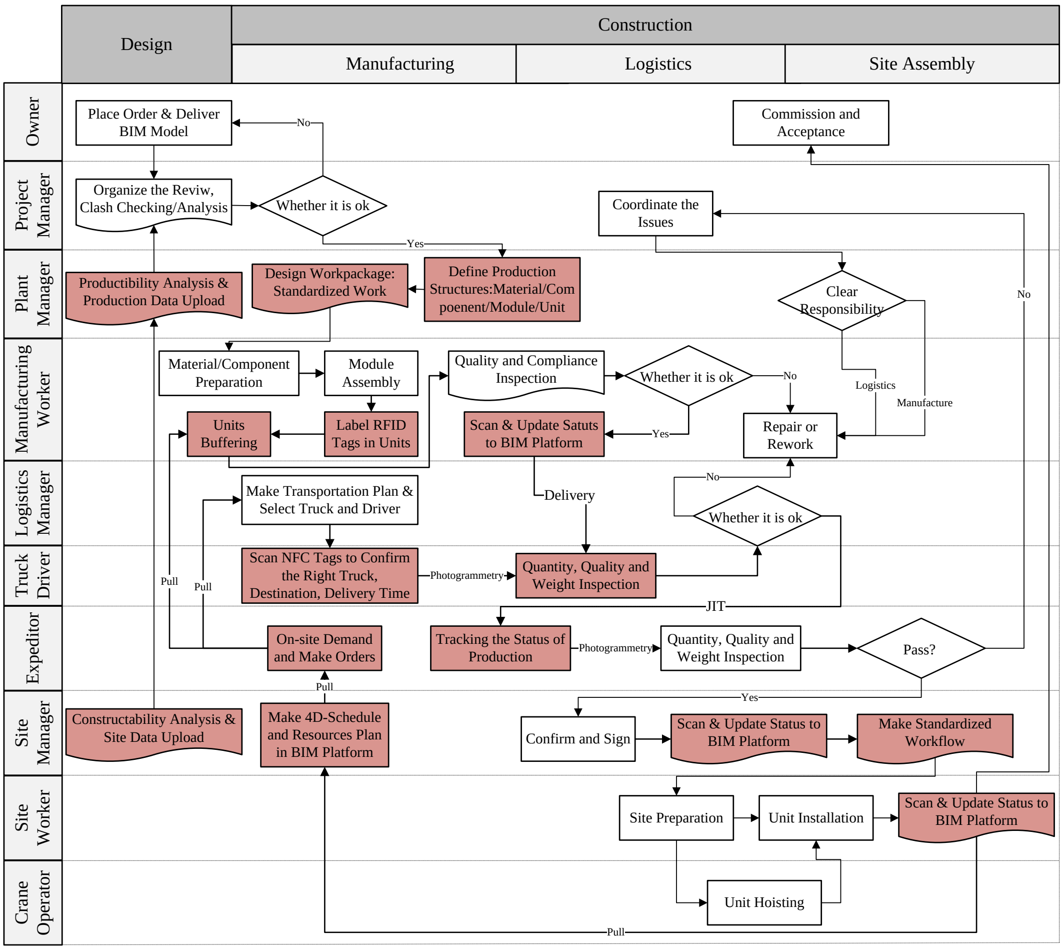


Figure 8.3 Lean/RFID/BIM round process

- Prefabrication Production Structure: The second round adopts a hierarchical modular structure from high-level to low-level, including units, modules, components, and materials (Bock & Linner, 2015). An example of the system is shown in Figure 8.4. This hierarchical modular structure can facilitate the object-oriented activities by the establishment of the standardized work in the manufacturing phase.

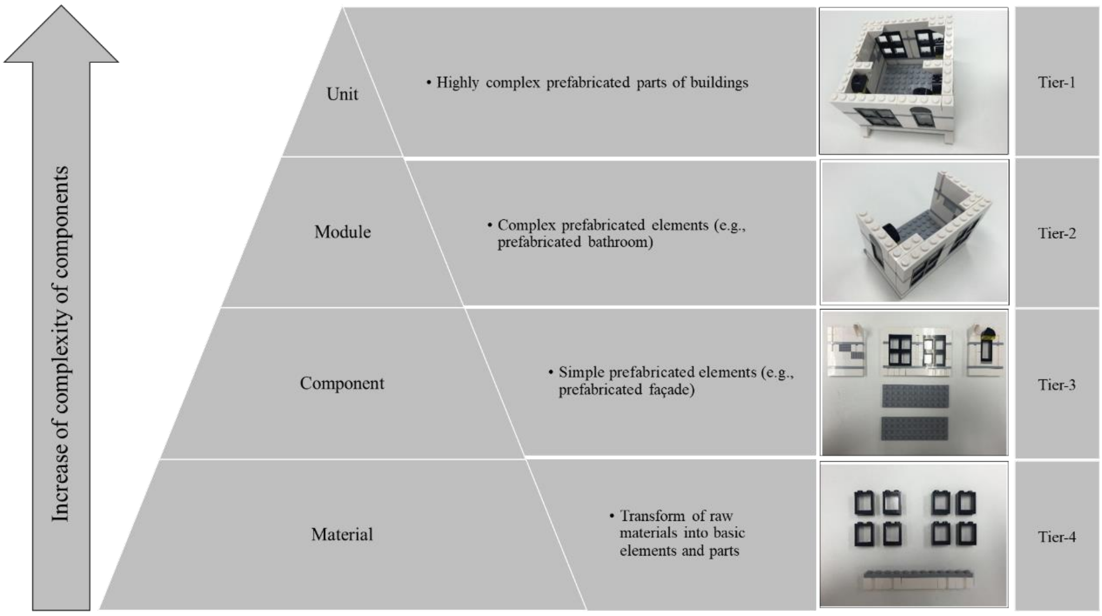


Figure 8.4 Hierarchical modular structure

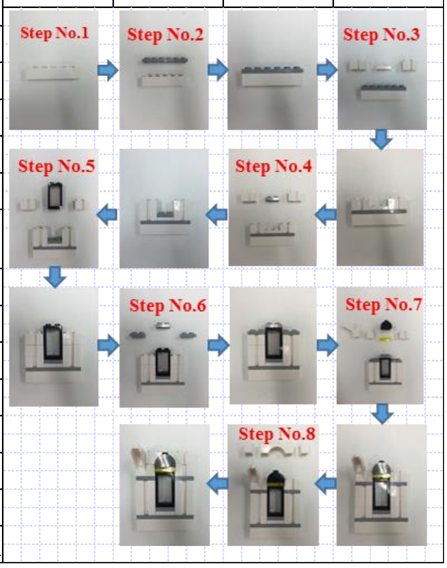
- Constraints Management & SWP: It is the same as the first round of Section 4.5.1.
- Standardized Work: In the second round, the standardized work chart (SWC) associated with the material/component/module/unit forms the work package to guide the workers. Take the wall assembly process in the manufacturing phase as an example (See Figure 8.5). There are eight steps in the wall assembly process. The work element sheet (WES) number is labeled with each step to guide the process. Each work step is measured from five different aspects (Mariz et al., 2012)

including design (the degree of conformity between completed production and BIM model), quality, waste, knack, rework. The schedule, cost, and percentage of plan completion (PPC) are also recorded in the SWC.

Standardized Work Chart					
Process Name:	Wall Assembly - Component				
Area:	Plant	Written by:	Xiao LI	Date:	8/30/2016

WES No.	Step No.	Work Step	Symbol	Time	Cost	PPC	Tooling Required
	1	Select a 6*1*1.2 white cuboid Lego Material					
	2	Assemble a 6*1*0.4 gray cuboid to Step No.1					
	3	Assemble two 2*1*1.2 white cuboids with construction splits and a 2*1*0.4 white cuboid to Step No.2					
	4	Assemble two 2*1*1.2 white cuboids with construction splits and a 2*1*0.4 gray cuboid to Step No.3					
	5	Assemble two 2*1*1.2 white cuboids with construction splits and a 2*1*3.6 black fixed window to Step No.4					
	6	Assemble three 2*1*0.4 gray cuboid Step No.5					
	7	Assemble a black lampshade, a 2*1*0.4 yellow lamp, a 1*1*1.2 white cuboid， a 2*1*1.2 white cuboid with construction split and a bracket beam to step No.6					
	8	Assemble two 1*1*1.2 white cuboids and a 4*1*1.2 white arched lintel					
Symbol Annotation							
			Total				

Manufacturing Worker	Manufacturing Worker	Manufacturing Worker	Plant Manager
Andy	Tore	Jennie	Neil



Design	✚	Quality	Q	Waste	▽	Knack	☺	Rework	▲

Figure 8.5 Standardized work chart

- Smart BIM Platform (SBP): In the second round, the SBP is utilized to eliminate stocks and buffers as much as possible. In addition, units are delivered from upstream to downstream workstations at the precise time and with accurate quantity. To achieve the above objectives, the units/trucks' traceability, information sharing, and communication are enhanced as smart construction objects in this platform. For example, the detailed process of SBP is shown in Figure 8.6. The SBP adopts RFID sensing and tracking technology to identify different objects in both passive and active manner. RFID tags are embedded in the prefabricated units. The gateway is set up as a data collector in the manufacturing plant, logistics trucks, and construction site. All RFID events are executed and stored on the tracking servers in the SBP, which can be shared among all the participants through SWP. The units/modules are represented in various colors based on the phases in the BIM platform, which can be blue (manufacturing), green (delivery), yellow (arriving at the site) to the actual color (assembly). The units are checked and documented by photogrammetry technology (e.g., using Autodesk 123D Catch Software to reconstruct the 3D model of the unit from the numerous photos) to compare the as-built model and as-designed model when leaving the plant and arriving at the site.The truck is identified and confirmed by using drivers' phone to scan the truck's NFC (Near Field Communication) tags.

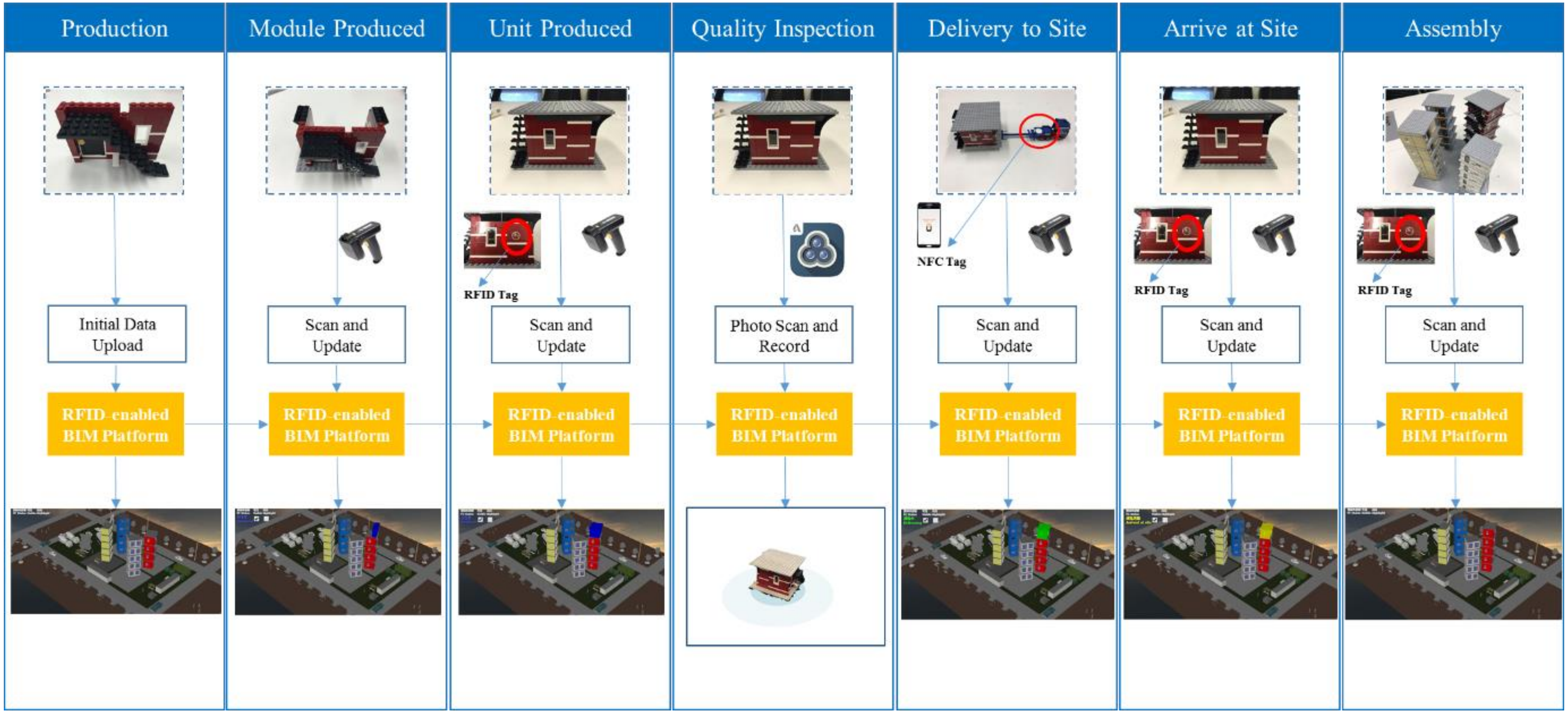


Figure 8.6 RBIMP workflow

8.2.5 Research Design

As discussed earlier, 68 participants are allocated to four workshops. Each workshop involves 17 participants for a two-round role-play game. The required duration of each workshop remains 140 minutes, based on several rounds of trials. The game instructions are provided before each round, and the ethics form are required to be filled before the game. The design of the workshop is shown in Figure 8.7.

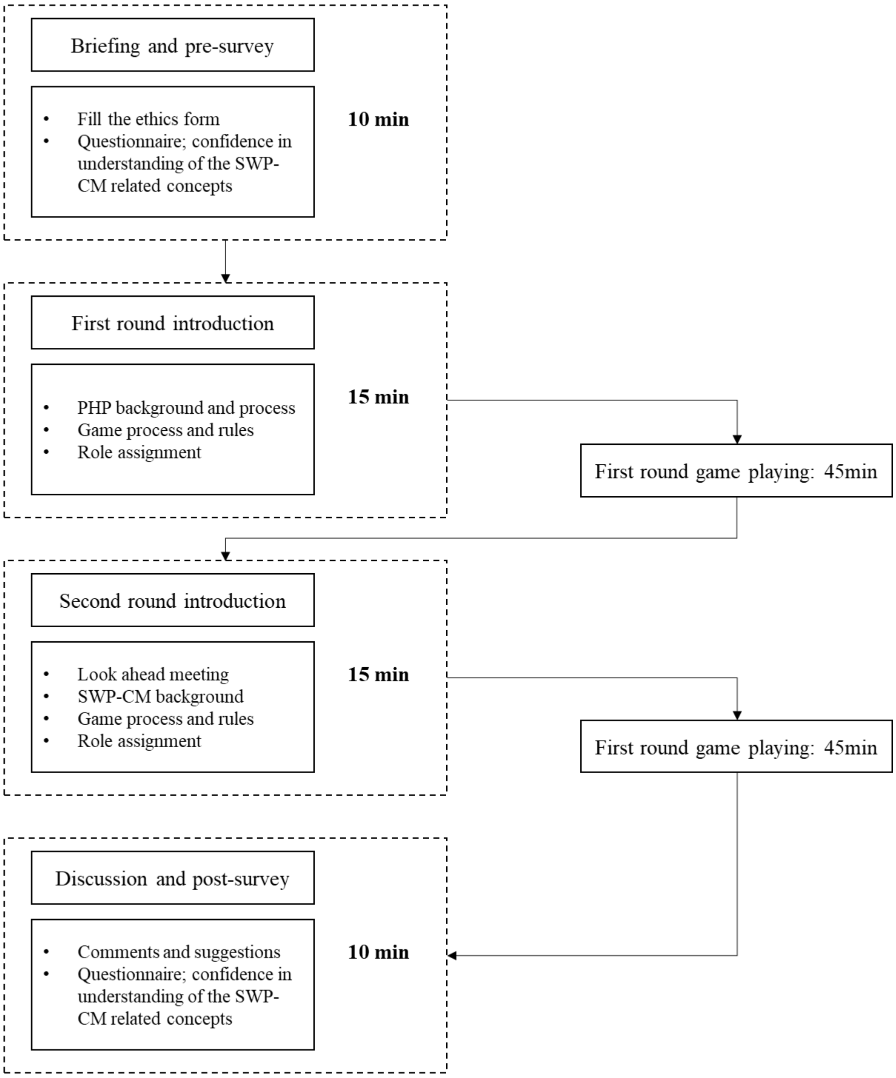


Figure 8.7 Workshop process

To evaluate the participants' confidence in understanding SWP-CM knowledge, a two-step evaluation process is adopted. Separate questionnaire surveys are conducted at the beginning and the end of the simulation game. The questionnaire contains ten questions to assess the confidence in understanding ten concepts, including prefabrication production structure, constraint management, standardized work, work package, JIT, pull/push, BIM, smart construction objects, information sharing and communication, real-time tracking and visualization. Participates are required to provide a rating about each question from 0 (not confident) to 10 (greatly confident). The differences in responses between the two surveys are analyzed by a paired sample t-test, if the data is normally distributed. The non-parametric test will be adopted if the data is not normally distributed. The normality is checked by Shapiro-Wilk test at a 0.05 significance level. Additionally, the radar chart is adopted to evaluate the variations of each question.

8.3 Results and Discussion

The ten questions are grouped into three aspects, including the concept of prefabrication (prefabrication production structure), lean philosophy & TOC (constraint management, standardized work, work package, JIT, pull/push), and information technologies (BIM, smart construction objects, information sharing and communication, real-time tracking and visualization). The radar chart (Figure 8.8) illustrates the average values of confidence in understanding the ten concepts in a scale from 0 (not confident) to 10 (greatly confident). The radar chart is widely adopted to monitor the improvement of multivariate data in practice (Salem et al., 2006) and education (González et al., 2015). The results indicate that all the participants have insufficient knowledge of SWP-CM concepts before the game and an average value of 3.59 is recorded. The post-game survey indicates an average value of 5.45; an increase of 51.8% on confidence in understanding SWP-CM knowledge. The improvements are identified in prefabrication production structure (from 3.81 to 6.43), standardized work (from 3.97 to 5.59), smart construction objects (from 3.62 to 5.72), information sharing and communication (from 3.63 to 5.72), real-time tracking and visualization (from 3.69 to 5.13). Thereinto, the constraint management concept is not only discussed and taught in the instruction stage of the RBL-based round, but also adopting advanced tools and methods to enhance the user experience in constraint identification, monitoring, and removal. This may lead to a significant improvement in this concept (from 2.62 to 5.66). The BIM technology has been widely discussed in the industry, leading to a marginal improvement in understanding the concept after the simulation game (from 4.84 to 5.97).

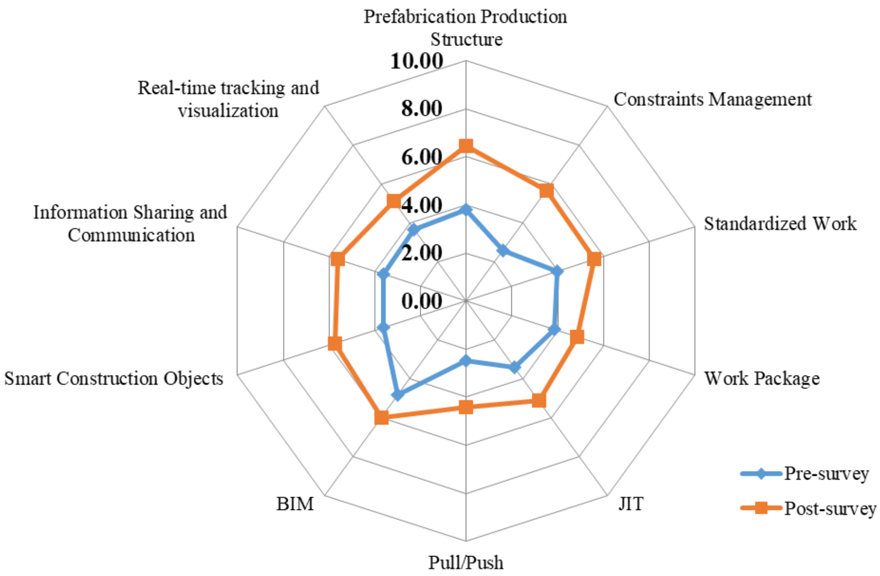


Figure 8.8 Average values of confidence in understanding the concepts

To explore the statistical significance of the above findings, the normality of results is tested by the Shapiro-Wilk test, which is shown in Figure 8.9, Figure 8.10 and Table 8.2. The null hypothesis is that the result is normally distributed. The *p*-values (0.076 and 0.172) in Table 8.2 are higher than the chosen significance level 0.05, indicating that the null hypothesis cannot be rejected. Meanwhile, the Q–Q plots and histograms) also verify the above conclusion.

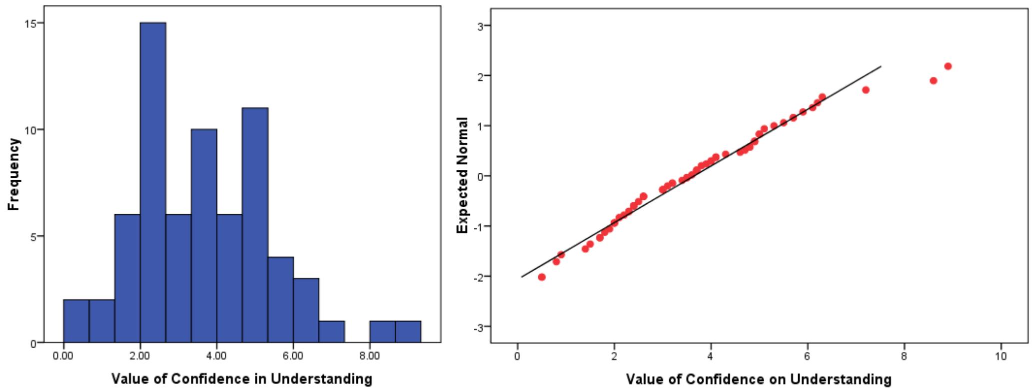


Figure 8.9 Histogram and Q-Q plot of ex-ante survey

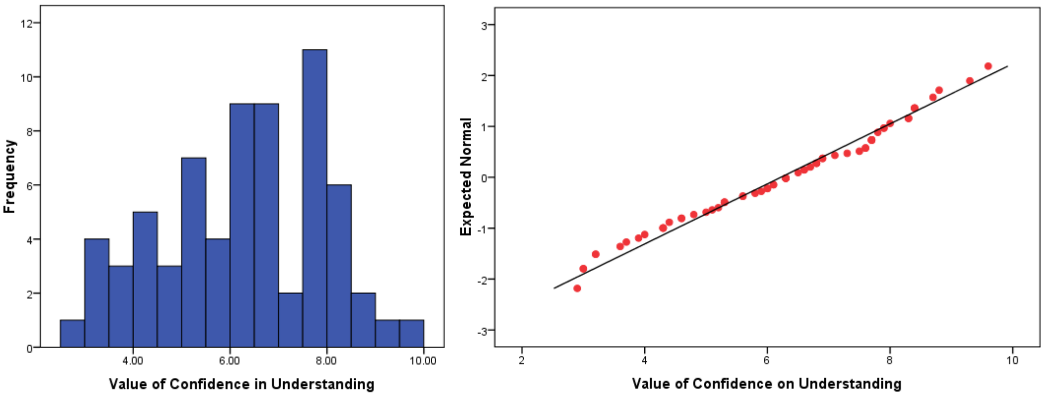


Figure 8.10 Histogram and Q-Q plot of ex-post survey

Table 8.2 Normality test of the two surveys by the Shapiro-Wilk test

Value of Confidence in Understanding	Shapiro-Wilk				
	Statistic	df	*p*-value	Mean	Std. Dev.
Ex-ante survey	0.968	68	0.076	3.65	1.77
Ex-post survey	0.974	68	0.172	6.22	1.694

The paired samples t-test are then applied to test the differences between the paired samples. The null hypothesis is that the true mean difference equals to zero. Table 8.3 shows the test results at a confidence interval of 95% and a 0.05 level of significance. The *p*-value (0.000) is much lower than the chosen significance level 0.05. This implies that the confidence in understanding SWP-CM knowledge after the simulation game is significantly improved.

Table 8.3 Paired-samples T-Test

	Paired Differences							
Value of Confidence in Understanding	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	*p*-value (2-tailed)
				Lower	Upper			
Presurvey-Postsurvey	-2.57	0.95	0.12	-2.80	-2.34	-22.30	67	0.000

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

8.4 Chapter Summary

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

The results demonstrate that this simulation game can help train and teach the participants about SWP-CM knowledge in a meaningful learning process. Participants (with and without industry experience) provide very positive feedback in applying this simulation game as a robust and efficient learning tool to integrate the information technologies, TOC, and lean construction principles into PHP. An average increase of 51.8% in understanding SWP-CM knowledge after playing this game is reported. Significant improvements are identified in understanding constraints management, prefabrication production structure, standardized work, smart construction objects, information sharing and communication, real-time tracking, and visualization.

There are several limitations to the current study. The level of modularization in real PHP projects is not as high as in the simulation game. Only the façade, staircase, ground floor water tank, panel wall, slab, and volumetric bathroom are prefabricated in real PHP projects in Hong Kong. In order to reduce the difficulties in tracking a large number of components in the RBIMP, the well-assembled unit is considered as one piece to transport to the construction site. Secondly, the logistics process is simplified in the simulation game due to its spatial constraints. Thirdly, the optimization approaches to resources management regarding people, materials, and equipment are not utilized in this simulation game. Further studies can be conducted to address these issues to improve the use of this simulation game.

CHAPTER 9 Conclusion

9.1 Introduction

This chapter first reviews the research aim and objectives to check whether they have been satisfied. Then, the key research findings are summarized, and the contributions to the body of knowledge and the industry are highlighted. Finally, the limitations and future studies are discussed.

9.2 Review of Research Objectives

Managing processes of prefabrication housing production (PHP), especially managing the on-site assembly process plays a vital role in achieving the project goals and performance. However, the schedule performance of PHP is still plagued by the constraints which are not be successfully satisfied in each task execution process. Thus, improving the capacity of constraints management is critical for preventing schedule delay. Since the work packaging method with the lean philosophy has been proved to be a practical approach for managing constraints, the constraints planning and control can be conducted in a certain detailed level. However, there is a lack of smartness in constraints modeling, optimizing, and monitoring. Therefore, this study intends to answer the following questions: “what kind of approach can improve the constraints management of PHP in a smart manner?” “How this new approach work on constraints management of PHP?”, “Can we disseminate it to the industry and education?”. To analyze and decompose the above questions. The aim and objectives of this research have been raised previously, see as follows:

The primary aim of this study is to develop an intelligent approach to manage the constraints of PHP in the on-site assembly process. This approach is developed under the context of product-oriented PHP and object-oriented BIM to help model, optimize, and monitor the constraints at a more detailed level for achieving value-added workflow. The specific objectives of this study are presented below:

(1) To define the concept and properties of smart work packaging (SWP), specify its functions and paradigm for constraints management (CM), develop its prototype representation, and propose the framework for SWP-CM.

(2) To develop the constraints modeling module in SWP for enhancing the sociability in the constraints identifying, mapping, and analyzing process;

(3) To develop the constraints optimizing module in SWP for improving the adaptivity in the constraints improvement process;

(4) To develop the constraints monitoring module in SWP for achieving the autonomy in the constraints tracking, updating and predicting process;

(5) To develop a simulation game for disseminating the concepts of SWP-CM in the industry and education.

To achieve Objective 1, Chapter 2 reviewed the challenges of current approaches for constraints management and the opportunities of smartness in PHP, which served as the theoretical foundation and solid reference for proposing smart work packaging. The findings of the review provided sufficient evidence to facilitate the establishment of the conceptual framework in Chapter 4. Chapter 4 clearly defined the SWP, specified its functions and paradigm for constraints management, and developed the framework for

SWP-CM. To achieve Objective 2, Chapter 5 provided a scenario to help identify the constraints, map constraints interrelationships, and conduct constraints analysis for achieving the function of constraints modeling. This constraints modeling service is developed by incorporating SNA and hybrid SD-DES model. To achieve Objective 3, Chapter 6 offered an optimization service to improve the most critical constraints (activity-level) identified in Chapter 5. The more specific constraints (task-level) in the most critical activity-level constraint were first prioritized, and a decision-making mechanism was developed to help conduct constraints improvement by considering the necessity. To achieve Objective 4, one specific task-level constraint was selected as the monitoring target. The deep learning algorithms are applied to build a monitoring service for tracking and updating the constraints status in a real-time manner. To achieve Objective 5, a role-play simulation game was developed to help train the students and practitioners with the related concepts of SWP-CM.

9.3 Summary of Research Findings

The key findings of this study are highlighted below.

Firstly, enlightened by the broadly accepted work packaging method and the SCOs model, the conceptual framework for defining and implementing smart work packaging (SWP) for constraints management in PHP is established. This framework has three primary functions, including constraints modeling, constraints optimization, and constraints monitoring. A layered abstract model as a prototype representation is also proposed to elaborate on the implementation of this framework for practitioners. Then a laboratory-based test is applied to validate the framework and concluded it could reduce 22.2% project duration with fewer defects and higher productivity. Through catalyzing current construction practices of the work packing method, SWP open new avenues for smart and sound constraints management for PHP projects.

Secondly, Proactive constraints modeling, including identifying these constraints and understanding their interrelationships, is crucial to ensure the task executions and enhance the sociability in collaborative working. However, current methods for constraints modeling are sluggish and heavily rely on human's commitments because there is no real-time information for decision-making. To address this issue, a constraints modeling scenario is proposed to establish the smart work packaging (SWP)-enabled constraints modeling service, which consists of three dynamic sub-services: social network analysis (SNA) service, hybrid system dynamics (SD)-discrete event simulation (DES) model service, and constraints scenario analysis service. It can equip the workers with the ability to (1) automatically identify the critical constraints, (2) dynamically explore interactional and interdependent relationships of these constraints, (3) simulate and analyze the impact on the schedule performance under different constraints scenarios. The five critical constraints are identified including C5_bad weather conditions, C14_lack of collision-free path planning, C20_lack of visible and audible communication mechanism, C22_lack of optimal buffer layout, and C23_lack of optimal installation sequence. Most interrelationships are depicted in the four modules of hybrid SD-DES model, including the assembly process, resource availability, operation efficiency, and schedule performance. Finally, the most influential constraint "C14_lack of collision-free path planning" to schedule performance is identified in the constraints scenario analysis process.

Thirdly, Lack of constraint-free crane path planning is one of the critical constraints in the dynamic on-site assembly process of prefabrication housing production. For decades, researchers and practitioners have endeavored to improve both the efficiency and safety of crane path planning from either static environment or re-planning the path when colliding with constraints or periodically updating the path in the dynamic environment. However, there is a lack of approach to the in-depth exploration of the nature of dynamic constraints and assist the crane operators in making adaptive path re-planning decisions by treating these constraints in different categories. To address this issue, the smart work packaging (SWP)-enabled constraints optimization service is developed as a scenario for constraints optimization. This service embraces the core characteristics of SWP, including adaptivity, sociability, and autonomy to achieve autonomous initial path planning, networked constraints classification, and adaptive decisions on path re-planning. This service is simulated and verified in the BIM environment, and it is found that SWP-enabled constraints optimization service can generate the constraint-free path when it is necessary.

Additionally, the fatigue of the crane operators is amongst the significant constraints can be selected as a scenario for monitoring. Otherwise, it may lead to inefficient crane operations and safety issues. Recently, many deep neural networks have been developed for fatigue monitoring of vehicle drivers by processing the image or video data. However, the challenge is to distinguish the slight variations of facial features among still and motion frames (e.g., nodding and head tilt, yawning, and talking). It can be exacerbated in the scenarios for crane operators due to their constant head moving to track the loads' position and recurrent communication (talking) with crane banksman. In contrast to previous approaches, which models spatial information and traditional temporal information for sequential processing, this study proposes a hybrid model as a constraint monitoring service can not only extract the spatial features by customized convolutional neural networks (CNN) but also enrich the modeling dynamic motions in the temporal dimension through the deep bidirectional long short-term memory (DB-LSTM). This hybrid model is trained and evaluated on the very popular dataset NTHU-DDD, and the results show that the proposed architecture achieves 93.6% overall accuracy and outperform the previous models in the literature.

Finally, the availability of appropriate training or pedagogical approaches to transfer and share the knowledge of SWP and constraints management has impeded their adoption. To address the issue, this research develops a hands-on learning tool, which is an advanced simulation game which simulates the process of PHP from manufacturing and logistics to the onsite assembly by integrating an RFID-enabled BIM platform with Lean Construction into training students and practitioners. Four workshops are conducted at Hong Kong Polytechnic University, Hong Kong, China, to assess the participants' learning experience by using ex-ante and ex-post surveys. In each workshop, the performance of PHP is tested separately in a traditional round and an SWP-enabled round on indicators including the percentage of the plan completed (PPC), extra cost, and the productivity index. The results indicate that the stability and efficiency of PHP are improved in the SWP-enabled round. In addition, the simulation game can significantly improve the understanding of various knowledge concepts in SWP-CM, such as prefabrication production structure, standardized work, work packaging, constraints management, smart construction objects, information sharing and communication, and real-time tracking and visualization. It can be adopted as a useful platform to effectively train practitioners in the PHP sector on the use of SWP-enabled constraints management approach.

9.4 Contributions of the Research

9.4.1 Theoretical Contributions to the Knowledge

This study makes theoretical contributions to the knowledge of prefabrication housing production (PHP) for constraints management in several aspects.

This study establishes the conceptual framework of SWP-CM, and the contributions are threefold. Firstly, Inspired by the theories of work packaging and SCOs, SWP is defined as PHP workflows which are decomposed in accordance with PBS of building systems that are made smart by augmenting with the capacities of visualizing, tracking, sensing, processing, networking, reasoning so that they can be executed autonomously, adapt to changes in their physical context, and interact with surroundings to enable more resilient process. And the three core characteristics of SWP are sociability, adaptivity, and autonomy. Secondly, equipped with three characteristics, a continuous improvement framework for constraints management with three functions, including constraints modeling, constraints optimization, and constraints monitoring are illustrated by several examples and scenarios. Thirdly, the SWP representation is proposed by developing a layered system model involving context provisioning layer (CPL), context integration layer (CIL), and smart work packaging layer (SWPL) to realize these three functions.

The contributions made from the constraints modeling are twofold: (1) enhancing the role of constraints management within dynamic modeling methods (e.g., SNA, SD, DES) and extending its contribution to achieving the sociability of the SWP at the task execution level. Previously, Li et al. (2018a) investigated the risk impact on the schedule performance of PHP and developed the hybrid dynamic model to improve the phase schedule which is a certain level of detail schedule covering general activities in PHP. However, there are many deterministic constraints have not been improved and removed in the more detailed schedule (e.g., daily work plan). In this study, it is assumed that the best way to improve schedule performance is to enhance workflow reliability at the work package level. (2) extending the process of constraints modeling upon the trades associated work package in a more structural and convenient way. The system dynamic models are established as reusable "task modules" to be encapsulated into the DES model. Thus, this hybrid model can be utilized to other PHP projects due to sufficiently generic nature of this model.

The contributions made from the constraints optimizing are twofold. Firstly, while acknowledging the merits of methods in traditional crane path planning and strategies in theoretical robot path planning, this study not only balances the efficiency and path quality but also consider the necessity in path re-planning by employing modified PRM, A*, and SWP_PathPlanner. Secondly, beyond the modeling and monitoring functions supported by SWP, this study argues for the optimization as a new dimension in the constraints management loop, which can improve the constraints in a more scientific manner.

The contributions made from the constraints monitoring are also twofold: (1) to detect and align the face, and extract the spatial features, the customized CNN is developed based on the baseline models which have excellent performance; (2) a deep bidirectional LSTM (DB-LSTM) is developed by considering both forward and backward dependencies to model the temporal pattern, which can learn compositional representations in space and time.

9.4.2 Practical Contributions to the Industry

This study proposes a practical approach of smart work packaging (SWP) with three functional services of constraints modeling, optimizing, and monitoring to equip the workers with the ability of constraints management in the prefabrication housing production (PHP). The contributions of this approach and this research in the industry are in the following aspects.

Firstly, the constraints modeling service can provide workers with a comprehensive understanding of constraints, relationships and interconnections, which is beneficial for identifying critical constraints and evaluating the delay caused by each constraint. The influence of delay can also be evaluated at an early stage or real-time to leave enough time for project teams to catch up.

Secondly, although this constraints optimization service only concentrated on the specific activity-level constraint optimization ("Lack of collision-free crane path planning”), this architecture of constraints optimization service can be extended and applied to other constraints improvement. The workflow of this constraint optimization service provides clear steps for other researchers interested in replicating dynamic path re-planning considering the necessity to the industry.

Additionally, the constraints monitoring service expands the vehicle driver drowsiness detection techniques to the crane operator fatigue monitoring and alerting. Automatically monitoring and warning the fatigue can provide timely support for crane operators, site superintendents, and safety directors to make the scientific shifts and breaks.

Finally, The simulation game enriches the learning tools of constraints management and SWP, particular in the PHP field, by integrating Lean construction principles into the RBIMP to simulate the process of PHP and adopting the Lego materials as the prefabricated components. Traditionally, students or practitioners learn the knowledge through a series of curricula or workshops by using chalkboards, handouts, and computer presentations, which often leads to negative feedback in learning effectiveness, especially when complex concepts are involved. In this research, the hands-on experience in a role-play simulation game can effectively and successfully transfer the knowledge to the students and practitioners in a vivid and thought-provoking environment. The pedagogical approach to disseminating the core concepts of modern PHP can remove constraints; enhance information sharing and communication, and realize real-time tracking in the PHP process.

9.5 Limitations and Future Research

This research not only intents to establish the theoretical framework of SWP-enabled constraints management in PHP but also provides three connected and practical scenarios to prove the validity and efficiency of the functions in SWP for constraints management. However, there are numerous limitations that need to be improved, and a significant number of future studies can be considered to enrich the body of knowledge in both SWP and constraints management in PHP.

9.5.1 Limitations of the Research

The limitations of this research can be summarized in five aspects.

Firstly, although the proposed theoretical framework of SWP for constraints management is a brand new view to improve the productivity and reliability of PHP processes, it still needs more validations from the real PHP projects in an integrated manner to enrich this approach from a practical aspect.

Secondly, for the constraints modeling service, the case study of crane path optimization is a) only a local optimization and its impact overall is likely to be marginal, but this has not been established empirically from site measurements of the existing state; b) it is not necessarily representative of the local optimization solutions that might be needed for other aspects;bc) it deals with optimization of a single operation within a process, and d) it does not deal with constraint removal, only constraint avoidance by path planning. Proactive constraint removal could be achieved, for example, by defining a virtual hoisting shaft space that is always free of obstruction, by controlling the other objects.

Thirdly, for the constraints optimization service, the continuation of changes in cost values of the path indicated by the distances between the path and specific constraint is the only information required in this study. Other sensory information of constraints in real-situation for decision-making and the uncertainty on the cost value of path caused by the sensory noisy will be considered in the future study.

Additionally, the constraints monitoring service only uses the dataset from vehicle drivers, and the dataset for crane operators has not been established. So it is still a laboratory-based test rather than the implementation in a real case. And the fatigue issues are highly specific and cannot be generalized to other monitoring problems, such as monitoring dimensional conformance of precast pieces

Lastly, not only the PHP processes but also the processes of constraints modeling, optimizing, and monitoring have been simplified in the simulation game. Particularly, the optimization approaches to each specific constraints are not adopted in this game.

9.5.2 Future Studies

SWP represents enormous opportunities to improve constraints management in PHP, particularly in conjunction with BIM. SWP can extract the context information (both physical and functional information) of product work packages from digital twin (BIM platform integrating with IoT). It can also insert the value-added as-built information into the BIM platform in a pull or push manner. SWP can also be combined with the IoT-enabled gateway to act as a loosely coupled, decentralized, multi-agent system to make the status of the constraints be connected at any time and anywhere. For example, constraints modeling service require enhancement for creating living digital simulation models by updating themselves from various sources to represent its near real-time modeling. Thus, the future study can focus on using sensor data, which conveys various aspects of the operating condition of SWP to generate the data-driven constraints modeling/optimization service. Additionally, devising more powerful features by combining multiple signals such as ECG, human audio, other physiological signals can be considered to achieve better accuracy and efficiency in constraint (fatigue) monitoring service.

It should be noted that SWP for constraints management is in the early stage of its development. There are several barriers to the development and implementation. For example, there are technical difficulties related to the integral approach in constraints identification and interrelationship mapping, the efficient algorithms for dynamic re-planning in constraints optimization, and robustness hardware (e.g., autonomous robots, vehicles, cranes) and software (location-based workflow engine, interoperability of connected system) for constraints monitoring. There are also challenges related to technology acceptance, organizational changes, and cost issue. However, by overcoming these challenges, it is believed that SWP can help establish safer, more adaptive, more proactive, more efficient and more sustainable PHP workflows.

Appendix I: Temporal Model in Constraint (Fatigue) Monitoring

```
class CreateModel(nn.Module):
    def __init__(self, args):
        super(CreateModel, self).__init__()
        self.args = args
        self.feature_dim = args.feature_dim
        self.device = args.device
        self.gpu_ids = args.gpu_ids
        if 'spherenet' in args.backbone:
            num_layers = int(args.backbone.split('spherenet')[-1])
            self.backbone = getattr(networks,
'spherenet')(num_layers, args.feature_dim, args.use_pool,
args.use_dropout)
        else:
            self.backbone = getattr(networks,
args.backbone)(args.feature_dim, args.use_pool, args.use_dropout)
        if args.pretrain:
            if args.backbone == 'spherenet20':
                path = '../pretrained/spherenet20_cvpr_backbone.pth'
            self.backbone.load_state_dict(torch.load(path))
            print('==> {} is
loaded.'.format('../pretrained/spherenet20_cvpr_backbone.pth'))
        self.backbone.to(self.device)
        # from torchsummary import summary
        # print(summary(self.backbone, (3, 112, 96)))

    def train_setup(self, class_num):
        if self.args.lstm:
            self.model_names = ['backbone', 'criterion', 'rnn']
            self.rnn = BiRNN(self.args)
            self.rnn.to(self.device)
        else:
            self.model_names = ['backbone', 'criterion']

        self.loss_names = ['loss_ce', 'lr']

        ## Setup nn.DataParallel if necessary
        if len(self.gpu_ids) > 1:
            self.backbone = nn.DataParallel(self.backbone)
            # if self.args.lstm:
```

```
            #     self.rnn = nn.DataParallel(self.rnn)

        ## Objective function
        self.criterion = getattr(losses, self.args.loss_type)
        self.criterion = self.criterion(class_num, self.args)
        self.criterion.to(self.device)

        ## Setup optimizer
        self.lr = self.args.lr
        self.save_dir = os.path.join(self.args.checkpoints_dir,
self.args.name)
        if self.args.lstm:
            classifier_params = list(self.criterion.parameters()) +
list(self.rnn.parameters())
        else:
            classifier_params = list(self.criterion.parameters())

        if self.args.pretrain:
            params = [{"params": self.backbone.parameters(), "lr":
self.args.lr/10},
                      {"params": classifier_params, "lr":
self.args.lr}]
        else:
            params = [{"params": self.backbone.parameters(), "lr":
self.args.lr},
                      {"params": classifier_params, "lr":
self.args.lr}]
        self.optimizer = optim.SGD(params, momentum=0.9,
weight_decay=5e-4)
        self.scheduler = MultiStepLR(self.optimizer,
milestones=self.args.decay_steps, gamma=0.1)

        ## Weight initialization
        # self.backbone.apply(weights_init)
        # self.criterion.apply(weights_init)

        ## Switch to training mode
        self.train()

    def update_learning_rate(self):
        self.scheduler.step()
        self.lr = self.optimizer.param_groups[0]['lr']

    def optimize_parameters(self, data):
```

```
        input, target = data
        self.score, self.loss_ce =
self.forward(input.to(self.device), target.to(self.device))
        self.optimizer.zero_grad()
        self.loss_ce.backward()
        self.optimizer.step()

    def get_current_losses(self):
        errors_ret = OrderedDict()
        for name in self.loss_names:
            if isinstance(name, str):
                # float(...) works for both scalar tensor and float
number
                errors_ret[name] = float(getattr(self, name))
        return errors_ret

    def save_networks(self, which_epoch):
        for name in self.model_names:
            if isinstance(name, str):
                save_filename = '%s_net_%s.pth' % (which_epoch, name)
                save_path = os.path.join(self.save_dir,
save_filename)
                net = getattr(self, name)
                if len(self.gpu_ids) > 1 and
torch.cuda.is_available():
                    try:
                        torch.save(net.module.cpu().state_dict(),
save_path)
                    except:
                        torch.save(net.cpu().state_dict(), save_path)
                else:
                    torch.save(net.cpu().state_dict(), save_path)

    def forward(self, input, target=None, is_feature=False):
        if self.args.lstm:
            # input in 'BLCHW' order
            B, L, C, H, W = input.shape
            input = input.view(-1, C, H, W)
            features = self.backbone(input)
            features = features.view(B, L, -1)
            features_lstm = self.rnn(features)
            if is_feature:
                return features_lstm
            else:
```

```
                return self.criterion(features_lstm, target)

        else:
            features = self.backbone(input)
            if is_feature:
                return features
            else:
                return self.criterion(features, target)

    def test(self):
        for name in self.model_names:
            try:
                if isinstance(name, str):
                    getattr(self, name).eval()
            except:
                print('{}.eval() cannot be implemented as {} does not
exist.'.format(name, name))

    def train(self):
        for name in self.model_names:
            try:
                if isinstance(name, str):
                    getattr(self, name).train()
            except:
                print('{}.train() cannot be implemented as {} does
not exist.'.format(name, name))


class BiRNN(nn.Module):
    def __init__(self, args):
        super(BiRNN, self).__init__()
        self.args = args
        self.lstm = nn.LSTM(args.feature_dim,
                            args.lstm_hidden_size,
                            args.lstm_num_layers,
                            batch_first=True,
                            bidirectional=args.lstm_bidirectional,
                            dropout=0.5)

    def forward(self, x):
        # Forward propagate LSTM
        out, _ = self.lstm(x)
        return out[:, -1, :]
```

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